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How downstream sub-basins depend on upstream inflows to avoid scarcity: typology and global analysis of transboundary rivers

We sincerely thank the reviewers and editor for their valuable comments on this manuscript. We greatly appreciate the reviewers' input in helping to point out areas of improvement. We agree with their concerns about definitions of dependency, which have encouraged us to provide further clarity. The definitions are now updated in the revised manuscript to hopefully clarify our key conceptual innovation. To address reviewers' concern regarding the complexity of the study, we have now simplified the transition map by considering only persistent scarcity and not occasional scarcity, which gives rise to four system regimes instead of 10. This simplification of the analysis will make the typology easier to understand without compromising the key novelty of the research or the main conclusions resulting from the study. We have also changed the case study from the Dnieper to the Oder river basin after leaving out occasional scarcity.

The reviewers have highlighted very useful points that helped us improve our originality by sharpening our conceptualisation, as well as description of why this approach to analysing upstream dependency is useful – tying especially to resilience literature about understanding system regime shifts. We have now split out a new sub-section in introduction - 'A resilience perspective on upstream dependency' to provide a useful way of thinking about this problem. Discussion has been modified substantially to address shortcomings and possible future work of this analysis in more detail.

Below we first reply to the editor's main concerns, followed by point by point responses to specific questions by the reviewers.

Response to Editor's comments

Comment 1: The paper is of some interest to better understand the dependency of downstream subbasin areas on upstream sub-basins. It is also quite cumbersome to read, in particular because some symbols are prone to confusion (e.g. S for stress or for scarcity or for shortage?). I find the two reviews illuminating, critical and very constructive. I expect the authors to benefit from these comments and to significantly improve the manuscript. In so doing, some choices have to be made. The authors must clarify the added value of their typology (Fig 6) for better understanding basin trajectories.

Response 1:

We are glad to hear that editor sees the interest in this topic and we are grateful for assistance in making it easier to read.

We have substantially revised the methodology, definitions used, as well as terminology. For the specific case of the symbol 'S', confusion arises from both 'stress' and 'shortage' being specific examples of scarcity, such that the symbol indeed stands for all three. In our revised manuscript, we

have now simplified the method considerably by dropping occasional scarcity and using only scarcity (S) and no scarcity (N) to identify different scarcity categories, which has now reduced the number of variables used in the analysis.

We have now reworked the argument underlying the transition map previously shown in Figure 6 (now Figure 5) to clarify its origins and motivation. The original concept for the analysis came from the literature on resilience of socio-ecological systems, which was not sufficiently acknowledged in the original submission. We regret the confusion that this omission has caused. Specifically, we use the definition from Walker et al (2004) that resilience is “*the capacity of a system to absorb disturbance and reorganize while undergoing change so as to still retain essentially the same function, structure, identity, and feedbacks*”. The state of the system is defined in terms of “*state variables*”, such that thresholds in those state variables are then used to define the points at which change occurs in the system function, structure, identity and feedbacks. As a short hand, we talk about a transition in system regime. Literature also talks about moving between basins of attraction and regime shifts. The former emphasizes stability and the latter tends to be associated with irreversible catastrophic failures. Our focus on transitions in system regime emphasizes simply that the system operates differently, in particular that structure, identity and feedbacks have changed (even if function may be preserved).

In our revised manuscript, we have added this description to clearly connect the study to the resilience literature. Introduction has been updated significantly to provide the link to the resilience literature in a new sub-section (1.1) in introduction- ‘*A resilience perspective on upstream dependency*’ -

“‘Resilience’ of a socio-ecological system is defined as “the capacity of a system to absorb disturbance and reorganize while undergoing change so as to still retain essentially the same function, structure, identity, and feedbacks” (Walker et al. 2004, p.01). Changes in the system are tracked in terms of ‘state variables’, such that thresholds in those state variables are used to define the points at which change occurs in the system function, structure, identity and feedbacks. When a threshold is crossed and changes occur, we say that the system has moved to a different ‘basin of attraction’, that there has been a ‘regime shift’, or a ‘transition between system regimes’. While some studies aim to quantify resilience, we focus on identifying circumstances in which these regime shifts occur.

Understanding thresholds and regime shifts is considered critical to adaptability and transformations in transboundary basin management (Green et al. 2013). In the case of upstream dependency, we would distinguish between different system regimes depending on whether or not water scarcity occurs and whether or not dependency occurs and its implication in the prevention of scarcity. Dependency occurs in a region when there is a transition between scarcity system regimes when considering cases where water is or is not available from upstream. We therefore compare whether scarcity occurs when water availability is calculated using solely local runoff, natural discharge (sum of local runoff and upstream runoff), and actual discharge (subtracting upstream water withdrawals from natural discharge). System regimes categorized as ‘Scarcity’ and ‘No scarcity’ are distinguished by a change in function of the system – water becomes insufficient in some sense. For the purpose of developing our analytical framework, occurrence of scarcity is determined using commonly used water shortage and water stress indicators (further discussed in Section 2.2.2). Water scarcity can also be socially induced. That is, social systems rather than climatic or hydrological factors are determining, disadvantaging groups within society, often those marginalised (Mehta 2013). Management actions may enable water to become sufficient and demonstrates a case where structural changes occur, and therefore also a transition between system regimes. However, as a first step to operationalize the concept of physical dependency over water, we focus on thresholds of physical scarcity, following existing studies (Brown and Matlock 2011, Kummu et al. 2010, Porkka et al. 2012).

Transitions in system regimes in terms of dependency can occur over time, and regions can be classified according to their dependency category. Based on the role of upstream inflows and withdrawals, a region

might experience: i) no dependency if scarcity is not affected by upstream inflows, ii) unbroken dependency if scarcity category is altered by upstream inflows but not by upstream water withdrawal, or iii) broken dependency if scarcity is altered after accounting for upstream water withdrawals. If a system transitions into an unbroken dependency regime, the structure of the system changes – upstream withdrawals can now alter the scarcity category. An unbroken dependency is potentially hidden: a downstream part of a basin might be avoiding water scarcity only thanks to upstream inflows, and water users may not actually realise this causal factor unless those inflows are no longer available, due to increased upstream withdrawals or lower upstream runoff due to climate change or variation. That is, there is a transition to a broken dependency regime, which can also occur due to further increases in local demand. The system may then have a loss of function (insufficient water), or change in structure (due to management actions). Examining these system regimes helps to understand possible transitions of a region, and the actions that may be needed to avoid or control transition processes, e.g. negotiating water treaties to prevent or smooth transition to a broken dependency regime. We emphasise repeatedly throughout this article that upstream withdrawals may also affect the intensity of scarcity – our focus here is specifically on transitions between regimes.” (Page 2, L56-L95)

We agree with the reviewers that the original typology used in the analysis was complex and gave rise to many new terms and definitions, which were difficult to follow. The complexity arose naturally when taking into account i) both persistent and occasional scarcity and, ii) min and max of local runoff, natural discharge and actual discharge. These conditions resulted in altogether 10 system regimes (in Figure 4 of the original submission), connected by a complex map of transitions. To reply to the reviewers' comments, we have now simplified the approach and we consider only persistent scarcity and no scarcity, leaving out occasional scarcity and using average discharge instead of min and max (as suggested by *Reviewer 1*). This simplification now gives rise to four system regimes (updated Fig. 4), connected by a simple map of transitions: NNN-SNN-SNS-SSS (updated Fig. 5).

In our revised manuscript, original Figure 6 has been removed and Figure 5 has been updated to capture the changes in the transition map. Though the typology of transitions is simplified, it still distinguishes between different experiences of scarcity and dependency as upstream withdrawals increase or decrease under each dependency type. These are discussed now in more detail under discussion-sub-section (4.1) *What are the implications for mitigation and prevention of scarcity?* -

“The literature on resilience and complex adaptive systems emphasises that it is difficult to predict what will happen in future, but we can identify what are the transitions that might occur to prepare ourselves such that the system either avoids or manages those transitions.” (Page 13, L371-L373)

And also in page 13, L385-391:

“Understanding these transitions provides a basic level of guidance for a region. In a no dependency system regime (e.g. most SBAs analysed), efforts can be made to keep water demand at low enough levels to be self-sufficient. If water demand is expected to increase, monitoring is useful to avoid being surprised by the breaking of a hidden dependency. While our analysis shows relatively few broken or unbroken dependencies in 2010, population growth and associated water demand means that the need for water scarcity-related negotiation in transboundary basins could become a much greater issue in future. It is specifically the emergence of dependencies that introduces the need for negotiation.”

Sub-section 2.2.4 *'Typology of possible transitions in dependency category'* from the previous manuscript has been removed and significant modified text has been added in sub-section (2.2.3) – *'Determinants of dependency category and possible transitions in them'* –

“So far, we have conceptualised change in dependency category in the context of a fixed set of water availability thresholds, obtained directly from estimated water availability volumes. The order of thresholds determines the transition in dependency category as local demand increases or decreases. In fact, even if upstream WW changes the values of the thresholds, their order will remain the same. These scarcity thresholds are naturally ordered because local water necessarily becomes insufficient before upstream water availability types respectively: $local \leq actual \leq natural$. We do, however, distinguish between headwaters vs middle stream and downstream SBAs.

Headwaters are the simplest case. Given they are the most upstream SBAs, they rely solely on local runoff, Increases in an SBA’s demand cause transition from ‘no scarcity’ to ‘scarcity’ category. Decrease in demand would have the opposite effect (Fig 5).

In the case of middle stream and downstream SBAs, transition occurs between four scarcity categories, which are connected by a simple map of transitions: NNN-SNN-SNS-SSS. Transition in the scarcity category depends on both local demand and upstream WW. As the local demand increases, the SBA moves from NNN to SNN, exposing it to a ‘hidden dependency’ as local runoff become insufficient, but the SBA still receives sufficient upstream inflows to meet the local demand. The next transition between SNN to SNS is dependent on both local demand and upstream WW until local demand increases to the level where all available water become insufficient - the SBA becomes SSS. The decrease in local demand and upstream WW will have the opposite effect.

Thus SBA crosses thresholds which not only change the scarcity category, but also change the dependency category, considered in this study as transitions between different ‘system regimes’. Note that we focus on the effect of increasing or decreasing local demand and upstream water withdrawal, leaving changes in water availability to future work.” (Page 9, L290-L310)

Comment 2: I have one significant problem with the paper, namely that the approach is completely blue water biased and green water blind – 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.

Response 2:

We agree that the paper is completely blue water biased, and it was indeed a shortcoming not to mention green water at all. Specifically, we can consider the effect of green water availability on three crucial variables in our analysis: *avail.local* (local runoff), *avail.natural* (natural discharge, i.e. including possible discharge from upstream), *avail.actual* (actual discharge, i.e. taking into account upstream water use). Green water availability increases the amount of locally available water (*avail.local*) by including soil water in addition to runoff. This affects scarcity, as the need for blue water should vary in response to changing green water availability, e.g. when there is less green water available, more blue water is needed. Decreases in availability of blue water (e.g. due to upstream withdrawals) may also push a region to use more green water. This is, however, a rather complex issue and not easy to quantify.

It is, however, important to note that green water is an important part of the local water availability, but by definition, it does not affect inflows from upstream. Water is called “green water” when evapotranspiration occurs directly from rain or soil water, without runoff occurring. There is no additional effect on *avail.natural*, other than that on *avail.local*. Incorporating green water into our analysis will not affect our *avail.actual* data either, as upstream withdrawals are in principle already accounted for in the water use model (including the effects of green water availability).

The thresholds for both water shortage and stress are highly uncertain, so the effect of green water on our results is difficult to anticipate. We now explicitly mention the importance of green water in the discussion, including these points.

Text has now been added to the new sub-section (4.3)-‘*Limitation and Future work*’ –

“Availability of green water has not been considered either. Green water increases the amount of locally available water by including soil water in addition to runoff. This affects scarcity, as the need for blue water should vary in response to changing green water availability, e.g. when there is less green water available, more blue water is needed. Decreases in availability of blue water (e.g. due to upstream withdrawals) may also push a region to use more green water. While green water is an important part of the local water availability, it does not affect inflows from upstream, by definition. Water is called “green water” when evapotranspiration occurs directly from rain or soil water, without runoff occurring. There is no additional effect on avail.natural, other than that on avail.local. Incorporating green water into the analysis will not affect avail.actual data either, as upstream withdrawals are in principle already accounted for in the water use model (including the effects of green water availability). The thresholds for both water shortage and stress are highly uncertain, so the effect of green water on the results is difficult to anticipate.” (Page14-page15, L460-L469)

Comment 3: Related to this I have problems with the use of Falkenmark’s per capita water availability as a measure of water scarcity (which the paper distinguishes from water stress). This is an old (1970s!) and very crude measure (with highly arbitrary thresholds of 1,700m³/cap/year for stress, and 1,000 m³/cap/year for water scarcity). It was precisely Prof. Falkenmark who later introduced the very important concept of green water, which taught us that it matters a lot whether one lives in a humid (with a lot of green water) or an arid (little green water) climate, how much blue water one needs. So fixed global threshold values do make little sense. Perhaps the paper does not need to use this flawed concept at all – omitting it may not alter the results nor the conclusions.

Response 3:

We entirely agree that per capita water availability has limitations as an indicator. But we still think that both stress and shortage are useful indicators of the more general concept of scarcity. Shortage, measured by per capita water availability, captures an important intuition that sufficiency of water availability depends on population. Leaving out shortage would mean that only the stress indicator is used. This would give the impression that it is only high water use that should be avoided, not deficiency in human needs. Even though, the thresholds are arbitrary, it provides a useful balance to understand the development of water scarcity (Kummu et al. 2016), as well as illustrating the generality of our analysis framework.

We already explicitly acknowledge that these are simplistic indicators, and highlight options for future work in original submission as –

‘the use of these thresholds is in line with existing studies and while there are notable limitations including that of simplification, we nonetheless utilize them as a first step in understanding upstream dependency.’ (page 8, L188-L189) & ‘Additional insights may be gained using other thresholds and/or other water scarcity indicators, such as food self-sufficiency (Gerten et al. 2011, Kummu et al. 2014) or sustainability of water withdrawals (Wada and Bierkens 2014)’ (page 21,L491-L492).

In our revised manuscript we now address this issue more explicitly in the sub-section (2.2.2)-
'Interpretation of upstream dependency in terms of water scarcity'-

'Falkenmark's per capita water availability as a measure of water scarcity has limitations as an indicator. Nevertheless, both stress and shortage are useful indicators of the more general concept of scarcity. Shortage, measured by per capita water availability, captures an important intuition that sufficiency of water availability depends on population. Even though the thresholds are arbitrary, using both indicators provides a useful balance to understand the development of water scarcity (Kummu et al. 2016), as well as illustrating the generality of the analysis framework. The use of these thresholds is in line with existing studies and while interpretation of the results is limited by the simplicity of the indicators, they provide a first step in understanding upstream dependency.' (Page 7, L213-L219)

Comment 4: A second concern that was not raised is the concept of environmental water requirements / environmental flow requirements (EFRs), which are water flows that literally run through all the SBAs and that are untouched by the riparians to safeguard the survival of aquatic ecosystems and the like. How would these feature in the typology? Atleast in the discussion section I would expect a reflection of the proposed method and how, if at all, EFRs could be included.

Response 4:

We agree that EFRs are important in transboundary water management. In addition, we agree that the paper should also have explicitly mentioned environmental flow requirements. The original manuscript did mention in passing "sustainability of water withdrawals" (page-21, L492) but we did not elaborate the issue further. In fact, the stress indicator does include environmental flow requirements, assuming 30% of the water is needed to satisfy EFRs (reference to Falkenmark et al. 2007 for example). It is true that we do not account for EFR in a spatially disaggregated way. In preparing this response, we did test the use of spatially variable EFRs, and note that doing so means that EFR becomes a factor that influences how stress changes between the three water availability types, i.e. it is a factor that influences dependency regime transitions. This introduces additional changes and additional complexity which makes the transition map more complex and more difficult to explain – and therefore better addressed in later publications. Moreover, global scale EFR methods could be criticized for not adequately capturing on the ground conditions – our treatment of environmental flows is fit for purpose given that our focus is on the resilience-based analytical framework.

In the revised manuscript, we now explicitly mention this in the new sub-section (4.3) in discussion-
'Limitations and future work'-

"EFRs (i.e. environmental flow requirements) are important in transboundary water management. The stress indicator used in the analysis includes EFRs, assuming 30% of the water is needed to satisfy the EFRs (reference to Falkenmark et al. 2007 for example). We do not account for EFR in a spatially disaggregated way as the analysis is conducted in the SBA scale, where spatially variable EFRs influences the dependency category, adding additional complexity to the transition map. EFRs are in any case a rather complex issue and not easy to quantify (Pastor et al. 2014). Global scale EFR methods could be criticized for not adequately capturing on the ground conditions –our treatment of environmental flows is fit for purpose given that our focus is on the resilience-based analytical framework." (Page 14, L451-L457)

Responses to Reviewer 1

The paper analyses the different types of dependency of downstream sub-basin areas (SBAs) on upstream SBAs, and provides a global overview of the types of dependency in 2792 SBAs. That is potentially interesting. However, the concepts used are not completely convincing and they are not always used consistently. Moreover, parts of the paper are overly complex.

