Department of Built Environment

Global analyses of drivers of water scarcity indicators in transboundary river basins

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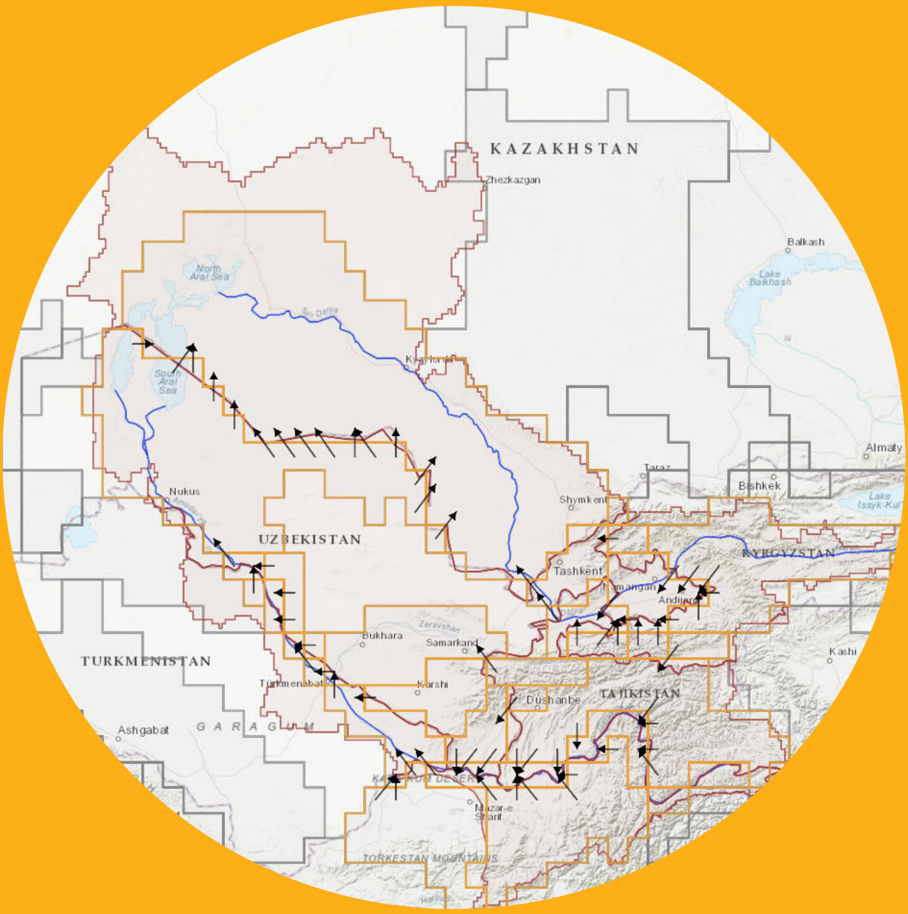
Hafsa Ahmed Munia



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Global analyses of drivers of water scarcity indicators in transboundary river basins

Hafsa Ahmed Munia

A doctoral dissertation completed for the degree of Doctor of Science (Technology) to be defended, with the permission of the Aalto University School of Engineering, at a public examination held at the lecture hall T2 of the school on 21 February 2020 at 12 noon.

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Aalto University publication series
DOCTORAL DISSERTATIONS 31/2020

ISBN 978-952-60-8960-7 (printed)
ISBN 978-952-60-8961-4 (pdf)
ISSN 1799-4934 (printed)
ISSN 1799-4942 (pdf)
http://urn.fi/URN:ISBN:978-952-60-8961-4

Painosalama Oy
Turku 2020

Finland

NORDIC SWAN ECOLABEL
Printed matter
4041-0619

Aalto University

Abstract

Aalto University, P.O. Box 11000, FI-00076 Aalto www.aalto.fi

Author
Hafsa Ahmed Munia

Name of the doctoral dissertation
Global analyses of drivers of water scarcity indicators in transboundary river basins

Publisher School of Engineering

Unit Department of Built Environment

Series Aalto University publication series DOCTORAL DISSERTATIONS 31/2020

Field of research Water and Environmental Engineering

Manuscript submitted 29 October 2019 **Date of the defence** 21 February 2020

Permission for public defence granted (date) 16 December 2019 **Language** English

☐ **Monograph** ☒ **Article dissertation** ☐ **Essay dissertation**

Abstract

Water scarcity management in the context of transboundary river basins is not limited to local water use and availability- upstream water demand and availability play an important role. The distinction between local and upstream water use and availability across countries sets transboundary water scarcity analysis apart from other water scarcity analyses.

This dissertation aims to improve the general understanding of the causes of water scarcity in the transboundary context. A novel framework is developed to understand the evaluation of water scarcity, as well as downstream dependencies on upstream water resources, for global transboundary river basins. By applying the framework with existing datasets and water scarcity indicators, it was possible to identify transboundary water scarcity hotspots, the dominant factors behind the scarcity and the role of upstream water both historically and under future socio-economic and climate change conditions. This global work thus provides new insights for transboundary water management.

Supported by global maps for this type of analysis for the first time, the thesis emphasizes a number of insights that are specifically relevant to the development and implementation of transboundary water scarcity adaptation strategies. One of the most important findings is that in the majority of cases, the downstream water stress is mostly due to local "overuse" of water. In the context of securing water availability in the downstream parts of a basin, a critical point is passed when local water demand is higher than the threshold for the sub-basin in question to be self-sufficient with locally originated runoff. In many basins, nevertheless, upstream water use intensifies water scarcity. This is expected to be more significant in future scenarios, due to both local and upstream population growth and the associated increased water demand. Most importantly, the dissertation highlights that to make sound decisions for transboundary water, a well-rounded understanding of the water demand and availability in both local and upstream sub-basins is needed. Analyses of this type provide unprecedented opportunities for understanding the physical relationships within transboundary river basins at a global scale.

Keywords transboundary, water scarcity, upstream dependency, climate change

ISBN (printed) 978-952-60-8960-7 **ISBN (pdf)** 978-952-60-8961-4

ISSN (printed) 1799-4934 **ISSN (pdf)** 1799-4942

Location of publisher Helsinki **Location of printing** Turku **Year** 2020

Pages 114 **urn** http://urn.fi/URN:ISBN:978-952-60-8961-4

Acknowledgements

Water & Development Research Group is one of the best things that happened in my life- yes, I can say that certainly as I was entirely confused about "What to do next?" when I first arrived in Finland for my Master's. For this opportunity, for the guidance and all the support, I want to thank my supervisor Associate Professor Matti Kummu. Matti, thank you very much for believing in me, for allowing me to do my M.Sc. thesis in this wonderful group which eventually took me to this wonderful journey- I have truly enjoyed most of these years.

I want to give a very special thanks to Dr. Joseph Guillaume for all his instruction, advice and hands-on work with my papers. Joseph, you have been a wonderful instructor, a mentor, and a teacher. I have always been grateful to you for the time you gave me to explain even very simple things over and over, for being so patient with me, for giving me the encouragement I needed at times. You became more than an academic instructor and I cannot imagine my doctoral journey without you.

I would like to take the opportunity to also thank my pre-examiners Associate Professor Bernhard Lehner and Dr. Naota Hanasaki for their generous and constructive feedback that helped me to refine the synthesis. Professor Fabrice Renaud, I am extremely grateful that you accepted the invitation to act as an opponent for the dissertation.

The research papers for this dissertation would not have been possible without all the co-authors I have had the privilege to work with: Dr. Miina Porkka. Prof. Yoshihide Wada, Prof. Naho Mirumachi, and Assistant prof. Ted Veldkamp. Virkki Villi joined me at the last moment and helped to do the model uncertainty analysis over and over. Thank you very much to all of you for your enthusiastic participation.

This dissertation would not be possible without the funding bodies that allowed me to work full time on this research during all these years. My special thanks belong to - Maa-ja vesitekniikan tuki ry, Aalto ENG Doctoral Programme, and Seven Hallin Research Foundation.

I would like to thank my present and past colleagues in water and development research group for creating such a nice working environment: Prof. Olli Varis, Prof. Marko Keskinen, Dr. Horton Alexander, Dr. Chrysafi Anna, Dr. Mika Jalava, Dr. Maija Taka, Dr. Suvi Sojamo, Lauri Ahopelto, Amy Fallon, Matias Heino, Anne Hyvärinen, Marko Kallio, Pekka Kinnunen, Elina Lehikoinen, Piipponen Johannes. A special thanks to Maija for all your logistic and mental support especially at the final stretch of writing this synthesis. You were always there when needed- I do not know how I would finish my thesis without you! Mika, you have been a life savior in the last couple of months- you have guided me through different steps of finalizing this synthesis starting from reading it, converting in to correct pdf resolution, applying fund, getting it printed. Thank you very much! I will never forget our office lunch team- Maija, Elina, Venla, Amy and the wonderful discussion we used to have- I will miss you all. Elina, your word and support have always encouraged me and helped me to believe that I am doing ok.

I would say that my journey as a doctoral student will be incomplete without mentioning some of the names who have contributed more than their part. My husband Ahsan, who has been so patient, has understood me (mostly!) and let me do what I want. I know, you had to share all my stress, made more sacrifices than you are expected to do. Writing this thesis would never be possible without your sacrifices, especially for taking care of Arash (our son). Arash, my son, you also deserve a big thanks for being so patient with Mumma, for not complaining when I was not present on those many occasions of your life. My sincere gratitude goes to my parents: my father Saleh Ahmed and mother Irene Chowdhury, for their everlasting encouragement, blessings, and love. A special thanks go to my sisters: Maisha and Sauda. Especially Sauda, there is no doubt that you will call me almost every day and ask me ‘How are you doing?’ I know I have always been bad at communication, I hate to make phone calls and love to be isolated in most times. But I have always waited for your phone calls and the ‘How are you?’ question. Thank you for making that extra effort for the last 6 years. My warmest thanks belong to the Bangladeshi community in Finland for helping me recharge my batteries after work during the evenings and at the weekends.

In the end, to my life-coach, my late grandfather Moslauddin Chowdhury: I dedicate this thesis to you because I owe it all to you. Many Thanks!

Espoo, January 24th, 2020
Hafsa Ahmed Munia.

Content

List of publications

This doctoral dissertation consists of a summary and the following publications, which are referred to in the text by their numerals.

I. **Munia, H.**, Guillaume, J. H. A., Mirumachi, N., Porkka, M., Wada, Y., & Kummu, M. (2016). Water stress in global transboundary river basins: significance of upstream water use on downstream stress. Environmental Research letters, 11(1), 014002. https://doi.org/10.1088/1748-9326/11/1/014002 (Available by CC BY 3.0 License)

II. **Munia, H.**, Guillaume, J. H. A., Mirumachi, N., Wada, Y. and Kummu, M., 2018. How downstream sub-basins depend on upstream inflows to avoid scarcity: typology and global analysis of transboundary rivers, Hydrology and Earth System Sciences, 22(5), 2795-2809. https://doi.org/10.5194/hess-22-2795-2018 (Available by CC BY 4.0 License)

III. **Munia, H.**, Guillaume, J. H. A., Veldkamp, T., Wada, Y., Virkki, V. and Kummu, M.: Transboundary water scarcity and its drivers under climate change: a global study, Submitted to Earth's Future on 17th July 2019 and subsequently accepted for peer review.

Author's contribution

I. The author designed the study with support from Prof. Kummu. The author was responsible for performing the analyses with the help and support of Dr. Guillaume and Dr. Porkka. Prof. Wada, and Prof. Mirumachi provided guidance in the overall structure of the analysis. The author was responsible for writing the article, with contributions from all co-authors.

II. The author designed the study together with Dr. Guillaume, with support from Prof. Kummu. Prof. Wada and Prof. Mirumachi contributed to the overall structure of the study. The author performed the analysis together with Dr. Guillaume. The author wrote the article with contributions from all co-authors.

III. The author designed the analysis with help and guidance from Prof. Kummu and Dr. Guillaume. Prof. Wada and Assistant prof. Veldkamp participated in formulating the focus of the article and assisted in designing the analysis. Virkki performed the model uncertainty analysis with input from the author. The author was responsible for writing the article, with contributions from all co-authors.

1 Introduction and objective

Water, a vital and yet finite resource, can be considered one of the most 'shared' resources on Earth. Since human survival relies on this natural resource, its scarcity has been a major concern. Currently, freshwater scarcity is an issue with huge socio-economic and environmental impacts. The global population is growing rapidly, and an increasing number of people are living under rising or even permanent water stress (United Nations, 2013, Publication **I**). Numerous global studies have been performed to identify the impact of climate change and socio-economic developments on water scarcity globally. Raskin et al. (1997) produced the first global water assessment at the national level. The fundamental view of future water scarcity is shown in Vörösmarty et al. (2000) and the basic techniques and procedures of model-based assessment is shown in Alcamo et al. (2003). Alcamo et al. (2007) analyzed and compared several indicators of water stress, and examined in more detail the socio-economic factors that lead to future changes in global water stress. It has been estimated that by 2050 more than half the world's population will live in water-stressed areas (Schewe et al., 2014). Further, it has been proposed that the higher the water stress, the more vulnerable the population to changing water scarcity (van Beek et al.,2011). The challenge is most daunting in the case of shared use of transboundary water resources.

"Transboundary Rivers" cover almost half of the globe's land surface and 60% of global water flow (United Nations, 2013). They are often considered difficult to manage because of the involvement of different countries, multiple political entities, and actors. Around the world, there are 310 large transboundary river basins (TFDD, 2017) and hundreds of transboundary aquifers (United Nations, 2013). In the case of transboundary river basins, downstream countries are constrained by natural asymmetries because of their relative position within the basin. The relationship between upstream/downstream riparian countries is thus critical, especially when upstream countries take advantage of their favored position within the basin by controlling the water resources available to the downstream riparian (Graversen and Heberger, 2011) .

Transboundary water resource management decisions are often considered to be greatly influenced by the power relations between riparian countries (Brochmann and Gleditsch, 2012; Giordano and Wolf, 2003; Gleick, 2014; Jägerskog and Zeitoun, 2009; Mirumachi, 2013, 2015; Wolf, 1998, 1999, 2007). Any water use within a shared basin is bound to create stress in some way for other possible users. Management approaches need to create benefits for everyone who shares the basin, including handling international trade, climate change adaptation, economic growth, water security, improved governance, and regional integration. Within the academic literature, a broad range of disciplines (politics, geography, management) have incorporated discussions of international water relations and management practices between upstream and downstream countries (e.g. Brochmann and Gleditsch, 2012; Giordano and Wolf, 2003; Gleick, 2014; Jägerskog and Zeitoun, 2009; Wolf, 1998, 1999, 2007). Some regional analyses have also been done from the perspective of legal and institutional effectiveness for the cooperative management of water resources (e.g. Jacobs, 2002; Vinogradov and Langford, 2001). The reasons identified for conflicts generally include unsustainable economic practices, environmental degradation, politics, serious social problems, and different interests (Ravnborg, 2004; Shustov, 2009; Wolf et al., 2003).