Response:

We sincerely thank you for your valuable comments on this manuscript. When revising the manuscript, we have considered all the comments and incorporated your suggestions to make the paper more understandable. Detailed answers to the specific questions are given below.

Comment 1: The paper distinguishes three types of dependency of downstream SBAs on upstream SBAs: no dependency, continuous dependency, and intervened dependency. According to the definition in table 1, no dependency means that for the SBA local runoff is sufficient. Yet, in table 3 and elsewhere other cases are qualified as "no dependency" as well: SBAs that experience occasional or persistent scarcity even if they were to receive all natural runoff from upstream. That is not consistent. Moreover, in the latter cases dependency on upstream SBAs is actually high: there is already little water, and every extra drop that is used upstream results in even less water for the downstream SBA.

For these cases, I would introduce a fourth type of dependency, which might be called "absolute dependency"

Response 1:

First, we thank the referee for pointing this out. We agree that the definitions given in the original Table 1 were not clear enough, and somewhat inconsistent with usage elsewhere in the paper. We revised the definitions and ensure in the revised manuscript that those are consistent throughout the paper. Further, we have now simplified the method of our analysis significantly to better communicate with the reader (please check our response to *Editor comment 1*). The most reliable definitions are in terms of scarcity experienced with local runoff, natural discharge and actual discharge (updated Figure 4, see response to *Editor comment 1*), and the text definitions are our attempts at making these less technical.

By 'No dependency', we mean that "*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. Note that the severity of scarcity may still be affected by upstream inflows*". Sufficiency of local runoff is a special case corresponding to the category NNN. A category SSS also implies no dependency – a sub-basin (SBA) under SSS experiences scarcity but this is not influenced by upstream inflows or water use. In other words, the sub-basin is under the same scarcity conditions regardless of upstream influence.

Secondly, the reviewer's description of absolute dependency refers to the severity of scarcity rather than whether or not scarcity is present or whether upstream conditions or actions influence it. We do already acknowledge that upstream inflows can change how severe scarcity is when it occurs. While we have studied this issue previously (Munia et al. 2016), this is not the focus of the current analysis.

We are instead making an argument that it is an important distinction to know whether a region would experience scarcity regardless of upstream additional inflows, or whether withdrawals might cause a scarcity category to shift. Introducing a new term (e.g. absolute dependency) would, in our opinion, make things even more complicated; we hope revising the definitions clears up the confusion.

In our revised manuscript, we updated the definitions in Table 1 (Page 3, L97-L98) and elsewhere to be more accurate and consistent. The updated definitions are:

Term	Definition
Water stress	<i>Demand driven water scarcity, calculated as use to availability ratio</i>
Water shortage	<i>Population driven water scarcity, calculated as water availability per capita</i>
Local runoff	<i>Runoff occurring internally within a region (in this paper a sub-basin).</i>
Upstream runoff	<i>Runoff of the possible upstream region (in this paper a sum of runoff of upstream sub-basins)</i>
Natural discharge	<i>Total water availability before taking into account possible upstream water withdrawals, here calculated as local runoff + upstream runoff.</i>
Actual discharge	<i>Total water availability after upstream water withdrawals; calculated as natural discharge – upstream withdrawals (local runoff + upstream runoff – upstream withdrawals).</i>
No dependency	<i>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. Note that the severity of scarcity may still be affected by upstream inflows and water withdrawals.</i>
Dependency	<i>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. Two sub-types of dependency can be distinguished (as follows).</i>
Unbroken dependency	<i>Scarcity category is altered by upstream inflows but not by upstream water withdrawals, i.e. additional water from upstream means the region experiences no scarcity instead of scarcity and upstream withdrawals do not change this.</i>
Broken dependency	<i>Scarcity category is altered after accounting for upstream water withdrawals, i.e. withdrawals mean that the advantages gained by upstream inflows are reduced or eliminated, and more intense water management regimes are needed downstream.</i>

Comment 2: (a) Continuous dependency is defined in two slightly different ways: on p. 2 as scarcity that is avoided thanks to upstream inflow, and in table 1 as a region that would experience scarcity if it did not have access to upstream inflows. The latter formulation seems to include actual water scarcity as a result of upstream water withdrawals ("intervened dependency"). This is probably an inaccuracy.

(b) More problematic is that “continuous dependency” covers very different cases: cases where upstream inflow is so big that downstream scarcity is just a theoretical possibility, and cases where downstream scarcity is a serious threat because of concrete plans to increase upstream withdrawals (or plans to increase water use downstream or the effects of climate change). It would be good to distinguish between these situations, at least in the discussion.

(c) In addition, I would replace the term "continuous dependency" by for instance "potential dependency" because there is no dependency if scarcity is just a theoretical possibility. “Intervened dependency" could then become "actual dependency."

Response 2: We reply below to each of the three points raised by reviewer:

- a) The idea is to distinguish a situation where scarcity is avoided thanks to upstream inflows from a situation where scarcity does occur with upstream withdrawals, but would have been avoided with natural upstream inflows. They should therefore be mutually exclusive, but are nested in some sense.

We agree that the definitions caused confusion and have now been clarified. (also see our responses to *Reviewer 1 comment 1*).

- b) We thank the reviewer for this interesting observation. We have now modified the presentation of analysis to emphasise the idea that conditions with no scarcity (N) and scarcity (S) represent fundamentally different system regimes. We explicitly note that we only use simple indicators of scarcity, and encourage further work that would more rigorously investigate what it means to experience scarcity, including identifying what levels of threshold are meaningful. Future work could also quantify “distance” from a threshold, which would further address the distinction between the reviewer’s two cases as we now mentioned in the text -

“Future work could also quantify “distance” from a threshold, which would further address the distinction between how close these basins are to scarcity.” (Page 15, L481-L482)

The discussion section of the paper is now revised to capture these limitations under sub-section (4.3) *Limitations and future work*– thank you for the suggestion.

- c) The reviewer’s suggestion of replacing the term "continuous dependency" by “Potential dependency” is, in our opinion, not accurate. “Potential” dependency would imply that the dependency is not currently realized. However, it is only scarcity that is not realized – scarcity is being avoided because of upstream inflows and the sub-basin therefore does not have to deal with it. The dependency is very real, it is not just a theoretical possibility – the sub-basin does need to deal with the fact that upstream withdrawals may cause them to experience scarcity. In the case of “Intervened dependency”, upstream inflows no longer help – the dependency is broken – and scarcity is realized. We have now used the terms ‘Broken’ dependency instead of intervened dependency and ‘Unbroken’ dependency instead of continuous dependency in our revised manuscript.

Comment 3: To calculate water availability in the different SBAs, the paper uses the PCR-GLOBWB model. It is not clear to me whether and how return flows were taken into account. Especially for industrial and domestic water withdrawals these can be significant.

Response 3:

In this analysis, we have used water withdrawals to calculate scarcity. Water withdrawals refer to the total amount of water withdrawn, but not necessarily consumed, by each sector; much of which is returned to the water environment where it may be available to be withdrawn again. The return flows from industrial and domestic sectors have been taken into account in PCR-GLOBWB and the recycling ratios for industrial and domestic sectors have been estimated (roughly 40-80%) and validated at a country level based on Wada et al. (2011a, 2014). We refer to Wada et al. (2011a, 2014) for the detailed descriptions. However, in this paper, 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). Thus, the return flow was not subtracted from withdrawals in the paper.

The revised *Data* section (2.1) is now explicitly mentioning this-

“The return flows from industrial and domestic sectors have been taken into account in PCR-GLOBWB and the recycling ratios for industrial and domestic sectors have been estimated (roughly 40-80%) at a country level and validated based on Wada et al. (2011a, 2014).” (Page 4, L133-L135)

The ‘*Limitations and future work section*’ (4.3) of the revised manuscript also explicitly discuss this issue.

“we used water withdrawals, which refer to the total amount of water withdrawn, but not necessarily consumed, by each sector; much of which is returned to the water environment where it may be available to be withdrawn again. The return flows from industrial and domestic sectors have been taken into account in PCR-GLOBWB and the recycling ratios for industrial and domestic sectors have been estimated and validated (roughly 40-80%) at a country level based on Wada et al. (2011a, 2014). However, in this paper, 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). We therefore did not include return flows when calculating water stress, but could in future.”(Page-14, L443-L450)

Comment 4: The authors distinguish between occasional scarcity - scarcity that occurs only in a dry year - and persistent scarcity - scarcity that also occurs in a wet year. They do not define wet year and dry year. What return period is used? And why not use instead of wet year average year? Wet year water availability seems to me a very shaky basis for water scarcity management. Please reflect on this.

Response 4:

In the original submission, wet year and dry year were selected by taking into account the highest and lowest discharge occurred in 30 years (1981-2010) period respectively. To simplify the study, we are now using only scarcity and no scarcity, leaving out occasional scarcity. We now use average water availability instead of wet and dry years (please see also our response to *Editor Comment 1*).

However, given that the discussion paper will remain in the public record, we still wish to clarify why we included occasional scarcity. Our aim was to focus on transitions between system regimes that

would require changes to either local water demand or upstream water withdrawals (WW). Our distinction between occasional and persistent scarcity was intended to capture differences in how each type of scarcity needs to be handled. We justify the division to these two scarcity types in L222-L223 of the original manuscript, '*While persistent scarcity is obvious because of low water availability in relation to water demand, people may not necessarily be prepared for occasional scarcity, or may need adaptive measures to be actively implemented*'. It is, however, difficult to specify the conditions where adaptive vs persistent measures are needed—our definition of occasional scarcity in terms of the simple stress and shortage indicators is only indicative. Additionally, we acknowledge it is problematic that the term “occasional” applies even if only a single year has sufficient water available. We believe including occasional scarcity in future analyses is still worthwhile, especially if these limitations can be addressed.

Comment 5: My most important concern is that the typology of possible transitions in dependency category is very complex and it is not clear to me how useful this typology is. What downstream SBAs need to know is how total water availability may change as a result of climate change, how water use upstream may develop, and what their own plans and expectations are concerning water use in their own SBA. On that basis they can anticipate (an increase in) water scarcity and decide to enter into negotiations with upstream SBAs. They do not need and probably would not benefit from a full overview of groups and orders of possible transitions in dependency category.

Response 5:

As we mentioned in our response to *Editor comment 1*, it is difficult to predict what will happen in future as there is significant uncertainty around future total water availability, upstream water use and even local changes in water use. The importance of a transition pathway is that, even if we cannot anticipate the future, we can map out possible or potential transitions between system regimes that sub-basins may face, which affects both local management actions and relationships with riparian neighbours. We have now simplified our analysis significantly (see our response to *Editor Comment 1*).

The introduction, results and discussion are considerably revised to add more context regarding the importance of this analysis, tying to literature and terminology relating to resilience in socio-ecological systems. The typology of transitions is also simplified, while still distinguishing different experiences of scarcity and dependency as upstream withdrawals increase or decrease under each dependency type (see our response to *Editor Comment 1*).

Comment 6: Finally three suggestions for the presentation.

- (a) First, the different formulation in line 255 can be simplified and made more uniform by removing "reliable" and "less reliable" and putting "dry year" and "wet year" (or "average year") always at the same place.**
- (b) Secondly, if no scarcity is N, occasional scarcity is O, why not use P for persistent scarcity?**
- (c) And thirdly, in table 4 the order in every column could be the same, e.g. always first no scarcity, then occasional scarcity, and then persistent scarcity.**

Response 6: Thank you for the suggestions.

- a) Consistent with our reply of *Reviewer 1 comment 4*, we will now be using 'average year', such that the terms "reliable" and "less reliable" are no longer relevant.
- b) We agree that this would have been clearer. As we dropped the occasional scarcity, in our revised manuscript we are now using only 'S' for scarcity (stress or shortage) and 'N' for no scarcity.
- c) In our revised manuscript, we now focus on average years instead of wet years and dry years. As a result, Figure 4 (check *Editor Comment 1*) has changed significantly. We have now also arranged the columns from low to high scarcity.

Responses to Reviewer 2

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.

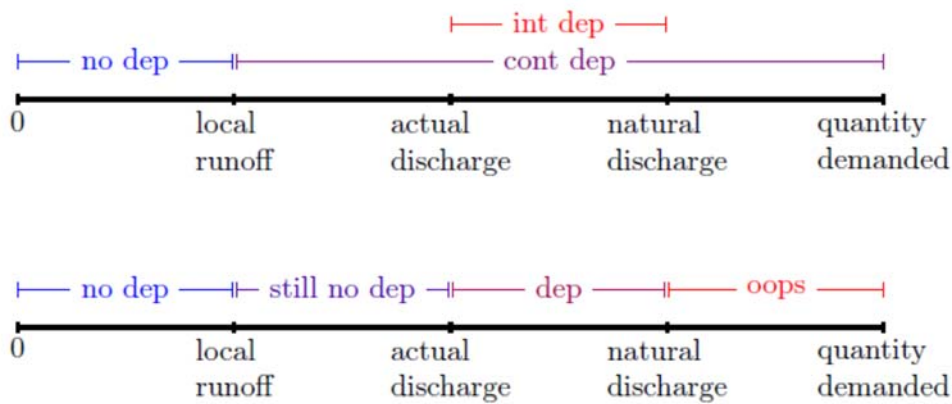


Figure 1: Dependency. Top plot according to Table 1. Bottom plot proposed by reviewer.

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, SNN, 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 both with and without scarcity. 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 sub-basin area (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 in Table 1.

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 sub-section (2.2.3) - *Determinants of dependency category and possible transitions in them* –

"In this study, 'demand' is used as a high-level umbrella term covering both actual withdrawals (for the stress indicator) and need for water (population, for the shortage indicator)." (Page 9, L274-L275)

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*) referred in the original submission 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 considered 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 are using *avail.actual* instead of *avail.afterup* and 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 have revised the order of presentation in Table 1 accordingly.

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 q_i denotes water use in sub-basin i , e_i denotes local runoff, and P_i 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:

- $x_i \leq e_i \rightarrow$ no dependency;
- $e_i < x_i \leq \hat{e}_i \rightarrow$ still no dependency (see bottom plot of Figure 1);
- $\hat{e}_i < x_i \leq \bar{e}_i \rightarrow$ 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 has been revised to reflect these links with treaties under section 4.1 ‘*What are the implications for mitigation and prevention of scarcity?*’ –

“While our analysis shows relatively few broken or unbroken dependencies in 2010, population growth and associated water demand means that the need for water scarcity-related negotiation in transboundary basins could become a much greater issue in future. It is specifically the emergence of dependencies that introduces the need for negotiation. Treaties have an indirect effect on physical upstream water dependency by limiting or coordinating development of water resources locally and upstream. Treaty design can be innovated to include functions that improve the stability of the dependency and hence prevent scarcity from occurring. If decision makers cannot avoid a transition to scarcity (i.e. a broken dependency), perhaps due to factors outside their control, then coordination can at least facilitate adaptation to cope with physical water scarcity. There are regions where physical water scarcity is to some extent expected – development is limited by water availability, such that fully utilising other resources (e.g. land) requires more water than is available. In addition, it should be pointed out that negotiation for rights to upstream inflows is only one strategy among many to try to meet water demand. In such cases, treaties can focus on mitigating the severity of impacts of scarcity.”(Page-13, L388-L399).

Minor Comments:

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

Response 5: The manuscript is corrected.

Comment 6. L53: ‘experiences’ → ‘may experience’.

Response 6: The manuscript is corrected.

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

Response 7: Manuscript has been updated.

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 now reworded the sentence to provide a stronger link with the dependency regime and avoid implying presence of an actor. Sentence is now revised as follows:

“If a system transitions into an unbroken dependency regime, the structure of the system changes – upstream withdrawals can now alter the scarcity category. An unbroken dependency is potentially hidden: a downstream part of a basin might be avoiding water scarcity only thanks to upstream inflows, and water users may not actually realise this causal factor unless those inflows are no longer available, due to increased upstream withdrawals or lower upstream runoff due to climate change or variation.” (Page-2, L85-L89)

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, with water availability calculated as summary values (in the new version, average water availability).

Explanation added in the sub section 2.2.2-*Interpretation of upstream dependency in terms of water scarcity* –

‘The 30-year period was used to capture the current hydro climatic characteristics.’(Page 7, L227)

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 (4.3) of the revised manuscript also explicitly discusses this issue (Page-14, L445-L450) (*Please see our response to Reviewer 1 comment 3*)

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. This is now explicitly said on page 6, L185.

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 L280 of original manuscript: “Over time, this change in dependency category could go forward and backward as water demand of the SBA increases or decreases” (Page 9, L286-L288, in revised manuscript) and in L295: “decrease in demand would have the opposite effect” (page 9, L297 in revised manuscript).

We have now modified Figure 5 (see *Editor Comment 1*, updated Figure 5) and added text to subsection (2.2.3) *Determinants of dependency category and possible transitions in them* -to better explain the reversed condition (see *Editor Comment 1*).