Increased water scarcity has been identified as another possible stimulus for international water conflict due to transboundary impacts on water availability (Ravnborg, 2004), although several studies argue and have found evidence that water scarcity encourages cooperation, not conflict (e.g. Dinar, 2009; Wolf et al., 2003). Most transboundary cooperation agreements so far do not address water scarcity directly (UNECE, 2018). However, some river basin organizations do consider this emerging topic. For example, the Senegal River Basin Development Organization considered equitable sharing and sustainable management for the basin's water resources management (Tignino, 2016). Transboundary water cooperation in the Colorado basin has addressed increasing scarcity by including a flexibility provision in the agreement and by starting the development of a joint water scarcity contingency plan (Sullivan et al., 2019).

It would thus be important to understand the upstream–downstream interactions on water resources and water scarcity to help inform river basins organizations and policy makers. While there are several case studies focusing on transboundary water scarcity (e.g. Delbourg and Strobl 2012, Nepal et al. 2014, Scott et al. 2003), transboundary water scarcity at a global spatial scale has often been left unstudied. Hoekstra (2012) studied monthly water scarcity for 405 river basins but did not address spatial variations of water availability within a transboundary context. In recent years, a few studies at different temporal and spatial scales have been conducted in order to understand the extent of the water scarcity problem in a transboundary context for present conditions, including several following the work in this thesis (e.g. Degefu et al., 2018, 2019; Munia et al., 2016, 2018; Veldkamp et al., 2017; Wada and Heinrich, 2013). However, none of these studies has addressed the impact of socio-economic and climate change on water use and availability.

An important aspect of a water scarcity assessment is to have reliable estimates of the amount of water available to each country, namely the streamflow, which an upstream country can also affect by withdrawing water for irrigation or storage for other uses. For example, in the Nile and Rio Grande basins, a large part of discharge comes from upstream, and thus they are dependent on the upstream precipitation pattern, land, and water use (Drieschova et al., 2008). Climate change increases variability in the flow of waters and thus requires the development of institutional mechanisms to ensure that this variability is cooperatively managed between the sharing countries. Predicting the future yield of shared water sources based on past hydrologic records may cause significant problems in reliability (Draper and Kundell, 2007). Therefore, the impact of climate change and socio-economic changes on future transboundary water scarcity is required to predict how future development would affect the transboundary water stress levels and dependency dynamics.

It is common to quantify water scarcity using a number of simple indicators, which are then categorized using thresholds to define whether or not the region is facing water scarcity. Over the years, water scarcity analyses have evolved from simple thresholds of per capita freshwater availability (Falkenmark, 1997, 2013b, 2013a; Falkenmark et al., 2007) to more sophisticated thresholds accounting for variability in demand (Alcamo et al., 2003; Rijsberman, 2006; Rockström et al., 2009), adaptive capacity (Molden et al., 2007; Ohlsson, 2000; Seckler, 1998), environmental water requirements (Pastor et al., 2014), as well as a range of social and environmental conditions (Liu et al., 2017).

In an era of global water models, a gap stands out in the existing literature, where there is an opportunity to examine physical drivers of transboundary water scarcity in ways that have not been possible before. Systematically varying assumptions in analyses using data from global water models enables estimation of the effect of upstream and local water availability and use on water scarcity indicators for the first time with global spatial coverage. While accuracy of the results is necessarily limited by the accuracy and resolution of the global water models, global maps resulting from such analyses can provide unprecedented opportunities for visualizing and understanding the physical relationships within transboundary river basins at a global scale.

Furthermore, the knowledge of water scarcity in transboundary river and lake basins at global scale is limited. A global assessment conducted at spatially explicit scale will enable the capture of variations in terms of water availability and water use within the basins. The insights gained from the research are important for water allocation negotiations within border crossing basins.

The overall objective of this dissertation is therefore to use data from global water models to perform a systematic analysis of global transboundary water scarcity and provide information to improve the understanding of the causes and factors involved. This objective is tackled with three specific research questions.

Firstly, given the existing use of water scarcity indicators in global analyses (including transboundary river basins), data from global water models provide the opportunity to examine how these indicators are affected by their components, i.e. the drivers of transboundary water scarcity (local vs upstream water availability and use). Despite the simplicity of this idea, such an analysis has not yet been performed in a transboundary context. Therefore the first research question this dissertation aims to address is:

RQ1. What are the dominant drivers of transboundary water scarcity indicators across the globe?

Secondly, water scarcity indicators are typically associated with thresholds categorizing whether or not water scarcity occurs in a region. Therefore there is an opportunity to examine how the water scarcity status of a region depends on the drivers of transboundary water scarcity—most importantly, upstream inflows. I refer to this as “upstream dependency.” The second research question aims to look at:

RQ2. How can we quantitatively characterize upstream dependency in transboundary water basins?

Thirdly, global water models provide internally consistent estimates of both historical water use and availability and potential future scenarios, accounting for both climatic and socio-economic changes. This enables the quantification of the historical and future development of water scarcity indicators in transboundary river basins and changes in upstream dependency. Therefore the third research question is:

RQ3. How and where has water scarcity in global transboundary river basins developed?

Each research question is answered with a journal publication (publications **I–III**). Each publication thus provides a partial solution to the overall research objective. The contributions of these papers are combined in this synthesis part of the dissertation.

Figure 1 illustrates an outline of the thesis and presents the steps taken to meet the thesis objectives by showing a broad overview of the appended publications (**PI, PII, PIII**) and the whole formed by the thesis.

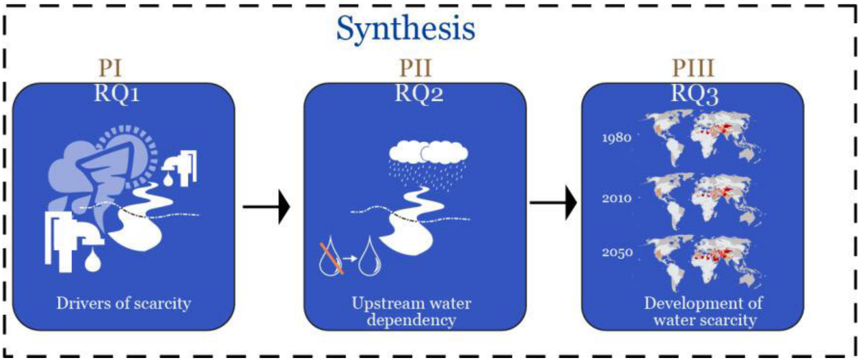

Figure 1. Graphical outline of the thesis. Primary research questions of the dissertation (RQ1, RQII, RQ3) and the publications under each question (PI, PII, PIII).

2 Research Background

2.1 Water scarcity

Water scarcity refers to the lack of freshwater resources to meet water demand. Water scarcity can take the form of physical or social water scarcity (Falkenmark et al., 2007). Physical water scarcity arises out of the low availability of water resources, while social water scarcity is caused by unbalanced power relations, poverty, and related inequalities (Falkenmark et al., 2007). Another important aspect of water scarcity is economic water scarcity, which occurs due to lack of investment in water or a lack of human capacity to satisfy the demand for water (Molden et al., 2007). The World Bank (2007) identified organizational scarcity and scarcity of accountability as different measures of water scarcity. While all these different kinds of water scarcity highlight important challenges for water resource management, this thesis focuses only on physical water scarcity, following existing studies (e.g. Brown and Matlock, 2011; Kummu et al., 2010, 2016; Porkka et al., 2012).

Over decades, many indicators have been developed for measuring physical water scarcity. The most commonly used indicator is the water shortage index, also known as population-driven water scarcity (Falkenmark et al., 2007; Kummu et al., 2010), calculated as water availability per capita (Falkenmark et al., 2007; Kummu et al., 2016). While it captures an important intuition that sufficiency of water availability depends on population, it is also criticized for several drawbacks. For example, annual national (or regional) averages conceal water scarcity at smaller spatial and temporal scales, and fixed thresholds are often unable to reflect variations across countries in their ability to adapt to water scarcity (Hanasaki et al., 2018). However, despite these limitations, in either original or adapted form, this indicator has become one of the most commonly used indicators for water scarcity studies because of its simplicity, and it enjoys widespread use in water scarcity assessments at both the global and regional scales (Wada et al., 2011a).

Another commonly used indicator is the water stress index (WSI), which captures demand-driven water scarcity (Falkenmark et al., 2007; Oki and Kanae, 2006; Wada et al., 2011a). WSI refers to the impact of high water use (either withdrawals or consumption) relative to water availability. It is often measured with the use-to-availability ratio (Rockström et al., 2009). It captures the difficulties in accessing the resource, including side effects (e.g. social and environmental impacts), which can occur even if the population is not large enough to cause scarcity according to the water shortage index. However, the criticality ratio depends on certain assumptions: (a) the data on water resources availability reflect how much of it could and should be made available for human use; (b) the water withdrawal data (if used) reflect how much of it is consumed (or evapotranspired) and how much could be available for recycling through return flows; and (c) the thresholds on the indicator capture a society's adaptive capacity to cope with stress.

Nevertheless, both stress and shortage are useful indicators of the more general concept of scarcity. This thesis uses both the concepts of stress and shortage as the starting point and/or first attempt to identify the drivers of transboundary water scarcity, upstream dependency, and the development of the transboundary water scarcity over the years. The water scarcity indicators were deliberately selected as simple examples. Despite their limitations, these indicators are considered as a globally applied standard metrics of water scarcity (Liu et al., 2017) and have been widely used in previous water scarcity research (e.g. Arnell and Lloyd-Hughes, 2014; Carr et al., 2012; Mianabadi et al., 2015; Veldkamp et al., 2017; Vörösmarty et al., 2000). Therefore, by using these commonly used indicators, it is possible to compare the findings from existing global transboundary studies (e.g. Degefu et al., 2018, 2019; Veldkamp et al., 2017; Wada and Heinrich, 2013), including some citing papers in this thesis.

The water scarcity calculation in this assessment incorporates only blue water, i.e., the section of the hydrological cycle that represents the running water found in rivers, lakes, and aquifers (Savenije, 2000). Green water scarcity, i.e., deficiency in relation to crop water requirements (Gerten et al., 2011), is left for future work, given its importance. Various indicators of green water availability and scarcity exist (Schyns et al., 2015). However, only a handful of studies have proposed methods of assessing water scarcity that take into account both blue and green water resources (Gerten et al., 2011; Kummu et al., 2014; Rockström et al., 2009), such that blue water is often studied in isolation. This thesis focuses on indicators for blue water, given that they are more mature and more widely accepted and that evaluation of the utility of the indicators is not the primary objective of this thesis. This assessment also leaves explicit analysis of transboundary groundwater relationships to future work, given their complexity compared to upstream-downstream hydrological relationships. Transboundary aquifers have previously been studied in terms of contributions of overlying countries to recharge and abstraction (Wada and Heinrich, 2013).

2.2 Drivers of transboundary water scarcity

The water stress and shortage indicators used in the analysis of water scarcity are usually expressed by the following equations:

$$stress = \frac{Use}{Availability} \tag{1}$$

$$shortage = \frac{Availability}{Population} \tag{2}$$

Therefore, the water stress indicator is determined by two main drivers, by definition: water availability and water use. Both of these drivers have well-known impacts on the hydrological cycle (Liu et al., 2017; Veldkamp et al., 2015). Falkenmark (2007) defined different levels of water stress, using a threshold value of 0.2 (20%) to 0.4 (40%) as moderate, and more than 0.4 (40%) as severe water scarcity in order to compare agricultural, industrial, and domestic water demands with the availability of freshwater resources. For stress, the threshold reflects the amount of water that can be used with minimal difficulties arising and therefore reflects capacity to capture, store, and share water. The cited thresholds (20%, 40%) originally applied to water withdrawals considering return flow, while in case of water consumption water is permanently abstracted or evaporated or consumed or otherwise removed from the immediate water environment. Therefore, using this threshold to calculate a consumption-based water stress index accounts for substantial return flows that are still available for downstream users (Hoekstra et al., 2012a, Kummu et al., 2016).

The water shortage indicator, on the other hand, is related to population and availability. A value of 1,700 m^3/cap/year of renewable freshwater was proposed as the threshold for water scarcity, below which social stress and a high level of competition for water emerge (Falkenmark et al., 1989; Liu et al., 2017). If water availability falls below 1,000 m^3/cap/year, then the area experiences high water scarcity, and below 500 m^3/cap/year, absolute scarcity (Falkenmark et al., 1989). For shortage, the threshold reflects the amount of water required to meet the needs of the population. Population growth normally leads to an increase in water demands in almost all sectors (domestic, industrial, agricultural, energy, and recreation) unless water management practices become more efficient (Schewe et al., 2014). Therefore, use and availability can be identified as the major drivers of water scarcity indicators.

Hydro-climatic systems and socio-economic processes are major forces behind changes in water scarcity in the future, by changing water demand and availability (Döll et al., 2015). Climate change refers to the significant change in climate conditions that can be attributed to human activities (IPCC, 2010). The impact of climate change on water scarcity will be felt through changes in precipitation and other climatic variables and may lead to significant changes in water supply in many regions (Schewe et al., 2014). The impact of socio-economic changes on water scarcity involves developments in water demand and changes in human control over freshwater resources. Changes in water demand are driven by a number of factors, such as GDP growth, changes in dietary requirements, population growth, and technological developments (Flörke et al., 2013; Wada et al., 2016). Changes in human control over freshwater resources involve factors such as the development of dams and reservoirs (Grill et al., 2019) and changes in land use and land cover (Pokhrel et al., 2016). Socio-economic drivers can also affect climate change impacts on water resources (Alcamo et al., 2007; Arnell, 2004; Arnell and Lloyd-Hughes, 2014; Veldkamp et al., 2017).

Numerous studies have evaluated the impact of socioeconomic developments and/or changes in hydro-climatic conditions on freshwater resources and water scarcity, using different scenarios to describe plausible future hydro-climatic and socio-economic conditions (Alcamo et al., 2007; Arnell, 2004; Arnell and Lloyd-Hughes, 2014; Gosling and Arnell, 2016; Haddeland et al., 2013; Hagemann et al., 2013; Hanasaki et al., 2012; Kiguchi et al., 2015; Kundzewicz et al., 2008; Oki and Kanae, 2006; Prudhomme et al., 2014; Schewe et al., 2014; Shen et al., 2014; van Vliet et al., 2013; Vörösmarty et al., 2000; Weiland et al., 2012). However, none of these studies analyse the issues specifically in a transboundary context. The risks imposed by climate change to transboundary water are discussed widely from the perspective of international law and sharing agreements between countries (e.g. Draper and Kundell, 2007; Cooley and Gleick, 2011) and adaptation mechanisms (e.g. Drieschova et al., 2009). Despite the widespread recognition of the importance of climate and socio-economic changes on transboundary water, so far, no quantitative research has been performed to unravel and understand its impact on transboundary water scarcity and its drivers globally.

In the case of transboundary waters, the roles of local vs upstream changes in water use and availability due to climate and socio-economic changes can be considered as especially troubling issues. Any changes in upstream, either due to changing climate or changes in water use, directly impact downstream water availability—a property that makes transboundary water management challenging. For example, many socio-economic developments, which are mostly targeted at local to regional scales, are known to impact the hydrological cycle which can affect streamflow on larger scales, such as in downstream areas (Wada et al., 2013, 2011b; Vörösmarty et al., 2015). Upstream water withdrawals from the streamflow may decrease water availability for downstream use (Döll et al., 2009; Wada et al., 2011b, 2013). Changes in climate would impact both local and upstream water availability. Therefore, water scarcity in the context of a transboundary basin is not only limited by local demand and local availability, but also by upstream water consumption and upstream inflows, which together are considered in this thesis to be the proximate drivers of transboundary water scarcity. It should be acknowledged here that the notion of upstream-downstream relationships applies generally, also between states or provinces within countries, and even between irrigation regions. The current coarse resolution of global models is, however, better suited to large transnational basins, which is also the context that is most prominent at global scale, in terms of international water law.