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 and *Editor Comment 1*), connected by a one simple map of transitions. We also further motivated 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 regime shifts, from the resilience literature (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’ category, see my comment 13. 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” (in current manuscript ‘broken 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. New results (excluding occasional scarcity) in the abstract highlights that *“386 million people (14%) live in SBAs that can avoid stress owing to available water from upstream and have thus upstream dependency. In the case of water shortage, 306 million people (11%) live in SBAs dependent on upstream water to avoid possible shortage.”*

While these percentages are similar to those cited by the reviewer (and therefore arguably low), it is important to note that the results look very different after considering occasional scarcity, e.g. in drought conditions. The previous manuscript (including occasional scarcity) 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. We also have now revised the discussion to reflect the above-mentioned implications of our results for transboundary cooperation under section 4.2 *Relation to existing work*- as mentioned now in Page 14, L437-L441-

“our analysis highlights the importance of local demand in causing scarcity and dependency. If local demand stays low enough and local water resources are sufficient to meet the demand, 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). These are fundamental ideas that are not widely recognized in existing literature.”

And also in Page-13-14, L412-L418,

“Our work distinguishes between dependency and scarcity and recognizes that dependency is primarily about potential for future scarcity, which transboundary cooperation aims to mitigate. To judge the importance of transboundary cooperation, it is more important to look at areas under no scarcity which are dependent on upstream inflows. The “broken dependency” category (SNS) and SSS only include cases where institutional arrangements have failed to prevent scarcity from occurring. Our work, however, highlights that negotiation to avoid needing to cope with scarcity is only part of the issue. As demand increases, negotiation among riparian countries will eventually turn to discussion of intensity and frequency of scarcity, and the level of demand at which it occurs.”

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

Response 17: Section 3.2 has been removed because of occasional scarcity has been left out 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 tried 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.

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How downstream sub-basins depend on upstream inflows to avoid scarcity: typology and global analysis of transboundary rivers

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Abstract: Countries sharing river basins are often dependent upon water originating outside their boundaries; meaning that without that upstream water, water scarcity may occur, with flow-on implications for water use and management. We develop a formalisation of this concept drawing on ideas about transition between regimes from resilience literature, using water stress and water shortage as indicators of water scarcity, ~~and including both persistent and occasional scarcity. Dependency. In our analytical framework, dependency~~ occurs if water from upstream is needed to avoid ~~either persistent or occasional water~~ scarcity. This can be diagnosed by comparing different types of water availability on which a sub-basin relies, ~~starting with reliable local runoff (available even in a dry year), followed by less reliable local water (available in the wet year), reliable dry year inflows from possible upstream area, and finally less reliable wet year inflows from upstream.~~ in particular local runoff and upstream inflows. At the same time, possible upstream water withdrawals reduce available water downstream, influencing the latter ~~two water availabilities. In this paper, we further present~~ availability. By developing a typology describing how ~~framework of~~ scarcity and dependency ~~evolve in transboundary river basins, and use this typology for a global analysis of,~~ we contribute to understanding on transitions between system regimes. We apply our analytical framework to global transboundary river basins at the scale of sub-basin areas (SBAs). ~~Four groups of SBAs are identified that experience scarcity and dependency differently depending on their i) location in the basin, and ii) hydro-climate characteristics, specifically the level of reliable support provided by natural upstream inflows. Each group has its own set of transitions in scarcity and~~

dependency category, driven by changes in local water demand and/or upstream withdrawals. Our results show that ~~almost one billion~~ 1175 million people ~~(33 live under water stress (42% of the total transboundary population) live in SBAs that are)~~. Of these, the majority (1150 million) suffer from stress ~~only due to their own excessive water use and possible water from upstream does not have impact on the stress status – i.e. they are not dependent on upstream water to avoid stress because of their own water use, while 500–~~ but could still impact on the intensity of the stress. At the same time, 386 million people ~~(17% of the total transboundary population)~~ 14% live in SBAs that can avoid stress owing to available water from upstream and have thus upstream dependency. In the case of water shortage, 306 million people (11%) live in SBAs dependent on upstream water to avoid possible shortage. The identification of ~~groups and their transitions enables discussion of the pathways SBAs might take between system regimes sheds light on how SBAs may be affected~~ in future, potentially contributing to further refined analysis of inter and intrabasin hydro-political power relations and strategic planning of management practices in transboundary basins.

Introduction

While water is a renewable resource, its availability is ~~still~~ finite. As population and water ~~use grows~~ demand grow, water ~~may become~~ becomes scarce. If local precipitation is insufficient to meet needs, a region may draw on external water resources, both physical and virtual (through food and goods trade) (Hoekstra and Chapagain 2011). External water resources constitute a considerable part of the total renewable water of some countries, and create hydrological, social and economic interdependencies between countries (Hoekstra and Mekonnen 2012). Transboundary water resources crossing national borders are a high-profile example. In basins like the Nile and Rio Grande, water availability of the downstream countries (Sudan, Egypt, Mexico) is ~~related to the~~ highly dependent on upstream precipitation patterns and upstream water use (Drieschova et al. 2008). Transboundary waterbodies cover almost half of the earth's land surface, and are home to about 1/3 of the world's population (~~UN Water 2013~~). Increase in water demand is among the main factors that are responsible for water scarcity in most of the transboundary river basins (~~Degefu et al. 2016~~); (UN Water 2013).

'Hydro-political dependency' in transboundary river basins is an important geopolitical issue bound up with concerns of sovereignty, affecting the power relations between riparian countries (Brochmann and Gleditsch 2012, Giordano and Wolf 2003, Gleick 2014, Jägerskog and Zeitoun 2009, Mirumachi 2013, Mirumachi 2015, Wolf 1998, Wolf 2007, Wolf 1999). Increase in water demand is among the main factors responsible for water scarcity in most transboundary river basins (Degefu et al. 2016). Uncontrolled land and water development in upstream regions can escalate risk of water ~~variability~~ supply uncertainty in the downstream region (Al-Faraj and Scholz 2015, Drieschova et al. 2008, Veldkamp et al. 2017). Concerns about water ~~variability~~ availability are already considered one of the most important issues for international co-operation and conflict concerning shared water basins (Beck et al. 2014). Regional and global studies already show that upstream water use has considerable impact on downstream water scarcity (Munia et al. 2016, Nepal et al. 2014, Scott et al. 2003, Veldkamp et al. 2017). When population (or water withdrawals) grow, downstream countries eventually become more reliant on the water available from upstream parts of a basin in order to satisfy their needs.

Thus, 'Hydro-political dependency' in the transboundary river basin becomes an important geopolitical issue affecting the power relation between riparian countries, and potentially sovereignty at national level (~~Brochmann and Gleditsch 2012, Giordano and Wolf 2003, Gleick 2014, Jägerskog and Zeitoun 2009, Mirumachi 2015, Mirumachi 2013, Wolf 1998, Wolf 1999, Wolf 2007~~). It has already been recognized that

upstream water use has considerable impact on downstream water scarcity by some regional and global studies (Munia et al. 2016, Nepal et al. 2014, Scott et al. 2003, Veldkamp et al. 2017). When population (or withdrawal) grows, downstream countries eventually become more reliant on the water available from upstream parts of a basin in order to satisfy their needs.

To complement this existing work, in this study, we aim to analytically explore the intuitive concept of a particular definition of 'upstream dependency'. Intuitively, one could say that upstream water dependency occurs if water from upstream is needed to avoid water scarcity. We argue that a sub-basin Dependency 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 realise it until those inflows are no longer available due to increased upstream withdrawals or lower runoff due to potential climate change impacts. Identifying a dependency involves comparing a sharp transition between cases where water scarcity is or is not experienced depending on whether water from upstream is or is not available. Transitions between cases is a key idea in resilience thinking, which therefore provides a promising way of approaching this problem.

A resilience perspective on upstream dependency

'Resilience' of a socio-ecological system is defined as "the capacity of a system to absorb disturbance and reorganize while undergoing change so as to still retain essentially the same function, structure, identity, and feedbacks" (Walker et al. 2004, p.01). Changes in the system are tracked in terms of 'state variables', such that thresholds in those state variables are used to define the points at which change occurs in the system function, structure, identity and feedbacks. When a threshold is crossed and changes occur, we say that the system has moved to a different 'basin of attraction', that there has been a 'regime shift', or a 'transition between system regimes'. While some studies aim to quantify resilience, we focus on identifying circumstances in which these regime shifts occur.

Understanding thresholds and regime shifts is considered critical to adaptability and transformations in transboundary basin management (Green et al. 2013). In the case of upstream dependency, we would distinguish between different system regimes depending on whether or not water scarcity occurs and whether or not dependency occurs and its implication in the prevention of scarcity. Dependency occurs in a region when sub-basin there is a transition between scarcity system regimes when considering cases where water is or is not available from upstream. We therefore compare whether scarcity occurs when water availability is calculated using either solely local runoff, natural discharge (sum of local runoff and upstream runoff), and actual discharge (subtracting upstream water withdrawals from natural discharge).

We can classify regions according to their dependency category. Based on the role of upstream inflows and withdrawals, a sub-basin might experience: i) no dependency if scarcity is not affected by upstream inflows, ii) continuous dependency if scarcity is avoided thanks to upstream inflows, or iii) intervened dependency if scarcity occurs after upstream withdrawals are taken into account. We also distinguish between whether scarcity occurs every year (persistent scarcity), or not in every year (occasional scarcity). While the precise cut-off between persistent and occasional scarcity could be disputed, this distinction captures the idea that occasional scarcity might be addressed when needed using adaptive measures, whereas persistent scarcity requires permanent arrangements. System regimes categorized as 'Scarcity'

and 'No scarcity' are distinguished by a change in *function* of the system – water becomes insufficient in some sense. For the purpose of developing our analytical framework, occurrence of scarcity is determined using commonly used water shortage and water stress indicators. ~~We are aware that water (further discussed in Section 2.2.2). Water~~ scarcity can also be socially induced ~~where. That is,~~ social systems rather than climatic or hydrological factors are determining, disadvantaging groups within society, often those marginalised (Mehta 2013). Management actions may enable water to become sufficient and demonstrates a case where structural changes occur, and therefore also a transition between system regimes. However, as a first step to ~~assessing global conditions of SBAs~~ operationalize the concept of physical dependency over water, we focus on thresholds of physical scarcity, following existing studies (Brown and Matlock 2011, Kummu et al. 2010, Porkka et al. 2012). ~~We note that other indicators could be substituted in future work. A summary of these key terms is given in Table 1.~~

Transitions in system regimes in terms of dependency can occur over time, and regions can be classified according to their dependency category. Based on the role of upstream inflows and withdrawals, a region might experience: i) no dependency if scarcity is not affected by upstream inflows, ii) *unbroken* dependency if scarcity category is altered by upstream inflows but not by upstream water withdrawal, or iii) *broken* dependency if scarcity is altered after accounting for upstream water withdrawals. If a system transitions into an unbroken dependency regime, the *structure* of the system changes – upstream withdrawals can now alter the scarcity category. An unbroken dependency is potentially *hidden*: a downstream part of a basin might be avoiding water scarcity only thanks to upstream inflows, and water users may not actually realise this causal factor unless those inflows are no longer available, due to increased upstream withdrawals or lower upstream runoff due to climate change or variation. That is, there is a transition to a broken dependency regime, which can also occur due to further increases in local demand. The system may then have a loss of function (insufficient water), or change in structure (due to management actions). Examining these system regimes helps to understand possible transitions of a region, and the actions that may be needed to avoid or control transition processes, e.g. negotiating water treaties to prevent or smooth transition to a broken dependency regime. We emphasise repeatedly throughout this article that upstream withdrawals may also affect the *intensity* of scarcity – our focus here is specifically on transitions between regimes.

A summary of the key terms used in the analysis is given in Table 1.

Table 1. Key terminology used in the analysis and their definitions.

Term	Definition
<i>No dependency</i>	A region would not experience water scarcity if they only had access to local runoff
<i>Continuous dependency</i>	A region would experience water scarcity if they did not have access to upstream inflows
<i>Intervened dependency</i>	A region experiences water scarcity after accounting for upstream water withdrawals, but would not experience water scarcity otherwise
<i>Local runoff</i>	Runoff occurring internally within a region
<i>Natural discharge</i>	Total water availability, calculated as local runoff + upstream runoff

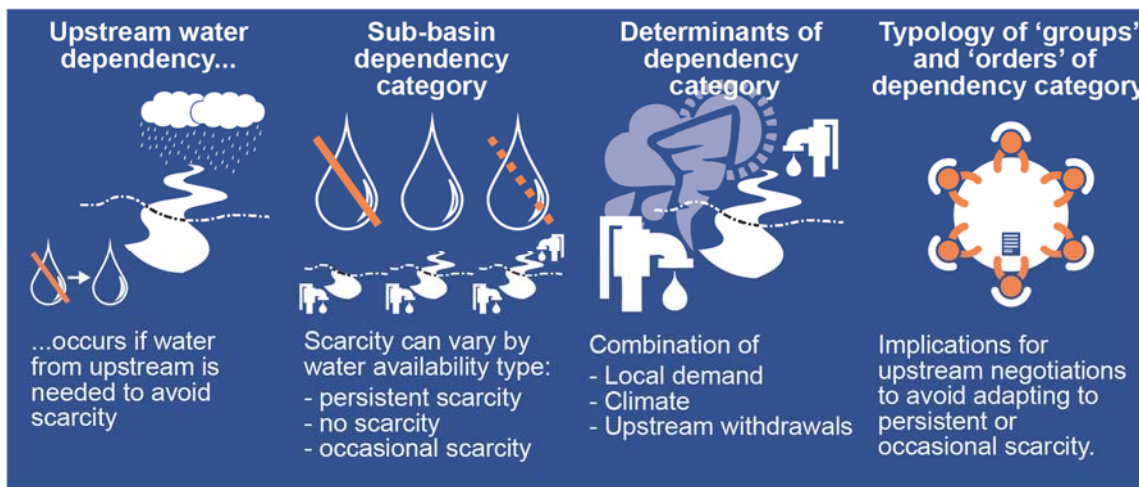
<i>Actual discharge</i>	Total water availability after upstream withdrawal (natural discharge – upstream withdrawal)
<i>No scarcity</i>	No scarcity occurs in any year
<i>Occasional scarcity</i>	Scarcity occurs, but not in every year
<i>Persistent scarcity</i>	Scarcity occurs every year
<i>Water stress</i>	Demand driven water scarcity, calculated as use to availability ratio
<i>Water shortage</i>	Population driven water scarcity, calculated as water availability per capita
<i>Local runoff</i>	<u>Runoff occurring internally within a region (in this paper a sub-basin).</u>
<i>Upstream runoff</i>	<u>Runoff of the possible upstream region (in this paper a sum of runoff of upstream sub-basins)</u>
<i>Natural discharge</i>	<u>Total water availability before taking into account possible upstream water withdrawals, here calculated as local runoff + upstream runoff.</u>
<i>Actual discharge</i>	<u>Total water availability after upstream water withdrawals; calculated as natural discharge – upstream withdrawals (local runoff + upstream runoff – upstream withdrawals).</u>
<i>No dependency</i>	<u>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. Note that the severity of scarcity may still be affected by upstream inflows and water withdrawals.</u>
<i>Dependency</i>	<u>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. Two sub-types of dependency can be distinguished (as follows).</u>
<i>Unbroken dependency</i>	<u>Scarcity category is altered by upstream inflows but not by upstream water withdrawals, i.e. additional water from upstream means the region experiences no scarcity instead of scarcity and upstream withdrawals do not change this.</u>
<i>Broken dependency</i>	<u>Scarcity category is altered after accounting for upstream water withdrawals, i.e. withdrawals mean that the advantages gained by upstream inflows are reduced or eliminated, and more intense water management regimes are needed downstream.</u>

These definitions of upstream water dependency and dependency ~~category~~categories form the basis of our quantitative analytical framework. ~~The framework is particularly suited to examining upstream-downstream hydrological linkages, and how they affect whether or not sub-basins need to be able to cope with occasional or persistent scarcity.~~The framework is used to conduct a global analysis that quantitatively distinguishes different ~~experiences of~~ scarcity and dependency ~~on upstream water~~regimes

at a transboundary sub-basin (SBA) scale, i.e. parts of basins that belong to different countries. Figure 1 summarises the key ideas of this paper. Specifically, we aim to answer the following research questions:

- What is the current dependency category of each sub-basin?
- How do climate, upstream withdrawals, and local demand influence dependency category? How could dependency category change in what transitions to other dependency categories are possible, that should perhaps be considered in planning for the future?
- How might dependency category do regime shifts involving unbroken (hidden) and its potential future evolution affect broken dependencies relate to negotiations with other sub-in transboundary basins?

Our analysis is based on modelled water availability and water use data (Sect. 0). Our method section builds up our analytical framework, defining sub-basins and calculating the different types of water availability (Sect. 0), interpreting upstream dependency in terms of water scarcity (Sect. 0), and unpacking determinants of dependency categories (Sect. 2.2.3), and identifying a typology of possible and transitions in dependency category as local demand and upstream water withdrawals change (Sect. 2.2.4), between them (Sect. 0). Applying this method to global transboundary basins, our results first describe dependency categories in year 2010 and how they affect the problems faced by the sub-basins (Sect. 3.1.0). We then describe how the sub-basins fit within the typology, transitions between scarcity and interpret how this affects dependency system regimes affect negotiation with upstream sub-basins to avoid the need to cope with occasional or persistent scarcity entirely (Sect. 3.20). We conclude with discussion of opportunities for further work building on and improving this method and dependency typology- (Sect. 0 & 0).



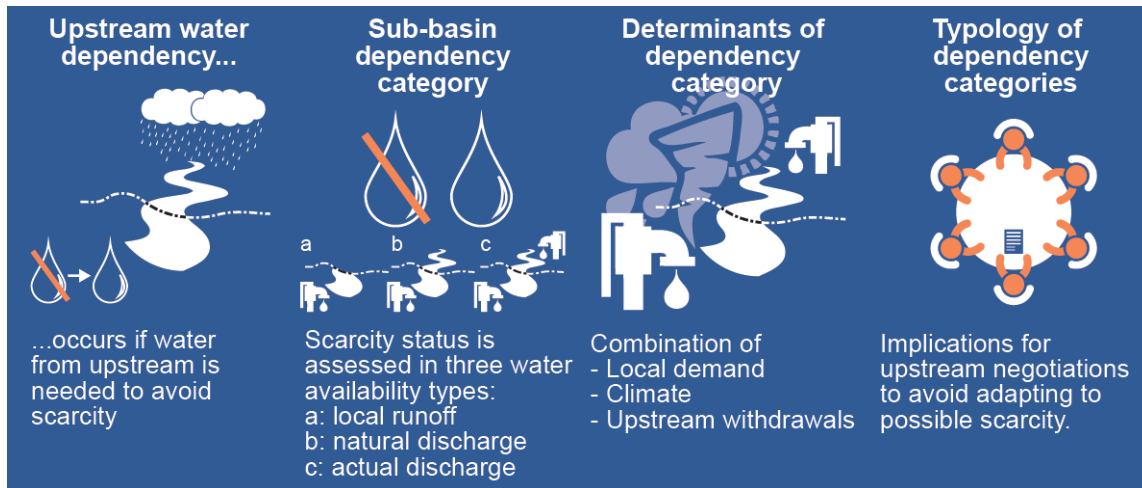


Fig. 1 Key ideas of this study: our definition of dependency and themes addressed by our research questions.

Data and Methods

To operationalise our definition of upstream water dependency, we used the global hydrological model PCRaster Global Water Balance (PCR-GLOBWB) to simulate water use and water availability at grid cell resolution (30 arc-min or roughly 50 km by 50 km at the equator). A basin-country mesh was used to sub divide the transboundary basins into sub-basin areas (SBAs). We then examine differences in the [ordering and volumes scarcity](#) of available water of the different types in order to provide a first explanation of why dependency occurs. Below we present [in more detail](#) the data, methods and analytical framework used for the assessment [in more detail](#).

Data

The data used for the study is summarized in Table 2. Runoff and water withdrawals (WWs) were calculated using the PCR-GLOBWB 30 arc-min model (Wada et al. 2011a, Wada et al. 2013). PCR-GLOBWB is a conceptual, process-based water balance model. In brief, it simulates for each grid cell and for each time step (daily) the water balance in two vertically stacked soil layers and an underlying ground water layer, as well as the water exchange between the layers and between the top layer and the atmosphere (rainfall, evaporation and snowmelt) (Wada et al. 2013). Discharge estimates from the model are extensively validated against observations from the Global Runoff Data Centre (GRDC) in existing publications by Wada et al. (2013, 2014). [The return flows from industrial and domestic sectors have been taken into account in PCR-GLOBWB and the recycling ratios for industrial and domestic sectors have been estimated \(roughly 40-80%\) at a country level and validated based on Wada et al. \(2011a, 2014\).](#)

Table 2. Datasets used in the study together with their source.

Data	Year	Source	Description
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Drainage direction	-	Döll (2002)	Global grid with 30 arc-min resolution
Runoff	1981–2010	Wada <i>et al.</i> (2011a; 2013)	Monthly data at global grid with 30 arc-min resolution
Irrigation withdrawal	water 1981–2010	Wada <i>et al.</i> (2011a; 2013)	Monthly data at global grid with 30 arc-min resolution
Industrial withdrawal	water 1981–2010	Wada <i>et al.</i> (2011a; 2013)	Monthly data at global grid with 30 arc-min resolution
Domestic withdrawal	water 1981–2010	Wada <i>et al.</i> (2011a; 2013)	Monthly data at global grid with 30 arc-min resolution
Population density data	1981–2010	Klein Goldewijk <i>et al.</i> (2010)	HYDE data set

Total WW were calculated for each SBA as the sum of three water use sectors: irrigation, domestic and industrial. The water use data for these sectors were obtained from the same model as the discharge simulations (Wada et al. 2011a, Wada et al. 2013). Water use estimates have also been previously validated against reported country data, notably FAO AQUASTAT, by Wada et al (2011a, 2011a). In this analysis, water withdrawals refer to the total amount of water withdrawn, but not necessarily consumed, by 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 subtracted from withdrawals in this analysis.

To provide an indication of need for water (rather than ~~demand~~withdrawals), population density information was obtained from the HYDE 3.2 dataset for each year from 1981 to 2010 (Klein Goldewijk et al. 2010). The data were first aggregated from 5 arc-min to 30 arc-min resolution and then for each SBA for every year over the 30-yr period.

The 30 arc-min raster dataset DDM30 (~~Döll 2002~~)(Döll 2002) described drainage direction for both surface flow routing in PCR-GLOBWB and definition of upstream-downstream links.

Country boundaries were first rasterized from Natural Earth Admin 0 boundaries (Natural earth 2017). Border cells were then manually assigned to countries to provide meaningful hydrological relationships. In general, single cell ~~sub-basins~~SBA were avoided. Cells where country borders follow a river were treated as separate “shared” zones. What we refer to as a “country” raster therefore includes both countries and shared zones.

Methods

Sub-basin definition and calculation of water availability

To explain the methods and analytical framework used for the global assessment, we use the Dnieper River BasinOder, a river in central Europe, as an example case study (Fig. 2). Dnieper(Fig. 2). Oder is a transboundary river that rises near Smolensk, Russiain the Czech Republic and flows through Russia,

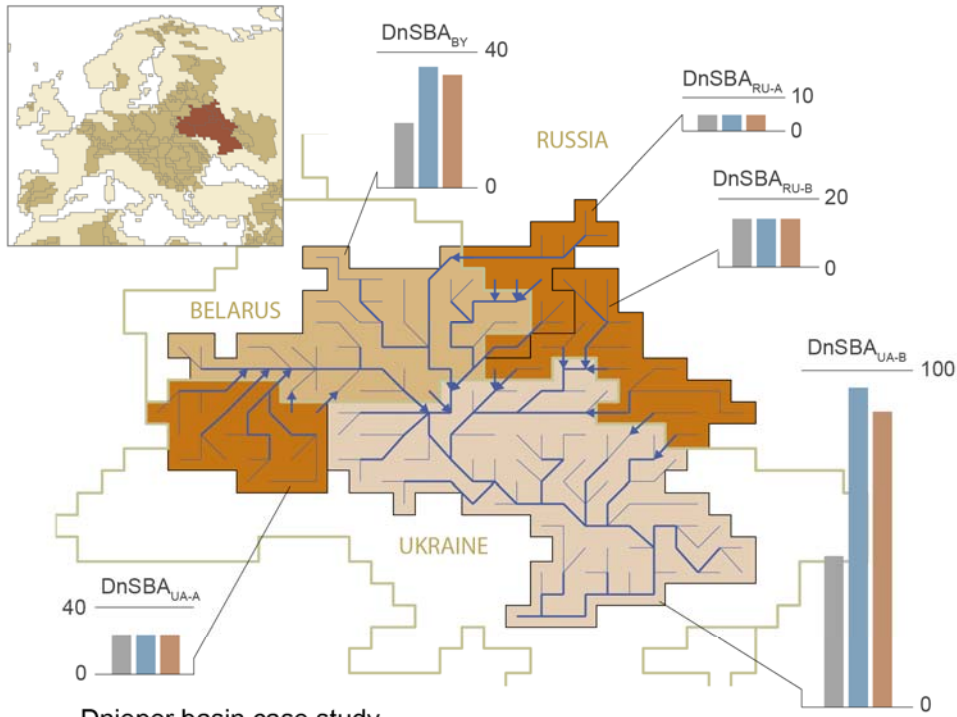
~~Belarus western Poland, later forming the border between Poland and Ukraine to the Black Sea. It is the fourth longest river in Europe. Germany.~~ We chose the ~~Dnieper~~Oder River Basin as an example case study because: i) it has non-trivial but sufficiently easy hydrological connections for illustrative purposes, ii) it includes upstream, middle stream and downstream SBAs, and iii) the water stress levels and downstream dependencies illustrate well the use of our analytical framework.

SBAs (i.e. sub-basin areas) were defined by breaking up the drainage direction map where it flows across country (and shared zone) boundaries, effectively yielding a mesh of river basin and country boundaries. Upstream-downstream relationships between these SBAs were defined by the flow direction dataset. The construction of the country raster (see Sect. ~~2.1~~2.1) ensured that the SBAs provide a meaningful representation of the hydrological system. A country can have multiple ~~sub-basins~~SBAs in order to capture different flow paths. In general, the drainage direction raster captures major tributaries even if finer details are missing. In the case of ~~Dnieper~~the Oder Basin, ~~Fig. 2~~Fig. 2 presents the ~~five~~four identified SBAs (~~DnSBA_{RU}~~OdSBA_{CZ}, OdSBA_{PO-A}, ~~DnSBA_{RU}~~OdSBA_{PO-B}, ~~DnSBA_{UA-A}~~, ~~DnSBA_{UA-B}~~, ~~DnSBA_{BY}~~OdSBA_{GE}) and the direction of flow between these SBAs. ~~Russia (DnSBA_{RU-A}, DnSBA_{RU-B}) and part of Ukraine (DnSBA_{UA-A}) were~~Czech Republic (OdSBA_{CZ}) has been identified as the most upstream, ~~Belarus (DnSBA_{BY}) part of Poland (OdSBA_{PO-A}) and Germany (OdSBA_{GE}, where the river forms the border)~~ as middle stream, and part of ~~Ukraine (DnSBA_{UA}) Poland (OdSBA_{PO-B})~~ as the most downstream (Fig. 2 Fig 2).

Three types of water availability were calculated in each of these SBAs, corresponding to local water (~~local~~ runoff), total inflows including upstream areas (natural discharge), and total inflows after upstream WWs (actual discharge) (see ~~also Table 1~~). ~~We used runoff and WW estimates together with a simplified routing approach to estimate discharge by summing runoff and subtracting WW-detailed definitions in Table 1.~~ ~~We approximate discharge as the sum of local runoff in local and upstream SBAs, such that there is an arithmetic relationship between the two.~~ This provides an easy to follow abstraction of the problem that emphasises upstream-downstream relationships while ignoring issues of land use change, timing of flows and conveyance losses.

WW for each SBA was calculated separately (referred to as *WW.local*) by summing up the three water use sectors (industrial, domestic and agriculture) and aggregating to SBA scale. Local runoff ~~water availability~~ for each SBA (*avail.local*) was given by its ~~annual~~average runoff. ~~Total water availability~~Natural discharge (*avail.~~total~~natural*) for each SBA was calculated by summing together the ~~local~~ runoff of the SBA and all its upstream SBAs.

~~Discharge after upstream WWs~~Actual discharge (*avail.~~after~~up~~actual~~*) was calculated from the SBA WWs and total water availability. 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~~ withdrawals are summed (*WW.upstream*). ~~The drainage network used here to identify upstream-downstream relationships has a clear hierarchical relation, with no distributaries, so water only flows to one immediately downstream SBA and there is no risk of double counting.~~ These water ~~use results~~withdrawals were then subtracted from natural discharge for the corresponding year, i.e. *avail.~~after~~up~~actual~~* = *avail.~~total~~natural* – *WW.upstream*. In some cases, *avail.~~after~~up~~actual~~* in excess of *avail.local* is considered to be fossil ground water or other available water that is not included in the calculation. In these cases, we set *avail.~~after~~up~~actual~~* to be equal to *avail.local* for that SBA.



Dnieper basin case study

Sub basin areas (SBAs)

- Upstream
- Middle stream
- Downstream

Rivers

- River network
- Flow direction at country border

Water Availability [$10^9 \text{ m}^3 \text{ yr}^{-1}$]

- Local runoff
- Natural ('Local runoff' + 'Upstream runoff')
- Actual ('Natural' - 'Upstream water use')

country sub-code
 DnSBA_{RU-A}
 basin country

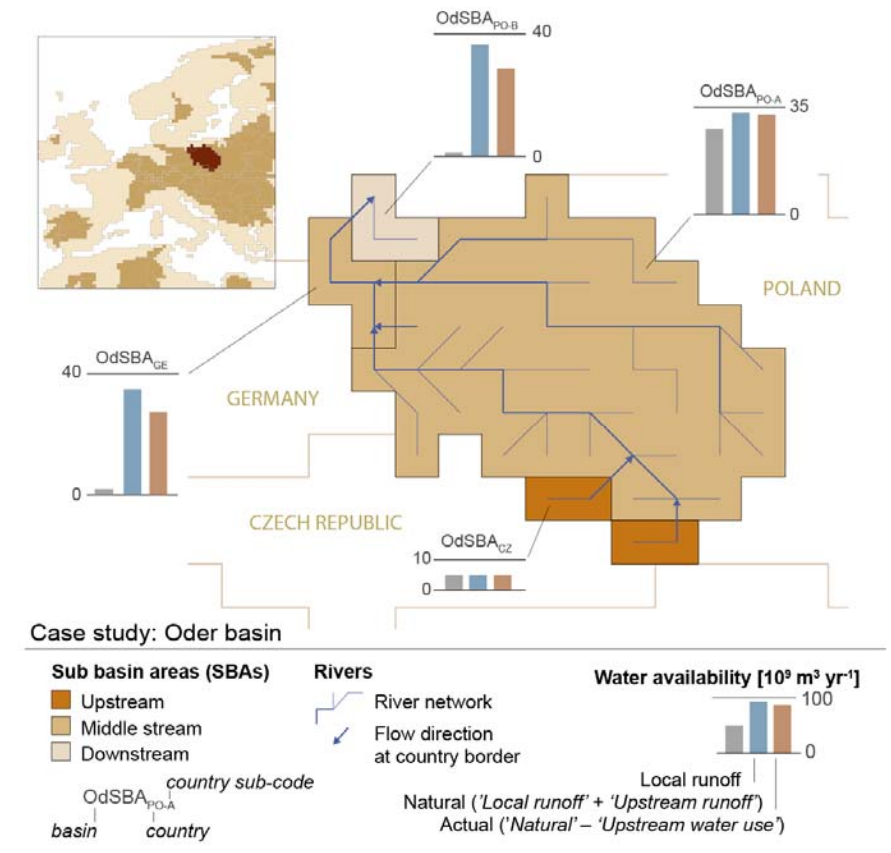


Fig- 2. Upstream-downstream relationship between sub-basin areas (SBAs) in the DnieperOder basin and average simulated annual water availability for 1981-2010. Drainage network and sub-basin division are based on DDM30 -(Döll 2002) and country borders (Natural Earth 2017) with additional manual assignment of border cells.

Interpretation of upstream dependency in terms of water scarcity

To understand the concept of upstream dependency, we first looked at the average availability of water (1981-2010) for the SBAs of the DnieperOder basin provides an illustration of the concept of upstream dependency (Fig. 2). Headwater SBAs (DnSBA_{RU-A}, DnSBA_{RU-B}, DnSBA_{UA-A}) The headwater SBA (OdSBA_{CZ}) obviously have no upstream dependency; the three types of water availability are the same. But in the case of SBAs DnSBA_{BY} and DnSBA_{UA-B}, OdSBA_{PO-A}, OdSBA_{PO-B}, OdSBA_{GE} upstream water availability and withdrawals influence water availability. These are the SBAs we are most interested in.

Dependency on upstream water can then be assessed by comparing an SBA's scarcity category across the different water availability types (i.e. local runoff, natural discharge, actual discharge – see definitions in Table 1). We calculated scarcity using the water stress and water shortage indices. Water stress refers to impacts from high use of water while water shortage refers to impacts from insufficient water availability per person (Falkenmark et al. 2007, Kummu et al. 2016). (Falkenmark et al. 2007, Kummu et al. 2016).