2.3 Water dependencies

Upstream–downstream relationships remain one of the many challenges of transboundary water scarcity management because of inequalities in the distribution of freshwater resources and population. The use of a transboundary water system by one country usually affects other states sharing the same system, through changes in water quality, alteration of river flow, or change in water availability over time (Leb, 2015). This creates not only the need for sharing but also a dependency on each other.

“Hydro-political dependency” in transboundary river basins is an important geopolitical issue bound up with concerns of sovereignty, and it affects the power relations between riparian countries (Brochmann and Gleditsch, 2012; Giordano and Wolf, 2003; Jägerskog and Zeitoun, 2009; Mirumachi, 2013, 2015; Wolf, 1998, 1999, 2007). Hydro-political dependencies between countries are widely regarded as having important implications for international water cooperation and conflict.

Bound up with political dependency, downstream areas can be “physically” dependent on upstream water resources. External water resources constitute a considerable part of the total renewable water of some countries, which can create interdependencies between countries (Hanasaki et al., 2012). In the case of transboundary basins, competing use among countries is a common challenge. Water availability in the downstream countries is often highly dependent on upstream precipitation patterns and upstream water use (Al-Faraj and Scholz, 2015; Drieschova et al., 2008; Veldkamp et al., 2017). An increase in water demand in upstream sub-basins can, however, reduce water availability downstream (Veldkamp et al., 2017). Sometimes local water is not sufficient to meet local needs, so then the region is dependent on upstream, and the two regions need to share their water. Therefore “upstream dependency” occurs within a river basin, where a downstream water user relies on water from a river or lake that has flowed from upstream (Section 3.4). If they did not have that water, they would be facing scarcity. This concept is defined in more detail in the Methods section. Conflict may arise if an upstream water user increases their water withdrawals, reducing the water available downstream.

When broadening the scope outside transboundary basins, there is yet another kind of water dependency known as “virtual water dependency” (Seekell et al., 2011). This occurs when a region cannot meet their water needs with their own available water and avoids water scarcity by importing the products or services they would have produced with that water (Porkka et al., 2017). They are “dependent” in the sense that if for any reason they were unable to import those products anymore, the region would experience the impact of water scarcity. Virtual water trade is often considered a solution to limited water availability in many regions (Carr et al., 2012). However, instead of solving regional and local water scarcity, this often increases inequities, as virtual water flows tend to be driven by gross domestic product and social development status (Seekell et al., 2011). However, in the case of transboundary basins, upstream dependency provides an alternative to virtual water dependency when local demand increases, and can be consider as an alternative— one can imagine that it is often easier to use inflows from upstream to meet water demand than to import products as a substitute.

3 Methods

3.1 Data sources

Various global datasets, including vector data of country boundaries, global river basins and rivers as well as various gridded data were used for the analyses. The most relevant datasets used are listed in Table 1.

Drainage direction data (DDM30) (Döll and Lehner, 2002) was obtained at 30 arc min resolution, which described the drainage direction for both surface flow routing and to define upstream–downstream links. Country boundaries were first rasterized from Natural Earth admin 0 boundaries (Natural Earth, 2017).

In this analysis, water use was estimated taking into consideration irrigation, domestic, and industrial water use. For Publication **I**, both consumption and withdrawal data for 2010 were used to calculate water use data, while for Publication **II** only water withdrawal data for 2010 was used to estimate water use. Both water use and availability data (Publications **I** & **II**) were obtained from PCR-GLOBWB—a conceptual, process-based water balance model (Wada et al., 2011b, 2013; Wanders and Wada, 2015), simulated at grid-cell resolution (30 arc-min, or roughly 50 km by 50 km at the equator). For Publication **I**, water availability for each SBA was calculated with river discharge data at the SBA outlet, while for Publication **II**, water availability was estimated as average annual runoff for the region (more details in Sections 3.3 & 3.4).

In Publication **III**, the analysis was extended to past, present, and future scenarios. The data were obtained from the Inter-Sectoral Impact Model Intercomparison Project (ISIMIP) (www.isimip.org) model –run archive also at a 0.5 degree grid resolution. ISIMIP provides a comprehensive collection of state-of-the-art global hydrological models (Publication **III**). In Publication **III**, consumptive water use data for 1981–2050 was used. Due to the varying model output availability for historical and future periods, data were collected from a few different sources—namely ISIMIP Fast Track for both historical and future runoff and irrigation water consumption, ISIMIP 2a for historical domestic and industrial water consumption, and WFaS (Wada et al., 2016) for future industrial and domestic water consumption. Simulation data were taken from four global hydrological models—H08, LPJmL, PCR-GLOBWB and WaterGAP (Table 1), as these are the only models that provide irrigation water consumption estimates at a global scale (more details in Publication **III**, Section 2.1).

To provide an indication of a need for water (rather than water use), population density information was obtained from the HYDE 3.2 dataset for each year from

1981 to 2010 for Publications **I** and **II** and from 1980–2050 for Publication **III** (Table 1). The population data were first aggregated from 5 to 30 arc min resolution and then for each SBA for every year.

Table 1. Datasets used in the dissertation and publications and datasets produced by the author.

		Datasets and source	Publication I	Publication II	Publication III
Global gridded data	Basin area data	Drainage Direction, (Döll and Lehner 2002)		X	X
		Country borders, Natural Earth Admin 0 boundaries (Natural Earth, 2017)		X	X
		River basin boundaries, (Wada et al., 2011b, 2013)	X	X	X
	Population data	Population, HYDE (Goldewijk et al., 2010)	2010	1981-2010	1980–2050
	Water Availability	River discharge, PCR-GLOBWB (Wada et al., 2011, 2013)	1960–2010		
		Runoff, PCR-GLOBWB (Wada et al., 2011, 2013)		1981–2010	
		Runoff, LPJmL, WaterGAP, H08, PCR-GLOBWB (www.isimip.org)			1971–2050
	Water Use	Water Withdrawal, PCR-GLOBWB (Wada et al., 2011b, 2013)	2010	2010	
		Water Consumption, PCR-GLOBWB (Wada et al, 2011b, 2013)	2010		
		Water Consumption, LPJML, WATERGAP, H08, PCR-GLOBWB (www.isimip.org)			1971–2050
Data sets produced by the author		Sub-basin delineation data (Publications I and II)	X	X	
		Transboundary water stress data (Publication I)	2010		
		Transboundary dependency category data (Publication II)		2010	

3.2 Delimitation of transboundary river basins

This study considers a river basin to be transboundary if it crosses at least one international political boundary. The study is limited to basins with a surface area of over 10,000 km^2. The unit of analysis used in the scarcity analysis is at the sub-basin scale, i.e. parts of basins that belong to different countries rather than at the national or global level.

A basin–country mesh was used to subdivide the transboundary basins into sub-basin areas (SBAs). For Publication **I**, SBAs were defined by effectively yielding a mesh of river basin boundaries (Wada et al., 2011b, 2013) with country boundaries of similar resolution. For Publications **II** & **III**, SBAs were defined by breaking up the drainage direction map where it flows across country (and shared zone) boundaries. Border cells were then manually assigned to countries to provide meaningful hydrological relationships. In general, single-cell SBAs 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.