The stress indicator was calculated as $\frac{withdrawal}{WW.local/avail}$, and the shortage indicator is calculated as $\frac{avail}{population.local}$. The stress indicator includes environmental flow requirements (EFRs), assuming 30% of the water is needed to satisfy the EFRs (Falkenmark et al. 2007). To determine whether water

stress or shortage occurs, we respectively used the thresholds 0.2 and 1000 m³/capita/yr, as defined by Falkenmark et al (2007). Crossing these thresholds respectively means that more than 20% of available water is withdrawn, leading to impacts from high use of water, and that water availability is below 1,000 m³/capita/yr, leading (2007) and used by other research too (Liu et al. 2017). Crossing this threshold leads to impacts from insufficient water availability per person, potentially limiting economic development, and human health and well-being (Falkenmark et al. 2007). As mentioned above, the use of these thresholds is in line with existing studies and while there are notable limitations including that of simplification, we nonetheless utilize them as (Falkenmark et al. 2007). Falkenmark's per capita water availability as a measure of water scarcity has limitations as an indicator. Nevertheless, both stress and shortage are useful indicators of the more general concept of scarcity. Shortage, measured by per capita water availability, captures an important intuition that sufficiency of water availability depends on population. Even though the thresholds are arbitrary, using both indicators provides a useful balance to understand the development of water scarcity (Kummu et al. 2016), as well as illustrating the generality of the analysis framework. The use of these thresholds is in line with existing studies and while interpretation of the results is limited by the simplicity of the indicators, they provide a first step in understanding upstream dependency.

Annual stress and shortage were calculated using WWs and population for 2010 as:

Equations for water stress with 1) local runoff, 2) natural discharge and 3) actual discharge. Equations for water stress:

$$1. \frac{withdrawal.local}{avail.local}; 2. \frac{withdrawal.local}{avail.total}; 3. \frac{withdrawal.local}{avail.total - withdrawal.upstream}; \frac{WW.local}{avail.local}; 2. \frac{WW.local}{avail.natural}; 3. \frac{WW.local}{avail.natural - WW.upstream};$$

Equations for water shortage:

$$1. \frac{avail.local}{population.local}; 2. \frac{avail.total}{population.local} - \frac{avail.natural}{population.local}; 3. \frac{avail.total - withdrawal.natural - WW.upstream}{population.local}.$$

When using average water availability over many years (in our case 30 years), the The water scarcity status was categorized as

- No scarcity (N) and
- Scarcity (S)

using average annual water availability from 1981 to 2010. The 30-year period was used to capture the current hydro climatic characteristics. Fig. 3a represents the changes in scarcity for the Dnieper three water availability types for the Oder basin under average conditions, shown within the Falkenmark matrix (Falkenmark et al. 2007, Kummu et al. 2016) which shows stress and shortage together. Archetypes in the Falkenmark matrix describe the water scarcity status (corresponding to position on the plot) and where both shortage and stress occur, according to which occurs first (Kummu et al. 2016).

Though none of the SBAs have any shortage as the per capita water availability (i.e. shortage) has never dropped below 1000 m³ cap⁻¹ yr⁻¹, DnSBA_{UA}, OdSBA_{PO-A} is stressed (S) under all three water availability types, and OdSBA_{CZ} is not stressed (N). OdSBA_{GE} and OdSBA_{PO-B} would both be stressed (S) as

it exceeds 20% threshold value) only if they were restricted to their own local runoff (Fig. 3a). After accounting for inflows from upstream (natural discharge), the stress level decreased from 0.3725 to 0.1701 (N) (Fig. 3a) for $OdSBA_{GE}$ and from 0.35 to 0.01 (N) for $OdSBA_{PO-B}$ (Fig. 3a). This change in stress category means that $DnSBA_{UA-B}$ both these SBAs is dependent on upstream water to avoid stress. We further see that upstream WW increases the stress level relative to natural conditions (to 0.19) (Fig. 3a) for both (Fig. 3a & c), but the threshold for stress was not crossed. The stress level changed without changing the stress category, such that the category of the dependency was not affected; we have a 'continuous' or 'unbroken' rather than 'intervened' or 'broken' dependency (definitions in Table 1). In the case of $DnSBA_{BY}$, locally available $OdSBA_{PO-A}$, local runoff was not sufficient to meet needs, such and that upstream water availability and water use does not influence the scarcity category of this SBA (Fig. 3a & c). This SBA is under the same scarcity conditions regardless of upstream influence (Fig. 3a & b), and it is thus categorized as 'No dependency', though the intensity of scarcity is still affected by upstream WW. The dependency category of an SBA can then be summarised using three letter codes representing the scarcity category using local runoff, natural discharge and actual discharge respectively: $DnSBA_{UA}$, $OdSBA_{GE}$ and $OdSBA_{PO-B}$ are SNN, $DnSBA_{BY}$, $OdSBA_{PO-A}$ is SSS, and $OdSBA_{CZ}$ is NNN (Fig. 3a). As illustrated by the above discussion, we can interpret possible scarcity an SBA faces using four different dependency categories as shown below in Fig 4.

So far we have looked at the dependency of the SBAs for average water availability conditions but water availability varies from year to year. To capture this variability, we calculated the water scarcity status using water availability for each year from 1981 to 2010.

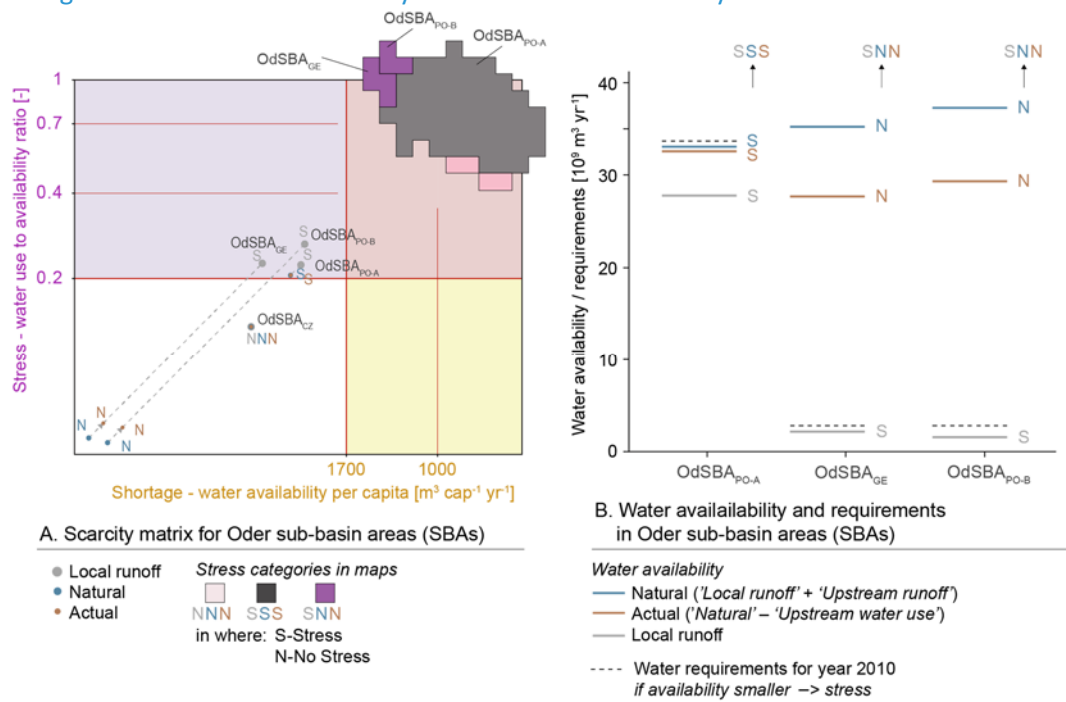


Fig-3. Scarcity is therefore further categorized as:

- No scarcity (N): no scarcity occurs in any of the years
- Occasional scarcity (O): scarcity occurs, but not every year
- Persistent scarcity (S): scarcity occurs every year

Persistent **and** occasional scarcity can equivalently be distinguished by identifying whether water scarcity occurs for wet and dry years respectively. While persistent scarcity is obvious because of low water availability in relation to water demand, people may not necessarily be prepared for occasional scarcity, or may need adaptive measures to be actively implemented.

When considering only average conditions, $DnSBA_{UA-B}$ had a continuous dependency, and $DnSBA_{BY}$ had no dependency. Accounting for occasional scarcity, $DnSBA_{UA-B}$ is described as 'SOO' (Fig. 3b). The dependency is still continuous, but we see that even with upstream inflows, occasional scarcity does occur. $DnSBA_{BY}$ falls under the **dependency category** 'ONN' (Fig. 3b & d). It would have occasional scarcity if only local water were available while it would be under 'no scarcity' category under natural and actual discharge (Fig. 3b). This SBA is thus dependent on upstream inflows to avoid occasional scarcity and the dependency is also continuous as the upstream WW does not change the scarcity category. In the cases where scarcity category under different water availability types remains the same (for example: $DnSBA_{RU-A}$, $DnSBA_{RU-B}$, $DnSBA_{UA-A}$), the SBA is considered to have 'no dependency' (Fig. 3b & d). When this occurs outside headwater SBAs, upstream WW may still affect the frequency and intensity of scarcity, and water availability at which thresholds occurs. Based on the above discussion, the interpretation of possible scarcity in terms of dependency is shown below in Fig 4.

Scarcity under local water availability (runoff)	Scarcity including upstream water (natural discharge)	Scarcity after accounting for upstream withdrawals (actual discharge)	Category name
No scarcity	→ No scarcity	→ No scarcity	----> NNN
Occasional scarcity	→ Occasional scarcity → No scarcity	→ Occasional scarcity	----> OOO
		→ No scarcity	----> ONN
		→ Occasional scarcity	----> ONO
Persistent scarcity	→ Persistent scarcity → No scarcity → Occasional scarcity	→ Persistent scarcity	----> SSS
		→ No scarcity	----> SNN
		→ Persistent Scarcity	----> SNS
		→ Occasional scarcity	----> SNO
		→ Persistent Scarcity	----> SOS

Scarcity and dependency category

No dependency
 Dependency
 Continuous dependency
 Intervened dependency

N = No Scarcity
 O = Occasional Scarcity
 S = Persistent Scarcity

Scarcity under local water availability (local runoff)	Scarcity including upstream water (natural discharge)	Scarcity after accounting for upstream withdrawals (actual discharge)	Dependency category
No scarcity	→ No scarcity	→ No scarcity	----> NNN (no dependency)
Scarcity	→ No scarcity → Scarcity	→ No scarcity	----> SNN (unbroken dependency)
		→ Scarcity	----> SNS (broken dependency)
		→ Scarcity	----> SSS (no dependency)

Scarcity and dependency category

No dependency
 Dependency
 Unbroken dependency
 Broken dependency

N = No Scarcity
 S = Scarcity

Fig 4. Definition of potential upstream water dependency categories. Dependency categories are obtained by summarizing three letter codes representing the scarcity category using local runoff, natural discharge and actual discharge respectively (see definitions in Table 1).

Determinants of dependency category and possible transitions in them

In order to evaluate possible responses to dependency, we need to understand what determines a dependency category and what can be done to achieve or to avoid change. Annual water availability can be thought of as a constraint on the environment in which a society operates. Society is able to influence that constraint, for example by building reservoirs (Veldkamp et al. 2017) – captured to some extent by the model. However, for a given hydro-climate and state of development, it is useful to think of the current water availability conditions regime as an integral, defining characteristic of a constant system regime. As population and WW increase in a region, the occurrence of shortage, stress and upstream dependency is determined by the volumes of the three types of water availability ~~evaluated in dry and wet years. Specifically, the analysis we have described so far can equivalently be described by saying that as a region's water needs and water use increases, they will cross six thresholds that result in changes in how the system operates.~~ A region will face scarcity or dependency as a result of:

- Insufficient ~~reliable~~ local ~~water availability, available even in a dry year~~ runoff (*avail.min.local*)
- ~~Insufficient less reliable local water, available in a wet year~~ (*avail.max.local*)
- ~~Insufficient reliable dry year discharge, from runoff and possible upstream inflows~~ (*avail.min.total*)
- Insufficient ~~less reliable wet year discharge, from local~~ runoff and possible upstream inflows (*avail.max.total.natural*)
- Insufficient ~~reliable dry year discharge~~ after upstream WW (*i.e. water withdrawals*) (*avail.min.afterupactual*)
- ~~Insufficient less reliable wet year discharge after upstream WW~~ (*avail.max.afterup*)

~~From a resilience perspective, these volumes of water can be thought of as thresholds, where an SBA would be under 'no scarcity' category when its minimum water availability average local runoff (*avail.local*) is sufficient to meet the water use demand in a given year (WW in case of stress and population in case of shortage). 'Occasional scarcity' occurs when an SBA's minimum water availability is insufficient but maximum water availability is sufficient. Finally, an SBA falls into the 'persistent and 'scarcity' category when its maximum water availability average natural discharge (*avail.natural*) is insufficient in relation to its water demand.~~

~~The advantage of thinking in terms of thresholds is that we can reason about how scarcity and dependency might change in future. Changes in upstream water use might then lead to crossing the scarcity threshold. In this paper, we focus on the effect of increasing or decreasing local demand and upstream water use, leaving changes in water availability to future work. study, 'demand' is used as a high-level umbrella term covering both actual withdrawals (for the stress indicator) and need for water (population, for the shortage indicator).~~

~~Fig. 5 Fig 5 shows the ordering of possible thresholds for the Dnieper's DnSBA_{UA-B}, an SBA based on water availability, and how the shortage and stress categories varies vary as demand changes, considering the case without changing upstream WW for the time being. To allow comparison, water availability, population, and withdrawal are all expressed as percentages respectively of *avail.max.total.natural*, carrying capacity (*avail.max.total.natural*/1000) and sustainable yield (*avail.max.total.natural* × 0.2). The current status of OdSBA_{GE} and OdSBA_{PO-B} is shown in the figure. Currently the DnSBA_{UA} OdSBA_{GE} and~~

OdSBA_{PO-B} is in the 'SOO'SNN' category for stress and 'NNN' category for shortage (Fig. 5). It has a continuous dependency (for Fig 3). They have unbroken dependencies (avoiding stress), as it is experiencing occasional rather than persistent scarcity thanks to upstream inflows. The average year inflows after upstream WW are sufficient to meet water demand. If the water demand in DnSBA_{UA} at these SBAs were to increase to a level where the maximum wet average year inflows after upstream WW (avail.max.afterup) would not be enough to meet the water use demand, the SBA would next transition from SOO'SNN to SOO'SNS category. Thus, with the increase in demand, the dependency category (e.g. 'SOO'SNS') would change based on the thresholds it crosses and ultimately the basin would become SSS, indicating that an SBA would be under scarcity every year under each availability type of water type availability considered. The same thing would happen with shortage as the population increases (Fig. 5). Over time, this change in dependency category could go forward and backward as water demand of the SBA increases or decreases. This order of thresholds determines the transition in dependency category for OdSBA_{GE} and OdSBA_{PO-B} as local demand increases or decreases.

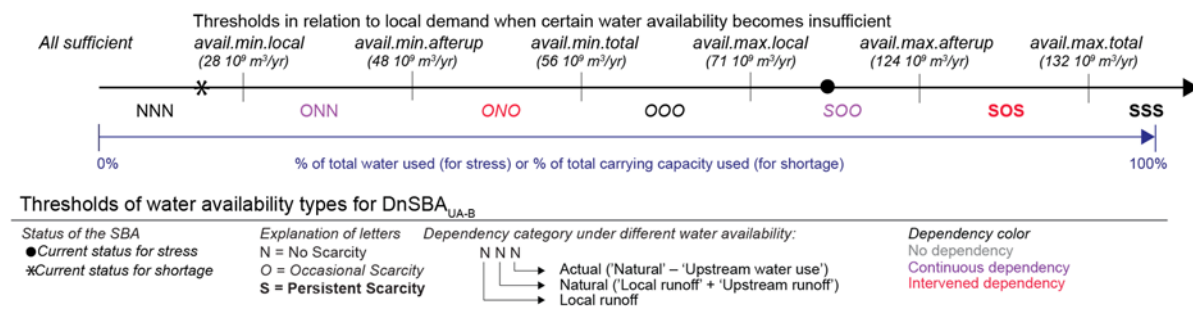


Fig. 5. Thresholds of water availability types for Dnieper's sub-basin area DnSBA_{UA-B} and its dependency category (for both stress and shortage) in 2010. See definitions of used terminology in Table 1.

1.1.1 Typology of possible transitions in dependency category

So far, we have conceptualised change in dependency category in the context of a fixed set of water availability thresholds, obtained directly from estimated water availability volumes. The order of thresholds determines the transition in dependency category as local demand increases or decreases. These thresholds are, however, expected to change depending on climate and upstream WW. It is therefore useful to build a typology of possible orders of thresholds to better understand potential future implications and changes to use. In fact, even if upstream WW changes the values of the thresholds, their order will remain the same. These scarcity thresholds are naturally ordered because local water necessarily becomes insufficient before upstream water availability types respectively: local ≤ actual ≤ natural. We do, however, distinguish between headwaters vs middle stream and downstream SBAs.

We begin from the observation that the scarcity thresholds are (partially) naturally ordered. In terms of how they are defined, reliable and local water necessarily becomes insufficient before less reliable and upstream water availability types respectively: local ≤ afterup ≤ total, and min ≤ max. Given that these constraints only partially determine the order in which scarcity and upstream dependency is experienced, SBAs can be categorised in four different groups and six distinct orders as follows (Fig. 6):

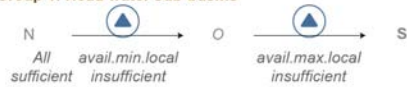
Headwaters (Group 1) are the simplest case. Given they are the most upstream SBAs, they rely solely on local runoff, and have a single ordering of thresholds (Order 1). Increases in an SBA's demand cause transition from 'no scarcity' to 'occasional scarcity' and finally to 'persistent scarcity' category. Decrease in demand would have the opposite effect (Fig. 6). (Fig 5).

The next distinction between orders separates out SBAs with *no reliable upstream support* (Group 2 in Fig. 6). In this group, the volume of reliable dry year inflows from upstream areas ($avail.min.total$) determines ordering of the thresholds. For Group 2 SBAs, discharge in a dry year is lower than wet year local runoff, i.e. $avail.min.total \leq avail.max.local$. In natural conditions, upstream inflows enable other SBAs to increase their demand beyond their wet year local runoff without experiencing any scarcity (SNN), though scarcity may still occur with high upstream WW (ONO). Group 2 SBAs do not even have this possibility, and instead experience occasional scarcity without upstream intervention (OOO). Group 2 only has one possible order of thresholds (*Order II*). We see in Fig. 6 that transitions in category can occur due to increases in either local demand or upstream WW where a dependency is present (ONN \rightarrow ONO, SOO \rightarrow SOS), but only due to local demand where there is no dependency or an intervened dependency (e.g. NNN \rightarrow ONN, ONO \rightarrow OOO). Conversely, transitions occur due to decreases in either local demand or upstream WW from an intervened dependency category (ONN \leftarrow ONO, SOO \leftarrow SOS), but only due to local demand in other cases. This is a result of our definition of dependency and holds true for all transitions.

In the remaining two groups, the ordering of thresholds is linked to whether upstream WW exceeds 1) the reliable upstream support ($avail.min.total - avail.max.local$), and 2) natural discharge variability, specifically, the range of downstream natural discharge ($avail.max.total - avail.min.total$) (Group 3 and 4 in Fig. 6). The level of upstream WW has implications for whether inflows help to avoid occasional and persistent scarcity. If upstream WW exceeds natural reliable upstream support, such that $avail.min.afterup \leq avail.max.local$, inflows no longer forestall occasional scarcity. The SBA experiences the transition ONN \rightarrow ONO rather than ONN \rightarrow SNN (Group 2 and 3 in Fig. 6). If upstream WW exceeds discharge variability, then inflows after upstream WW even in a wet year will be lower than natural inflows in a dry year ($avail.max.afterup \leq avail.min.total$), meaning that inflows no longer forestall persistent scarcity. The SBA faces the transition SNO \rightarrow SNS rather than SNO \rightarrow SOO (Group 2 and 3 in Fig. 6).

The two groups can therefore be differentiated by whether reliable support is greater or less than natural discharge variability. We define Groups 3 and 4 as having low and high reliable support respectively (see Fig. 6). Group 3 has reliable support $<$ discharge variability. Group 4 has reliable support $>$ discharge variability. The combination of the two upstream WW conditions yield four orders: III, IVa, IVb, V. Orders III and V are cases where upstream WWs are respectively higher and lower than both reliable support and natural discharge variability. Order IVa occurs when upstream WW are higher than reliable support and lower than natural discharge variability, which is not possible in Group 4, and therefore only occurs in Group 3. Conversely, order IVb occurs when upstream WW is lower than reliable support and higher than natural discharge variability, and only occurs in Group 4.

Group 1: Head water sub-basins



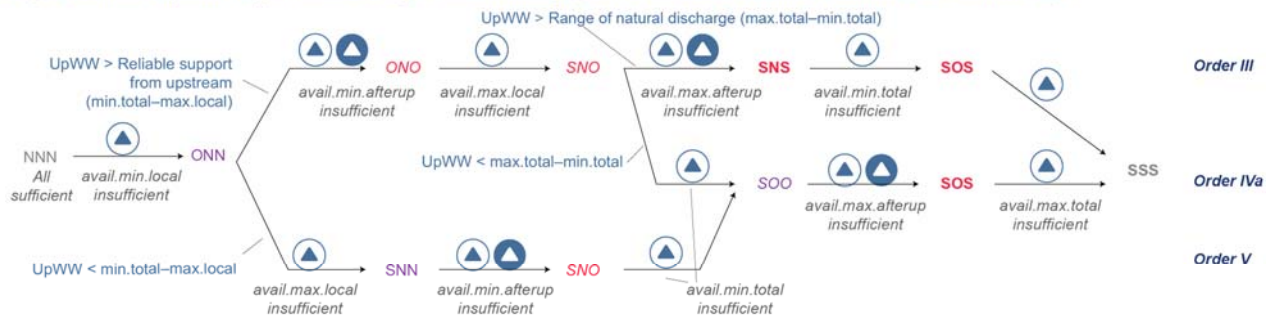
Order I

Group 2: No reliable upstream support (avail.min.total < avail.max.local)



Order II

Group 3: Low reliable upstream support relative to range of natural discharge (avail.min.total – avail.max.local < avail.max.total – avail.min.total)

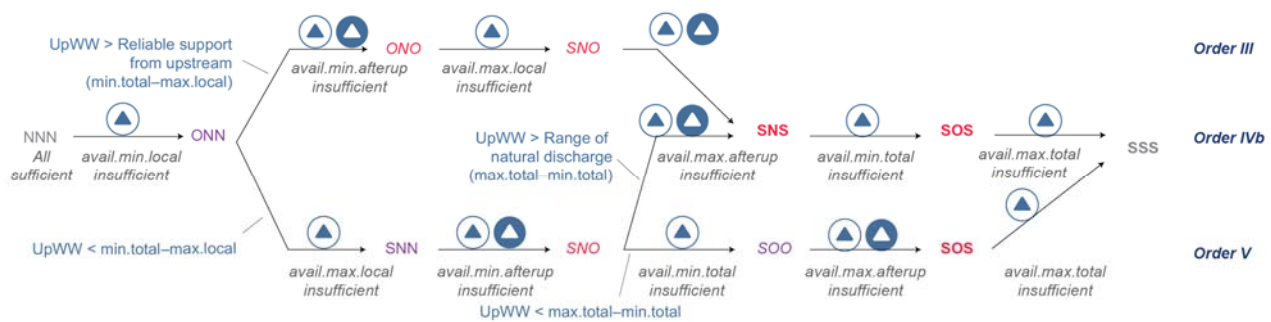


Order III

Order IVa

Order V

Group 4: High reliable upstream support relative to range of natural discharge (avail.min.total – avail.max.local > avail.max.total – avail.min.total)



Order III

Order IVb

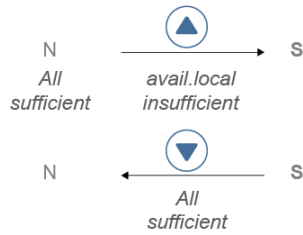
Order V

Explanation of letters	Dependency category under different water availability:	Dependency color	Drivers of transitions
N = No Scarcity	NNN → Actual ('Natural' – 'Upstream water use')	No dependency	▲ Local demand increases
O = Occasional Scarcity	NNN → Natural ('Local runoff' + 'Upstream runoff')	Continuous dependency	▲ Upstream withdrawals increases
S = Persistent Scarcity	NNN → Local runoff	Intervened dependency	

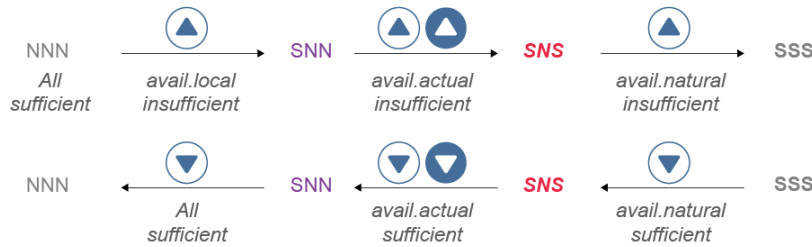
Fig.-In the case of middle stream and downstream SBAs, transition occurs between four scarcity categories, which are connected by a simple map of transitions: NNN-SNN-SNS-SSS. Transition in the scarcity category depends on both local demand and upstream WW. The experience of dependency in the Oder basin is therefore generally applicable to all middle and downstream SBAs. As the local demand increases, the SBA moves from NNN to SNN, exposing it to a 'hidden dependency' as local runoff become insufficient, but the SBA still receives sufficient upstream inflows to meet the local demand. The next transition between SNN to SNS is dependent on both local demand and upstream WW until local demand increases to the level where all available water become insufficient - the SBA becomes SSS. The decrease in local demand and upstream WW will have the opposite effect.

Thus SBA crosses thresholds which not only change the scarcity category, but also change the dependency category, considered in this study as transitions between different 'system regimes'. Note that we focus on the effect of increasing or decreasing local demand and upstream water withdrawal, leaving changes in water availability to future work.

Head water sub-basins



Middle stream and downstream sub-basins



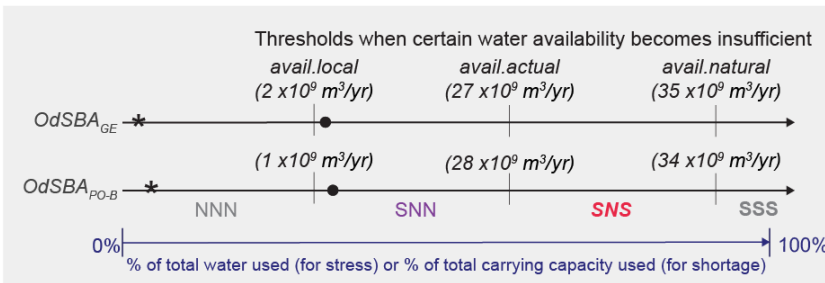
A. Typology of possible transitions in dependency category

Explanation of letters
 N = No Scarcity
 S = Scarcity

Dependency category under different water availability:
 N N N
 ↳ Actual ('Natural' - 'Upstream water use')
 ↳ Natural ('Local runoff' + 'Upstream runoff')
 ↳ Local runoff

Dependency color
 No dependency
 Unbroken dependency
 Broken dependency

Drivers of transitions
 Local demand: increases decreases
 Upstream withdrawals: increases decreases



B. Status of Oder sub-basins (2010)

★ Current status for shortage ● Current status for stress

Fig 5. Typology of groups and orders of possible transitions in dependency category, as local water demand or upstream water withdrawals (WW) increase/decrease. (a). Upstream WWs decrease the downstream water availability, while local water demand increases the pressure on available resources and thus, their impact on water scarcity differs given the group, order and. Current (2010) status of a given sub-basin area (SBA)-OdSBA_{GE} and OdSBA_{PO-B} (for both stress and shortage) is shown in the transition map (b). See definitions of used terminology in Table 1.

Results and interpretation of global: Global analysis of dependency categories

The analysis was applied to 246 international transboundary basins to understand the dependency category of these basins and possible future transitions, using water use withdrawal and population data from 2010.

1.2 Identified sub-basins under different dependency categories

The 246 transboundary basins were divided into 886 SBAs based on country borders (as well as shared zones along those borders). As shown in Table 3, in the case of stress, most SBAs had no dependency in 2010 (88%, 782/93%, 824 SBAs), though a substantial number (88 while 52 SBAs) did have a continuous unbroken dependency – water available from upstream WW does lift the SBA from scarcity and upstream WWs do not change the scarcity categories. In these cases, upstream users are not responsible for the occurrence of downstream scarcity, but might intensify scarcity (where it occurs, see Discussion). In total 16 (210 (1%) SBAs out of 886 SBAs are identified where the dependency was ‘intervened’ broken’, meaning that upstream water use has changed withdrawals change the downstream stress category (Table 3). The picture was similar for (Table 3). In the case of shortage, with 7235 SBAs with continuous were under unbroken dependency and only 7 with intervened under broken dependency. Upstream water withdrawals thus only rarely play a role in causing low water availability per capita.

Table 3. Number of sub-basins SBAs under different dependency categories in the year 2010.

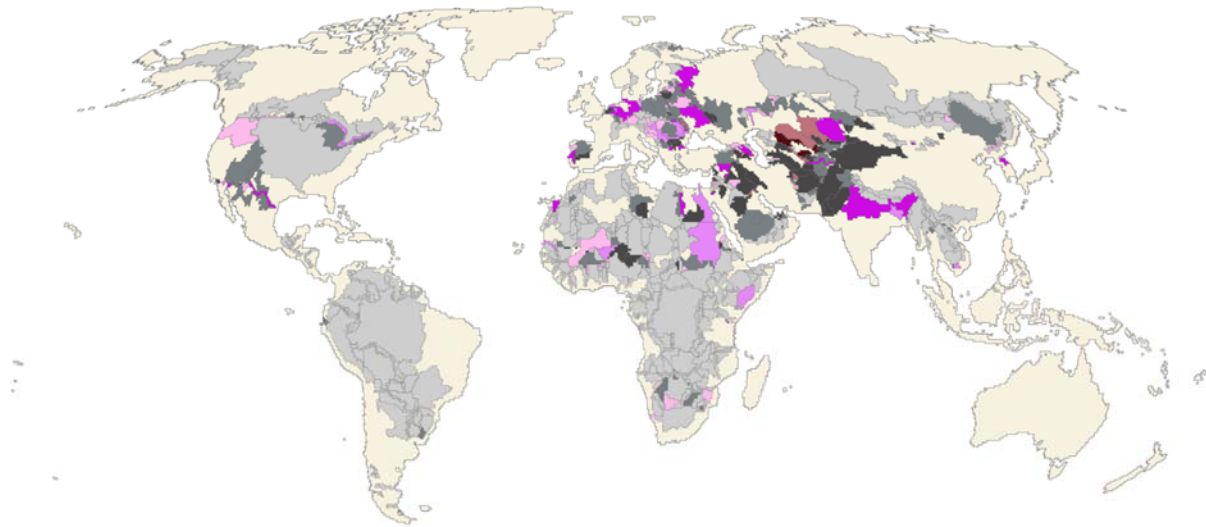
	Dependen cy category	Stress		Shortage	
		No of sub- basins	Population (×10 ⁶)	No of sub- basins	Populatio n (×10 ⁶)
No upstream dependency	NNN	595688 (78%)	782 (881231) (44%)	1102799 (90%)	7112312 (83%)
	SSS	78136 (15%)	1150 (41%)	40350 (6%)	33172 (6%)
Continuous Dependency	NNN	43	59		242
	SSS	88 (10%)	75	72 (8%)	
Unbroken dependency	SNN	2252 (6%)	386 (14%)	35 (4%)	306 (11%)
	SSO	23	608	9	157
Intervened Dependency Broken dependency	NNNS	210 (1%)	25 (0.9%)	16 (2 (0.2%))	72 (0.87%)

SNS	0	0	0	0
SNO	9	8	1	0
SOS	5	18	0	0
Total		886	2792	886
				2792

'No dependency' is observed in ~~88~~93% of cases for stress and ~~91~~96% of cases for shortage (Table 3). It is worth noting that scarcity can still be experienced without a dependency – it simply means that current upstream inflows (and WWs) do not influence whether scarcity occurs. ~~There~~For example, in the case of water stress, 41% of the population living in SBAs under 'no dependency' are under stressed conditions (Table 3). Further, even if an SBA in question is under no dependency category, upstream WW might still intensify the possible scarcity. In this category, there is not currently a problem with relationships with upstream ~~basins~~SBAs, but to plan ahead, we need to understand how the situation could evolve, as ~~will be~~is discussed in Sect. 3.2.4.1.

'~~Continuous~~Unbroken dependency' is observed for both stress and shortage mostly in Africa, ~~Europe,~~and some parts of Southeast Asia, and ~~North America~~ (Fig. 7a)Europe (Fig. 6a, b). ~~Continuous~~Unbroken dependency means that ~~maintaining good~~ relationships and assessing water use and potential changes with upstream basins are important. ~~Many~~ to avoid scarcity. A number of SBAs, in which currently no scarcity is observed (Fig. 7), (Fig. 6), are actually ~~suffering from~~subject to upstream dependency. If inflows ~~were to~~ decrease sufficiently due to ~~increased~~ upstream WWs, scarcity could occur, ~~or become persistent rather than occasional.~~ In these SBAs, this ~~does~~has not yet ~~happen~~happened, though upstream WWs may be influencing the ~~frequency and~~ intensity of scarcity, and the level of development (population or use) at which thresholds occurs. Therefore, understanding of how the situation can evolve is needed to know how to manage the relationship with upstream water users.