Upstream–downstream relationships between these SBAs were defined initially by taking into account the maximum altitude of each SBA, the river network (CIA World DataBank II 2004), and also taking information from the Transboundary Freshwater Dispute Database (TFDD) data set with some manual assignment (Oregon State University, 2007) (Publication **I**). This was further developed in Publication **II** where we used the DDM30 drainage direction dataset (Döll and Lehner 2002). The drainage network used here to identify upstream-downstream relationships has a clear hierarchical relation, so water only flows to one immediately downstream sub-basin and there is no risk of double counting. The detailed method of identification of upstream-middle stream-downstream SBAs is given in Publication **II**, Section 2.2.1. Publication **III** used the same SBA and upstream–downstream definition as used in Publication **II**.

3.3 Effect of upstream water use on water stress and hydro-political interactions

To calculate the effect of upstream water use on an SBA’s stress level (Publication **I**), we used the use-to-availability ratio (WSI) to calculate stress considering only local water use (Eq. 3) of each sub-basin based on the country-basin mesh, then compared with the situation where upstream water use (sum of all upstream SBA’s water use) was subtracted from downstream water availability (Eq. 4).

Calculation of stress under local water use:

$$stress = \frac{\text{local water use}}{\text{local water availability}} \qquad (3)$$

Calculation of change in stress due to upstream water use:

$$Change\ in\ stress = \frac{\text{local water use}}{\text{local water availability}} - \frac{\text{local water use}}{\text{local water availability} - \text{upstream water use}} \quad (4)$$

Water stress is analyzed taking into account both consumptive and withdrawal water use to show the upper and lower ranges of stress. The analysis used irrigation, domestic, and industrial water as total water use. Local water availability in each SBA was calculated taking the average annual river discharge over the period 1960–2010 (see Table 1). The change in water stress level due to upstream water use was compared with the International Water Event Database (1950-2008) to assess whether there is a link between increased water stress due to upstream water use and the occurrence of conflictive and cooperation events.

3.4 Analysis of upstream dependency

In this thesis, upstream dependency is considered as dependency of a downstream sub-basin on upstream inflows to meet their needs in avoiding water shortage and stress (Publication **II**). To understand the concept and evaluation of upstream water dependency, an analytical framework was developed (Figure 2). The framework identifies different types of dependency, calculated in terms of water scarcity under different types of water available to an SBA. Three different types of water availability are considered—local runoff, natural discharge, and actual discharge. Note that the analysis method did not consider the case where actual discharge may be greater than natural discharge. The definitions of dependency in terms of water availability volumes are given below and defined in more detail in Publication **II**:

- Dependency: 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.
- No dependency: Upstream inflows do not influence whether or not a region experiences scarcity.
- Hidden dependency: Scarcity category is altered by upstream inflows but not by upstream water withdrawals.
- Open dependency: Scarcity category is altered after accounting for upstream water withdrawals.

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).

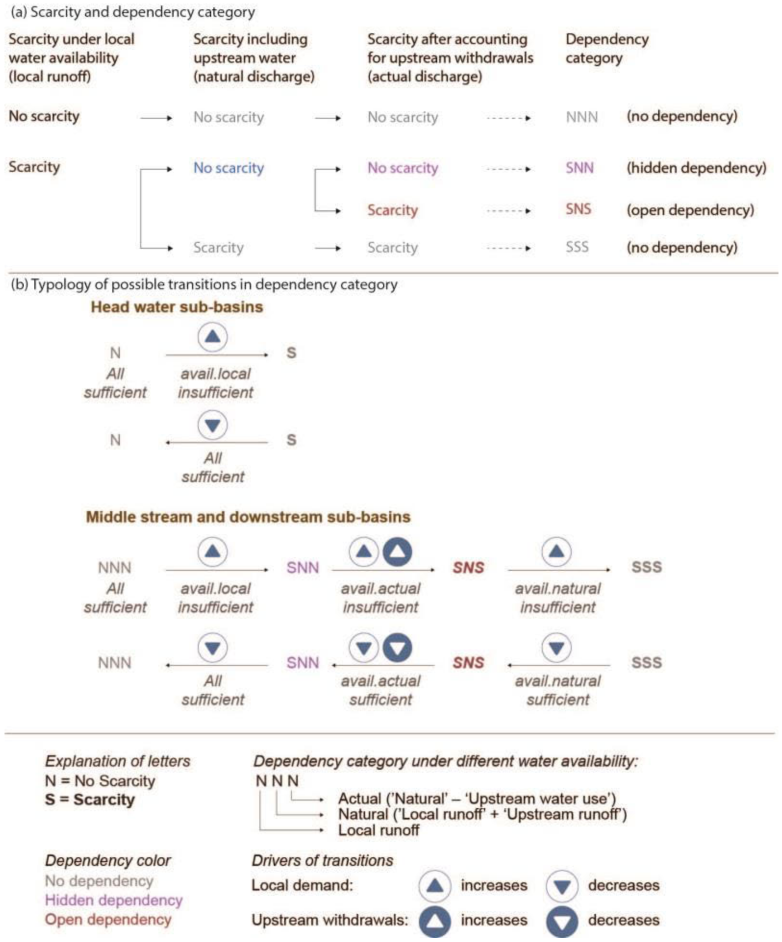

Figure 2. Definition of upstream dependency and possible transition pathways in dependency category as local water demand and upstream water withdrawals increase or decrease. Modified from Publication II.

Water use data were calculated using annual average water withdrawal data over the period 1981–2010 (see Table 1). Local runoff for each SBA was calculated by its average runoff. Natural discharge for each SBA was calculated by summing together the local runoff of the SBA and all its upstream SBAs runoff, i.e., local runoff + upstream runoff, while recognising that this is a coarse approximation of actual streamflow routing processes. Actual discharge was calculated from the SBA WWs and total water availability expressed as: local runoff + upstream runoff – upstream withdrawals. Both water stress index (use to availability) and water shortage index (per capita availability) were used to understand the development of upstream dependency. The analysis used a resilience perspective, defining tipping point thresholds involving change in scarcity categories. The framework describes possible transitions in dependency category as local demand and upstream water withdrawal changes. The analysis in Publication **II** further assigned all global sub-basins to different scarcity and dependency categories. It then interpreted these categories in terms of how they affect negotiation with upstream sub-basins aimed at entirely avoiding the need to cope with scarcity. The analysis applied the analytical framework to 246 global transboundary river basins at the scale of sub-basin areas (SBAs), using local water use and population data for the year 2010.

3.5 Past and future drivers of water scarcity indicators and upstream dependency

In Publication **III**, climate change together with population growth and socioeconomic change projections are considered in the calculation of water stress and upstream dependency for past, present, and future years in the transboundary context. The analysis used scenarios, constructed as combinations of Shared Socioeconomic Pathways (SSPs)(O'Neill et al., 2014) and Representative Concentration Pathway (RCPs) (Vuuren et al., 2011) for future projections. Scenarios used in the analysis are adopted from the Water Futures and Solutions (WFaS) initiative (Wada et al., 2016). The analysis uses three RCPs and three SSPs, representing four possible combinations (more detail in Publication **III**):

- Sustainability scenario resulting in low challenges with respect to sustainability, mitigation and adaptation, low population, and low emissions scenario (SSP1-RCP2.6);
- Sustainability scenario resulting in low challenges with respect to sustainability, mitigation and adaptation, low population, and moderate emission scenario (SSP1-RCP 4.5);
- Middle of the Road scenario, intermediate challenge with moderate population and high emission scenario (SSP2-RCP6.0);
- Regional Rivalry scenario with high challenges, very high population growth, and high emission scenario (SSP3-RCP6.0).

For each scenario, the model output from an ensemble of four global hydrological models (see Table 1), forced with five global circulation models, was used to obtain decadal water availability and water consumption data from 1971 to 2050 (more detail in Publication **III**). In this part of the analysis, only consumptive water was used to calculate the total water use. This analysis uses the simple water stress equation (Equation 1) and the dependency framework developed in Publication **II** (also see Section 3.4) to calculate the development of past, present, and future transboundary water stress and upstream dependency.