(a) Sub-basins under different dependency category incase of stress



(b) Sub-basins under different dependency category incase of shortage

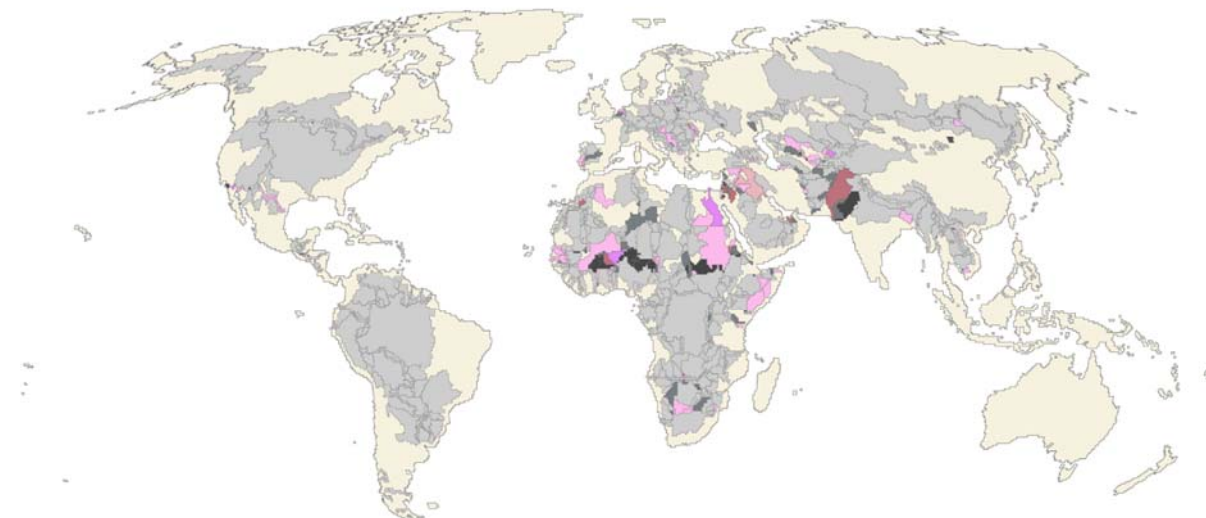


Fig. 7. Dependency categories for each SBA for the year 2010 using a) Water stress threshold value of 0.2 b). Water shortage threshold value of 1000 cubic meter/year.

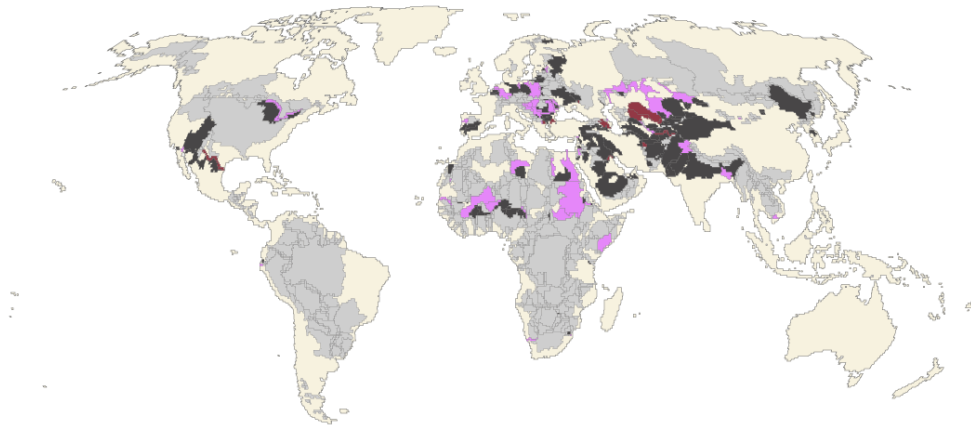
'Intervened'/'Broken' dependency' occurred most notably in different parts of central Asia for both stress and shortage (Fig. 7a, b). Intervened some parts of North America for stress and for shortage, only in areas categorised as shared zones as part of the Jordan basin (Israel, Syria, and Lebanon) and the intermittent Wadi Al-Batin (forming the border between Kuwait and Iraq) (Fig. 6a, b). Broken dependency indicates that scarcity occurs and could be attributed to upstream water use, such that there is a potential for tension with upstream water users over water allocation. There as things currently stand. But while there would be no scarcity or only occasional scarcity if it were not for upstream WWs—but, reducing local water needs or WWs could similarly also avoid shortage or stress. As a result, avoiding scarcity in these

SBA's ~~water management has become an~~requires cooperation rather than uncoordinated competition between the upstream and the downstream region. Such a situation is already evident in the case of Central Asia (Dukhovny 2014). (Dukhovny 2014). However, understanding of the evolution of the situation may show that small decreases in local or upstream WWs may not be sufficient to avoid scarcity or dependency. It may be necessary to find means to reduce needs or adapt to impacts from high water use.

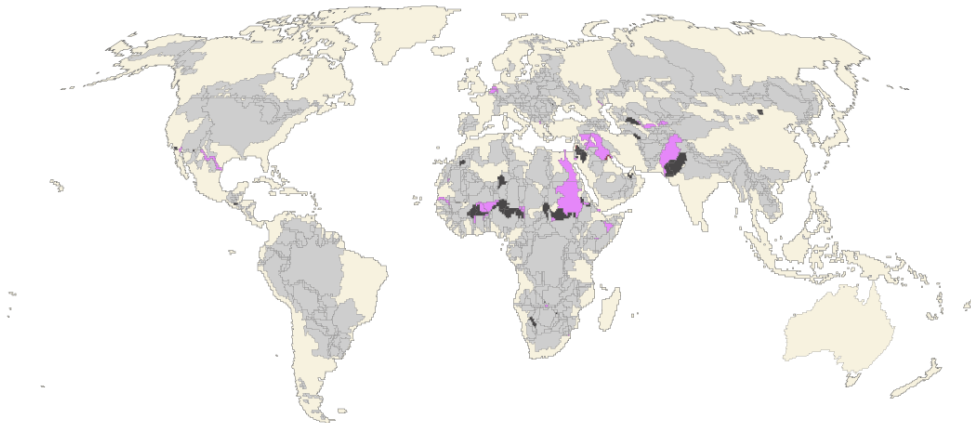
1.3 — Possible future transitions and implications

Rather than trying to predict the future, we look at the potential future transitions that can occur in each sub-basin. Fig. 8 shows the scarcity threshold orders and the dependency category of SBAs under these orders for both stress and shortage, for current climate and corresponding upstream WWs (1981–2010). Fig. 9a in turn maps where the different orders occur.

a. Sub-basins under different dependency category in case of water stress



b. Sub-basins under different dependency category in case of water shortage



- No dependency
 - NNN
 - SSS
- Unbroken dependency
 - SNN
- Broken dependency
 - SNS

Explanation of letters

- N = No Scarcity
- S = Scarcity

Dependency category under different water availability:

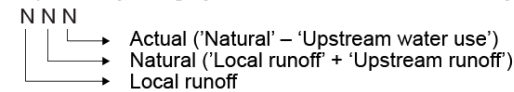


Fig 6. Dependency categories for each sub-basin area (SBA) for the year 2010 using a) Water stress threshold value of 0.2; and b) Water shortage threshold value of 1000 m³/year/capita. See definitions of dependency categories in Fig. 4 and definitions of key terminology in Table 1.

Understanding potential transitions as well as current dependency category allows us to make suggestions for how negotiation in upstream-downstream relationships might be influenced. Headwaters obviously have no upstream dependency (Group 1, *Order I*)—the management of their relationships will be guided by how they influence downstream SBAs.

Dependency categories in all orders except *Order I* begin with NNN-ONN and end with SSS (Fig. 8). The need to engage with upstream water users begins with an increase in local water demand, creating a situation where scarcity depends on upstream withdrawals. From that point on, an SBA's experience of water scarcity depends on the group and order to which they belong, which is determined by the climate-dependent level of reliable upstream support as well as the level of upstream withdrawals. However, if local demand increases sufficiently, any SBA can find itself in a situation of persistent scarcity that is not dependent on upstream (SSS). If an SBA wishes to avoid the need to cope with occasional or persistent scarcity, negotiation with upstream is only relevant when local demand is sufficiently low (but negotiation may still affect the severity of scarcity and its impacts).

Revisiting the results of Table 3 in this context, the need for negotiation in transboundary basins could become a much greater issue in future. In terms of stress, 72% of SBAs (638) are still in the preliminary stages (NNN & ONN), and only 8.8% (78) have reached the final stage where persistent scarcity is accepted as a fact of life. Shortage is even less developed, with 87% of SBAs (770) at NNN or ONN, and 3.7% (33) at SSS. There are more cases of SSS in Group 2 than 3 and 4, likely as a result of lower reliable upstream support. The intricacies of groups and orders are likely to become relevant to these SBAs in future, if local water demand increases.

A first key pattern is whether an SBA transitions from ONN to ONO or to SNN (Fig. 8). In the case of ONO, the SBA experiences occasional scarcity for the first time, and this would not (yet) have occurred without upstream withdrawals (it is an intervened dependency). In the case of SNN, the SBA escalates their dependency—persistent scarcity would occur without upstream inflows. In Group 2, ONO is unavoidable (Fig. 8). The lack of reliable upstream support means that negotiation with upstream can only tweak how much local demand can increase before occasional scarcity will occur. However, in Groups 3 and 4, SNN could be achieved if upstream withdrawals are kept sufficiently low. Currently, for stress most SBAs fall in SNN, and for shortage the SBAs are approximately equally distributed. Further work would be needed to understand why the upstream-downstream water allocation turned out that way. In Group 2, very few SBAs are in ONO, likely because minimum flows are relatively low (less than *avail.max.local*).

A second key pattern relates to transitions between no, intervened and continuous dependencies. Continuing increases in local demand in Order II (Group 2) mean that the SBA reaches states where there is no dependency on upstream water, i.e. OOO and SSS. The preceding continuous (ONN, SOO) and intervened dependencies (ONO, SOS) are only intermediate states. Keeping upstream WWs low delays the occurrence of occasional scarcity, but it would occur regardless of upstream WWs if local demand continues to increase. If the intention is for local demand to continue increasing, negotiating to avoid occasional or persistent scarcity is of limited use. Negotiation could instead be focused on timing, frequency and intensity of scarcity.

A similar effect occurs in Order IVa and Order V. Transitions from SNO to SOO mean that occasional scarcity caused by upstream withdrawals would occur even with natural discharge as local demand increases. Again, if a region intends to develop its resources far enough, it will eventually need to be able to cope with occasional scarcity anyway. These no-dependency transitions provide anchor points in negotiation. An upstream SBA can argue that its downstream neighbour would eventually need to adapt to occasional scarcity anyway. There are a large number of SBAs in these orders (Fig. 8; Fig. 9a). There is also a large potential for latent conflicts due to the low level of upstream development (and hence potential for growth) and high level of downstream development before scarcity emerges.

In Order III and Order IVb, all transitions from ONN or SNN onwards are to intervened dependencies. Downstream SBAs can argue that they would not need to deal with occasional/persistent scarcity, were it not for upstream withdrawals. In the case of Order IVb, a counter argument is that expansion of local demand beyond SNN suggests that the downstream SBA is in fact choosing to have to deal with intervened dependencies. If upstream demand is stable, this means that the conflict is effectively of their own making. There are relatively few cases in Order III and none in Order IVb. The most evident cases are in Central Asia (Fig. 8; Fig. 9a) where downstream SBAs are highly dependent on upstream inflow and their dependency is intervened by upstream WW (Fig. 7). Further investigation would be needed to determine whether these orders are being avoided by coincidence, or by effective negotiations.

Transitions from orders V->IVa->III and V->IVb->III unsurprisingly increase the need for negotiation with upstream SBAs. Common ideas in water allocation are relevant. The idea of precedence is raised when we look at transitions as demand increases, keeping upstream WWs fixed. Scarcity, continuous dependencies and intervened dependencies only emerge as problems when local demand crosses a threshold. This gives the impression that it is the local user that is responsible for the new problem, even though it may simply be that they are late to the game. Considering both local and upstream demand simultaneously, instead, emphasises a negotiation on more equal terms, where both local and upstream users are responsible for the scarcity outcomes occurring in the downstream region. The precedence paradigm is visible in prior appropriations regimes in USA, while negotiated allocations are arguably implemented by water markets in Australia and elsewhere (Grafton et al. 2011). Even in negotiations, existing water needs and WWs are often taken into account, including at an international level.

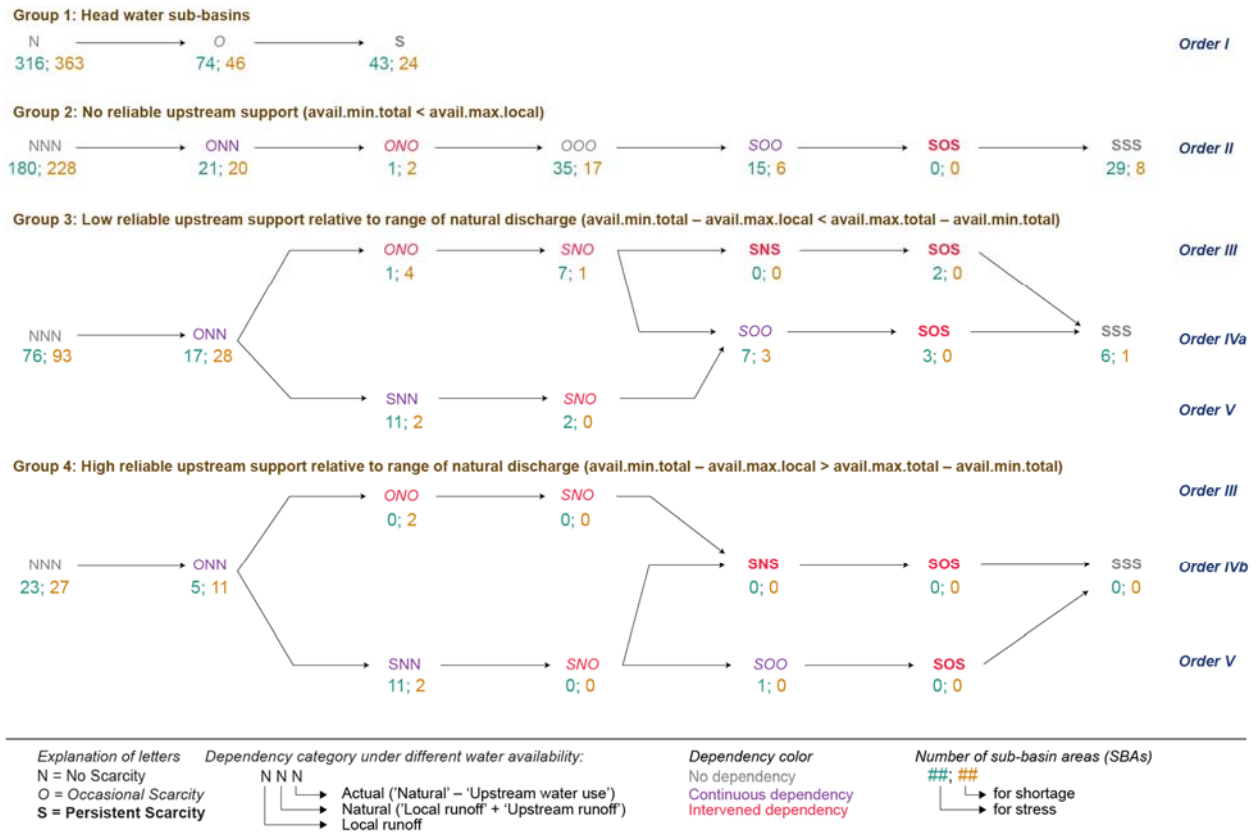


Fig. 8. Current (2010) dependency category of SBAs in the context of their order and group.