4 Results

This chapter presents the key findings from the appended publications. The findings address the set of research questions identified in the Introduction section. Some of the results of the research publications and other data created that is relevant for other research have also been made publicly available (Table 1). These datasets include a global spatial database on flow relationships within transboundary river basins (Publication **I**, available as a supplement at doi.org/10.1088/1748-9326/11/1/014002) and a reconstructed sub-basin definition for global transboundary river basin as a shape file and dependency categories of 886 sub-basins (Publication **II**, available as a supplementary data file at doi.org/10.5194/hess-22-2795-2018).

4.1 Effect of upstream water use

The analysis performed in Publication **I** first identifies the role of local water use (consumption and withdrawals) and water availability (both local and upstream) in transboundary water stress using the water stress index. According to the analysis, 33–51% of the population in transboundary river basins are facing some level of water stress due to their local water use in the present condition (year 2010). The analysis identified that these are mainly heavily irrigated, densely populated, and/or water scarce regions, e.g. Central and South Asia, China, South Europe, USA, Mexico and the MENA region (Middle East and North Africa) (**Figure 3**).

In the second step, the analysis included upstream demand to quantify the role of upstream water use on the downstream water stress levels. As per the analysis, in most middle-stream and downstream SBAs, there was some change in stress level for both withdrawal and consumption (288 out of 298 SBAs) due to upstream water uses, with only 10 SBAs having no identified change. Altogether 5–12 SBAs were identified, which "jumped" to the next category of water stress. For example, SBA of Al Batin (Kuwait) moved from the moderate stress zone to the extreme stress zone, while the most downstream SBAs in Kura (Azerbaijan) were re-classified from no stress zone to the moderate stress zone when upstream basin water uses were included.

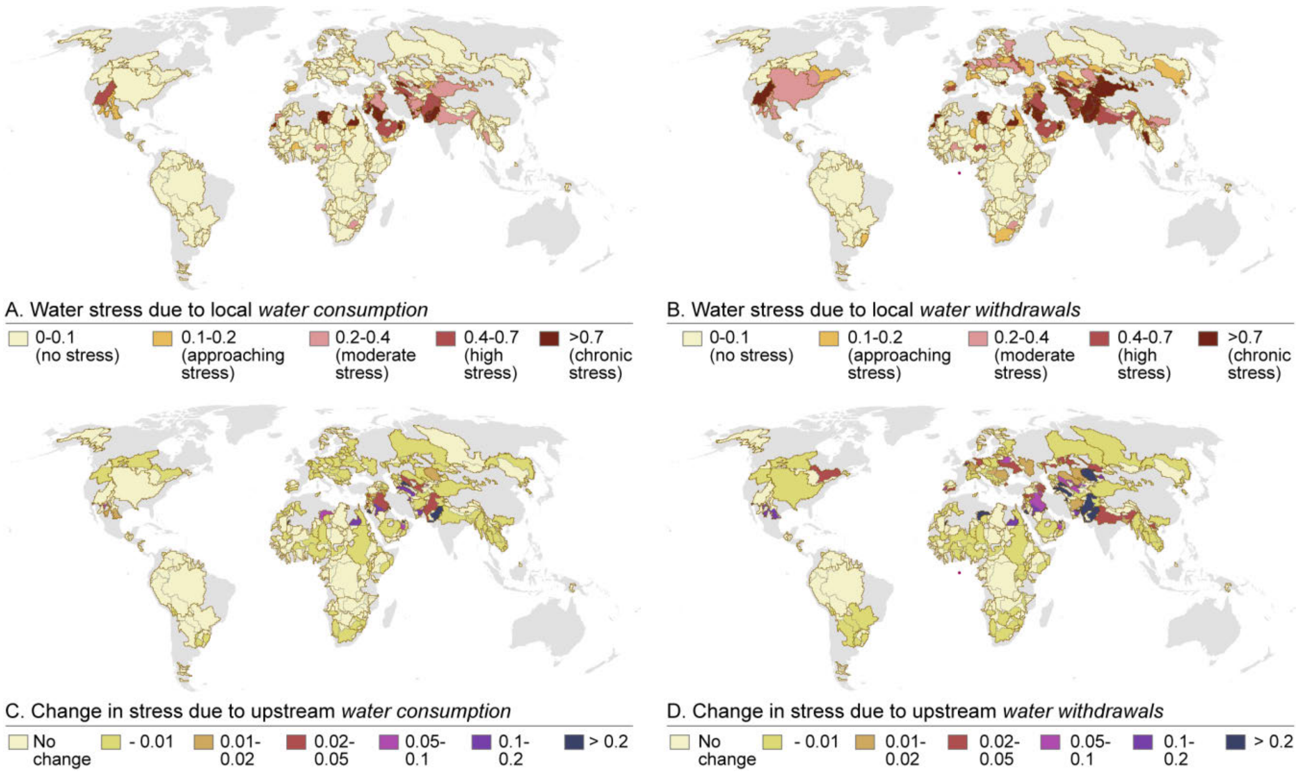

Figure 3. Mapped water stress (measured as water stress index—WSI): (A) water stress due to basin's local water consumption only; (B) water stress due to basin's local water withdrawals only; (C) change in stress index due to upstream water consumption; and (D) change in stress index due to upstream water withdrawals. Adopted from Publication I.

When looking at local vs. upstream (the whole upstream area of an SBA in question), it was found that the average local water consumption per capita is marginally higher than that of upstream SBAs, and the average water withdrawal per capita was found to be significantly higher in more downstream SBAs.

The results indicate that the population under water stress is already high when only local water use is included. Even the most stressed region identified in the analysis indicates local water use as the dominant reason for stress, while upstream use played a minor role. Upstream water use increases the population under water stress only slightly (1 percentage point), while it considerably intensifies the stress in many areas, particularly in Central Asia, Europe, and parts of North America, Middle East, and Asia (**Figure 3**).

4.2 Upstream dependency

The results in Publication **II** revealed that in 2010 the majority of transboundary basins were not dependent on upstream inflows, whether to avoid shortage or stress (**Figure 4**). As per the analysis, in 2010 about 93% of SBAs for stress and 96% of SBAs for shortage were identified to have no dependency, which means that current upstream inflows and withdrawals have no influence on whether or not a region experiences scarcity. However, it is worth noting that scarcity can still be experienced without a dependency. For example, 41% of the population living in SBAs under “No dependency” are under a stressed condition in 2010. Local water use is high enough that stress would occur even without upstream water use.

The analysis identifies “Hidden dependencies” (about 14% of the population for stress and 11% of the population under shortage) in some high profile cases such as the Nile and Danube, meaning that local runoff is not enough to meet the local demand but additional water from upstream helps the region to experience no scarcity instead of scarcity. In the case of hidden dependency, it is important to put in place water allocation arrangements to make sure upstream inflows remain sufficient in the future.

There are a few sub-basins identified with “Open dependencies” (about 1% of the population for both stress and shortage), including SBAs in the Aral Sea and the Jordan Basin. These are the places where upstream water withdrawals change the downstream stress category. Open 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. It is likely that negotiation with upstream is needed to maintain water availability, and conflict resolution may be necessary.