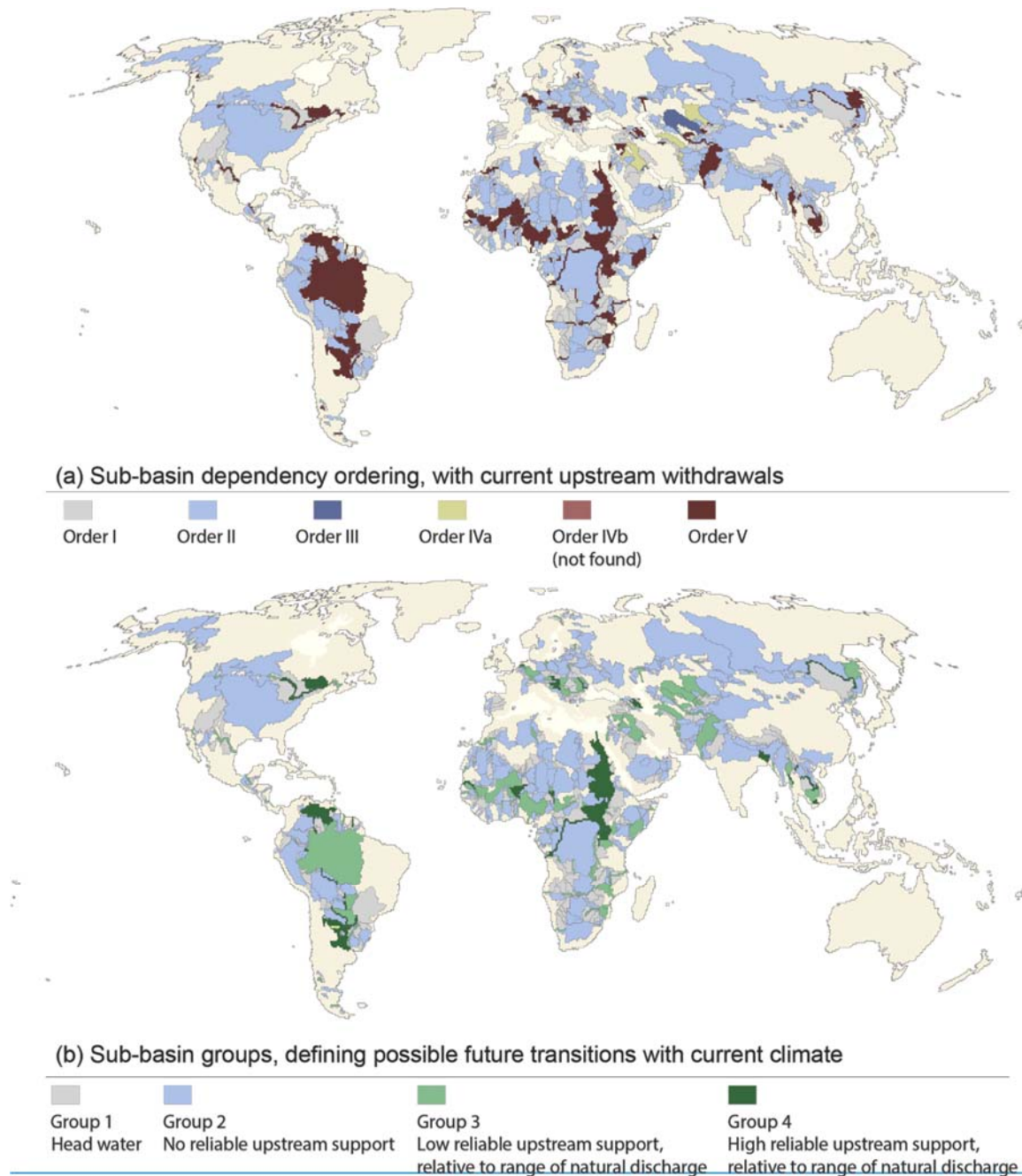


Fig. 9. a) Sub-basins under different dependency ordering b) Sub-basins under different groups. The first defines possible future transitions if local demand changes with upstream withdrawals staying at current levels. No sub-basin was found under order IVb. The second defines what transitions are possible with changes in both local demand and upstream withdrawals, with current climate.

Discussion

In this analysis, transboundary water dependency was examined ~~through~~[based on](#) the ~~idea~~[concept](#) that a ~~sub-basin~~[sub-basin SBA](#) is dependent on upstream inflows if it requires those inflows to avoid water scarcity (e.g. stress, shortage [as used here](#)) and associated impacts. [We proposed that regime shifts discussed in the](#)

[resilience literature provide a useful way of thinking about this problem, and we provide a first exploration of how this concept can be analysed.](#)

We aimed to address three research questions. Firstly, we identified the current dependency category of each [sub-basinSBA](#). Examining occurrence of scarcity with different types of water availability allows classification of ways in which upstream and downstream SBAs are dependent on each other (Sect. [2.2.2](#), [3.1](#)), [2.2.2](#), and Sect. 3). To answer the second question, we further developed the analytical framework by explaining how climate, upstream withdrawals and local demand influence the dependency categories (Sect. 2.2.3). This ~~in turn allowed us to describe yields~~ [a typologysequence of possible transitions in dependency categories \(Sect.2.2.4\)](#). ~~The typology is built on the observationbetween system regimes that different types of water availability define tipping point thresholds involving changesdescribe what future changes in scarcity categories, and that these thresholds can be ordered differently depending on climatic characteristics and upstream withdrawals. The dependency are possible.~~ This leads to our third research question ~~involved exploring: how dependency category and its evolution might affect does this relate to water management and negotiations with other sub-in transboundary basins. We have provided a first step in this direction by proposing?~~

[What are the implications arising from key patternsfor mitigation and prevention of scarcity?](#)

[The literature on resilience and complex adaptive systems emphasises that it is difficult to predict what will happen in future, but we can identify what are the transitions that might occur to prepare ourselves such that the system either avoids or manages those transitions. According to our framework, the starting point is a system regime with low water demand, easily satisfied by local runoff \(NNN\). There is no need to use upstream inflows, such that upstream withdrawals have no effect on local water scarcity. The need to engage with upstream water users begins with an increase in local water demand, transitioning to a system regime where scarcity depends on upstream withdrawals \(SNN\). It is in the interest of both downstream and upstream to avoid breaking this dependency \(SNS\), which could happen because of either increases in local demand or upstream WW \(as well as changes in climate\). Despite the invisible consequences of transition to SNN, it would be worthwhile to expose the hidden dependency. Negotiation to reduce water withdrawals may fix a broken dependency, but there is also another possible outcome. If local water demand continues to increase, the dependence on upstream disappears again. Very high water demand cannot be met even with upstream inflows \(SSS\), such that upstream withdrawals can no longer solely cause scarcity, even if they contribute to its severity. In this system regime, negotiation with upstream regions is not sufficient to avoid scarcity, so it may be more worthwhile to look for other solutions, such as those within the political economy \(Allan 2002\).](#)

[Understanding these transitions provides a basic level of guidance for a region. In a no dependency system regime \(e.g. most SBAs analysed\), efforts can be made to keep water demand at low enough levels to be self-sufficient. If water demand is expected to increase, monitoring is useful to avoid being surprised by the breaking of a hidden dependency. While our analysis shows relatively few broken or unbroken dependencies in 2010, population growth and associated water demand means that the need for water scarcity-related negotiation in transboundary basins could become a much greater issue in future. It is specifically the emergence of dependencies that introduces the need for negotiation. Treaties have an indirect effect on physical upstream water dependency by limiting or coordinating development of water resources locally and upstream. Treaty design can be innovated to include functions that improve the stability of the dependency and hence prevent scarcity from occurring. If decision makers cannot avoid a transition to scarcity \(i.e. a broken dependency\), perhaps due to factors outside their control, then](#)

coordination can at least facilitate adaptation to cope with physical water scarcity. There are regions where physical water scarcity is to some extent expected – development is limited by water availability, such that fully utilising other resources (e.g. land) requires more water than is available. In addition, it should be pointed out that negotiation for rights to upstream inflows is only one strategy among many to try to meet water demand. In such cases, treaties can focus on mitigating the severity of impacts of scarcity.

Downstream areas with increasing water demand should be mindful that, in a way, they are ‘choosing’ to have to deal with dependencies and potential scarcity. If upstream withdrawals are stable, it can be argued that any conflict is effectively of their own making. Scarcity and dependency only emerge as problems when local demand crosses a threshold. This gives the impression that it is the local user that is responsible for the new problem, even though it may simply be that they are late to the game. typology (Sect. 3.2). On the other hand, if upstream withdrawals later increase, downstream regions might argue that they would not need to deal with scarcity, were it not for upstream actions. These interpretations of responsibility rely on the idea of precedence. The precedence paradigm is visible in prior appropriations regimes in USA, while negotiated allocations are arguably implemented by water markets in Australia and elsewhere (Grafton et al. 2011). Even in a negotiated approach, however, existing water needs and WWs are often taken into account, including at an international level – hybrid approaches are common. These examples illustrate the close connection between water allocation and different views about responsibility for transitions.

Relation to existing work

Our work distinguishes between dependency and scarcity and recognizes that dependency is primarily about potential for future scarcity, which transboundary cooperation aims to mitigate. To judge the importance of transboundary cooperation, it is more important to look at areas under no scarcity which are dependent on upstream inflows. The “broken dependency” category (SNS) and SSS only include cases where institutional arrangements have failed to prevent scarcity from occurring. Our work, however, highlights that negotiation to avoid needing to cope with occasional or persistent scarcity is only part of the issue. Negotiation As demand increases, negotiation among the riparian countries will eventually turn to discussion of intensity and frequency of scarcity, and the level of demand at which it occurs. Other existing work also distinguishes different types of rivers and basins to help understand why some riparians riparian on international rivers have been able to successfully negotiate treaties and others have not, – taking into account, for example, civilization, size of population, GDP, upstream-downstream relationship, and asymmetries in economic and political power among riparian states (Delbourg and Strobl 2012, Song and Whittington 2004, Wolf et al. 2003). Increasing water scarcity has been identified as a risk factor, but has not previously been systematically explored in terms of upstream dependency. —Our dependency category typology complements this existing work, and relations to other typologies could be explored in future.

One of the main advantages of our analytical framework, compared to existing knowledge, is that it highlights the possible ‘hidden’ dependency of upstream water, which has not been assessed in these terms before. Previous studies on transboundary river basins identified clear evidence of the impacts of upstream water use to downstream water availability and water scarcity level (Al-Faraj and Scholz 2015, Munia et al. 2016, Nepal et al. 2014, Veldkamp et al. 2017). It has already been found that about 0.95–1.44 billion transboundary people are under stress because of local water use, while upstream water use withdrawals increased the stress level by at least 1 percentage-point for 30–65 sub-basins SBAs,

affecting 0.29–1.13 billion people (Munia et al. 2016). Our analysis provides a different view of the issue by revealing that 932386 million people (3314% of the total transboundary population) are dependent on upstream water to avoid possible stress because of their own water usedemand and 464306 million people (1711% of the total transboundary population) are dependent on upstream water to avoid possible shortage (Table 2)–(Table 3). Along with previous work, including broader discussion of hydro-political dependency (Brochmann et al. 2012, Giordano and Wolf 2003, Gleick 2014, Jägerskog and Zeitoun 2009, Mirumachi 2013, Mirumachi 2015, Wolf 1998, Wolf 2007, Wolf 1999), our analysis highlights the importance of local demand in causing scarcity and dependency. If local demand stays low enough and local water resources are sufficient to meet the demand, 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). These are fundamental ideas that are not widely recognized in existing literature.

~~The analytical framework itself is admittedly relatively complex, and much of our theoretical work has involved trying to unpack it and make it accessible to a sufficiently broad audience. The categories of dependency and order discussed in the paper emerge logically when looking at whether water scarcity occurs occasionally or persistently with local runoff or with upstream inflows. The ultimate aim is relatively simple. The typology developed in the analysis aims to describe how the upstream dependency evolves, while emphasizing relationships with upstream WW. Ordering helps to explain the current situation of the SBA in question and the reason behind the situation. Ordering also provides a framework to anticipate an SBA's possible future experience of scarcity and dependency, as local demand and upstream WW increase or decrease. It further helps to manage the risk of water scarcity based on preparedness rather than a crisis approach.~~

Limitations and future work

In our analysis, we used water withdrawals, which refer to the total amount of water withdrawn, but not necessarily consumed, by each sector; much of which is returned to the water environment where it may be available to be withdrawn again. The return flows from industrial and domestic sectors have been taken into account in PCR-GLOBWB and the recycling ratios for industrial and domestic sectors have been estimated and validated at a country level based on Wada et al. (2011a, 2014). However, in this paper, 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). We therefore did not include return flows when calculating water stress, but those could be taken into account in future.

EFRs (i.e. environmental flow requirements) are important in transboundary water management. The stress indicator used in the analysis includes EFRs, assuming 30% of the water is needed to satisfy the EFRs (Falkenmark et al. 2007). We do not account for EFR in a spatially disaggregated way as the analysis is conducted in the SBA scale, where spatially variable EFRs influences the dependency category, adding additional complexity to the transition map. EFRs are in any case a rather complex issue and not easy to quantify (Pastor et al. 2014). Global scale EFR methods could be criticized for not adequately capturing on the ground conditions –our treatment of environmental flows is fit for purpose given that our focus is on the resilience-based analytical framework.

Nuances of water availability were not taken into account in this analysis. Industrial or domestic pollution may occur in upstream parts of a basin, which might make water unusable for irrigation or domestic

purposes (Thebo et al. 2017). Availability of green water has not been considered either. Green water increases the amount of locally available water by including soil water in addition to runoff. This affects scarcity, as the need for blue water should vary in response to changing green water availability, e.g. when there is less green water available, more blue water is needed. Decreases in availability of blue water (e.g. due to upstream withdrawals) may also push a region to use more green water. While green water is an important part of the local water availability, it does not affect inflows from upstream, by definition. Water is called “green water” when evapotranspiration occurs directly from rain or soil water, without runoff occurring. There is no additional effect on *avail.natural*, other than that on *avail.local*. Incorporating green water into the analysis will not affect *avail.actual* data either, as upstream withdrawals are in principle already accounted for in the water use model (including the effects of green water availability). The thresholds for both water shortage and stress are highly uncertain, so the effect of green water on the results is difficult to anticipate.

The main emphasis of the paper was the development of the analytical framework to understand the concept of upstream dependency categories and their orders from a resilience perspective. In this study, we provide the first attempt to link the dependency order to management strategies that could be taken to ease the possible scarcity situation. In future studies, it would be important to develop this further to identify more concrete strategy options, for example integrating with existing work on infrastructure development (e.g. storage using reservoirs or aquifers) (Daneshmand et al. 2014) and treaty formation (Brochmann et al. 2012, Dinar et al. 2011, Kliot et al. 2001). In connecting to management, the relevance of frequency of scarcity could be further examined in order to provide a more meaningful distinction between occasional and persistent scarcity: at what frequency of scarcity do management options need to be implemented permanently rather than only adaptively? e.g. trading of temporary vs permanent water allocations (Bjornlund 2003). TheIn future studies, in order to evaluate which transitions are actually plausible in future, the analytical framework could also be applied to water availability and demand scenarios based on future climate change scenarios (Representative Concentration Pathways, RCPs) (Van Vuuren et al. 2011) as well as Shared Social Pathway scenarios (SSP) (O’Neill et al. 2014) to identify what outcomes may be plausible within the full typology described in this paper. (O’Neill et al. 2014). In doing so, the scarcity criteria could also be revisited, given the simplicity of the indicators and thresholds used here, as acknowledged in Section 2.2.2. The analysis can be integrated with the concept of ‘adopting adaptation tipping points (ATP)’ to understand what strategies are needed (Kwadijk et al. 2010) to cope up with the scarcity status. Additional insights may be gained using other thresholds and/or other water scarcity indicators, such as food self-sufficiency (Gerten et al. 2011, Kummu et al. 2014) or sustainability of water withdrawals (Wada and Bierkens 2014). Further, our estimation of water availability does not take into account potential industrial or domestic pollution in upstream parts of a basin, which might make water unusable for irrigation or domestic purposes (Thebo et al. 2017). (Gerten et al. 2011, Kummu et al. 2014) or sustainability of water withdrawals (Wada and Bierkens 2014). Future work could also quantify “distance” from a threshold, which would further address the distinction between how close these basins are to scarcity.

Our method was applied here at the basin scale, considering only international transboundary basins. It can, however, also be applied to understand the dependency at different scales to interpret, for example, more localised water dependencies, e.g. between states within countries (Garrick 2015). Moreover, instead of using average water availability, analysis can be performed using water availability for each year to capture variability. Thus, the evolution of scarcity and dependency of an SBA for a given climate

can be categorized into different transition pathways along which a SBA progresses as its water demand or water availability changes. An early attempt at this was made in the “discussion paper” version of this article (Munia et al. 2017). In connecting to management, the relevance of frequency of scarcity could be further examined in order to provide a more meaningful distinction between scarcity that occurs every year and scarcity that occurs in some year: at what frequency of scarcity do management options need to be implemented permanently rather than only adaptively e.g. trading of temporary vs permanent water allocations (Bjornlund 2003).

Conclusions

In this paper, we aimed to explore the relationships between SBAs (i.e. sub-basin areas) of global transboundary river basins, in terms of dependency of downstream on upstream inflows to meet ~~their~~ needs/water demand and avoid ~~water~~ shortage and stress. Transboundary water dependency was examined through changes in scarcity category across different types of water availability (runoff, ~~naturalized~~ naturalised discharge and actual discharge). ~~The evolution~~ We used the idea of regime shifts to illustrate the importance of dependency for basin management. The advantage of thinking in terms of thresholds is that we can reason about how scarcity and dependency ~~of an SBA for a given climate can be categorized into different orders of dependency categories along which a SBA progresses as its~~ might change in future. In this paper, we focused on the effect of local demand and upstream water use or withdrawals, leaving possible changes in water availability ~~changes. This framework helps to understand the dependencies on which the SBA in question relies in order to avoid water stress and shortage, and what may happen if the demand (or population) increases further., due to climate change for example, to future work.~~ Understanding of the dependency category of an SBA ~~may have~~ has important policy implications regarding negotiation and redistribution of water among stakeholders, which may assist in improving water management ~~– in transboundary basins.~~

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