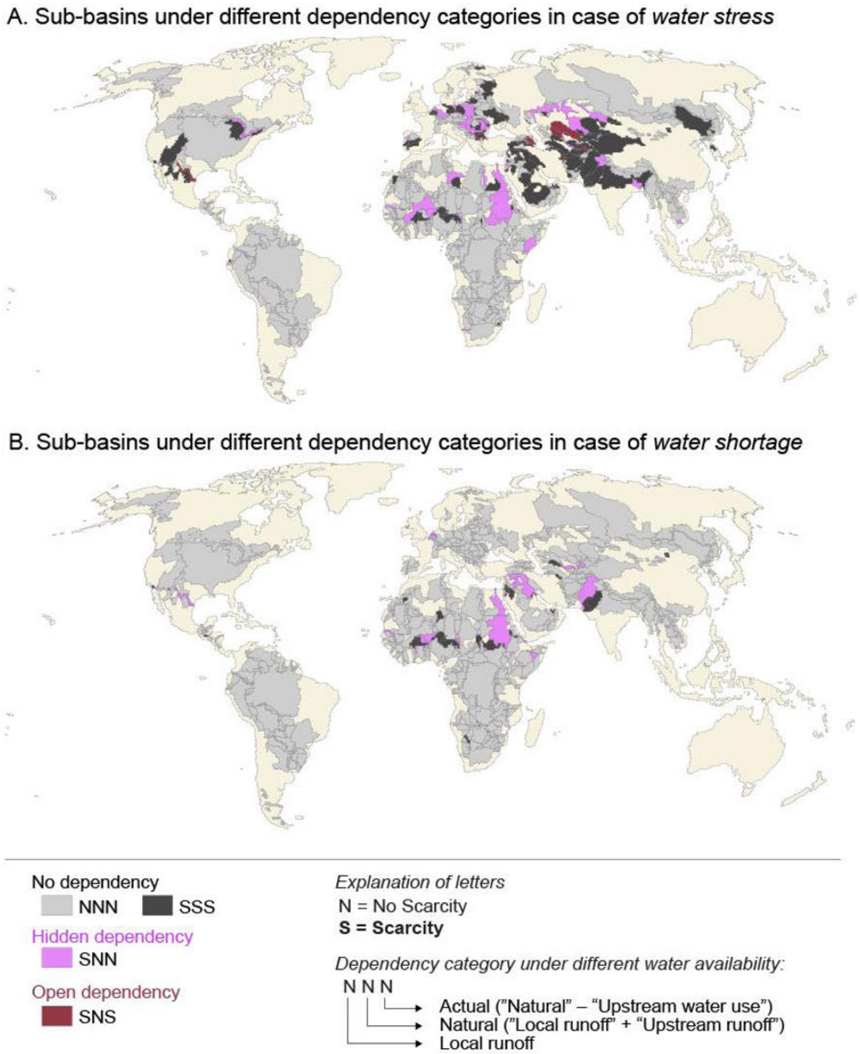

Figure 4. Dependency categories for each sub-basin area (SBA) for the year 2010 using (A) a water stress threshold value of 0.2 and (B) a water shortage threshold value of 1000 m3 yr−1 cap−1. See definitions of dependency categories in Section 3.4. Reproduced from Publication II.

4.3 Transboundary water scarcity: Past, present and future

The analysis in Publication **III** applied the framework developed in Publications **I** and **II** to quantify water stress in the past, present and future. The analysis identified Middle East and North Africa as hotspots where either stress level, dependency category, or both have changed in the past and are predicted to change in the future (**Figure 6**). The results indicate that over the years, stress has intensified mostly in the already stressed area, and this will happen in the future as well. SBAs in Asia, Middle East, and North Africa were identified as having moderate to extreme stress. Central and Southeast Asia and Northern Africa are the regions where the highest changes in stress are predicted for the future (2050), compared to the past (1980) and present years (2050) (**Figure 6A**).

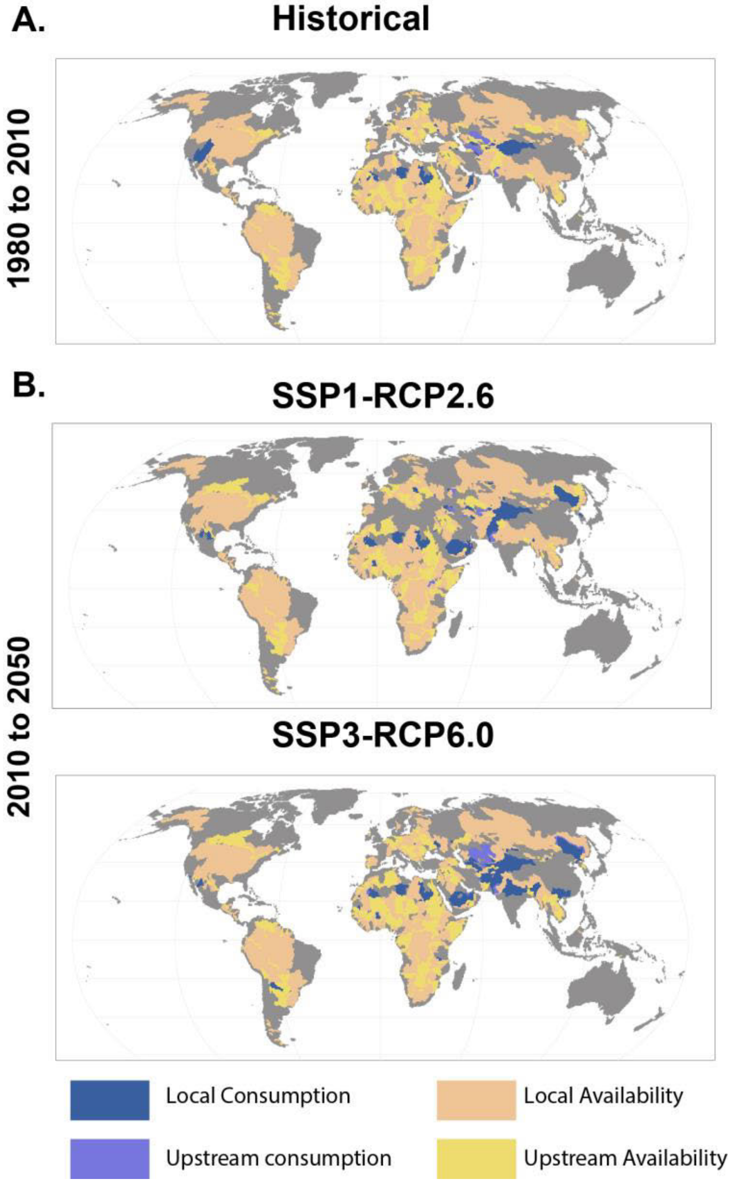

Figure 5. Maximum changes in stress drivers from (A) past (1980) to present (2010) and (B) from present (2010) to future (2050). For the future, the results for two extreme scenarios (SSP1-RCP2.6 and SSP3-RCP6.0) are presented here. Modified from supplementary information in Publication III.

The population under water stress more than doubled from 1980 to 2010 and is expected to increase by almost 50–100% under low and high emission scenarios. The analysis identified that for the most part, local water use provided the maximum relative contribution among the stress drivers to both historical and future changes in the availability of freshwater resources and water scarcity. The majority of people currently suffer from water stress because of heavy use of their available water. In the future, under different climate and socio-economic scenarios, the situation remains the same.

The analysis looked at how different drivers of the stress indicator have changed from the past and how they will change in the future. Change in upstream availability has been identified as the dominating driver of change in water availability in some places, for example in some SBAs in Asia, Africa, Europe, North America, and South America for past and all future scenarios (**Figure 5**).

The dependency framework developed in Publication **II** was applied to estimate the percentage of the world's population that will be living in regions dependent on upstream water for future scenarios. In this analysis, dependency categories were calculated using a water stress threshold value of 0.2. The results indicate an increase in the "Hidden dependency" condition for all the future scenarios. This means that there will be more SBAs sensitive to water availability, and decreases in upstream inflows may cause stress to occur. This analysis identified regions like Central Asia and Northern Africa, where special attention needs to be given in the near future (**Figure 6B**).

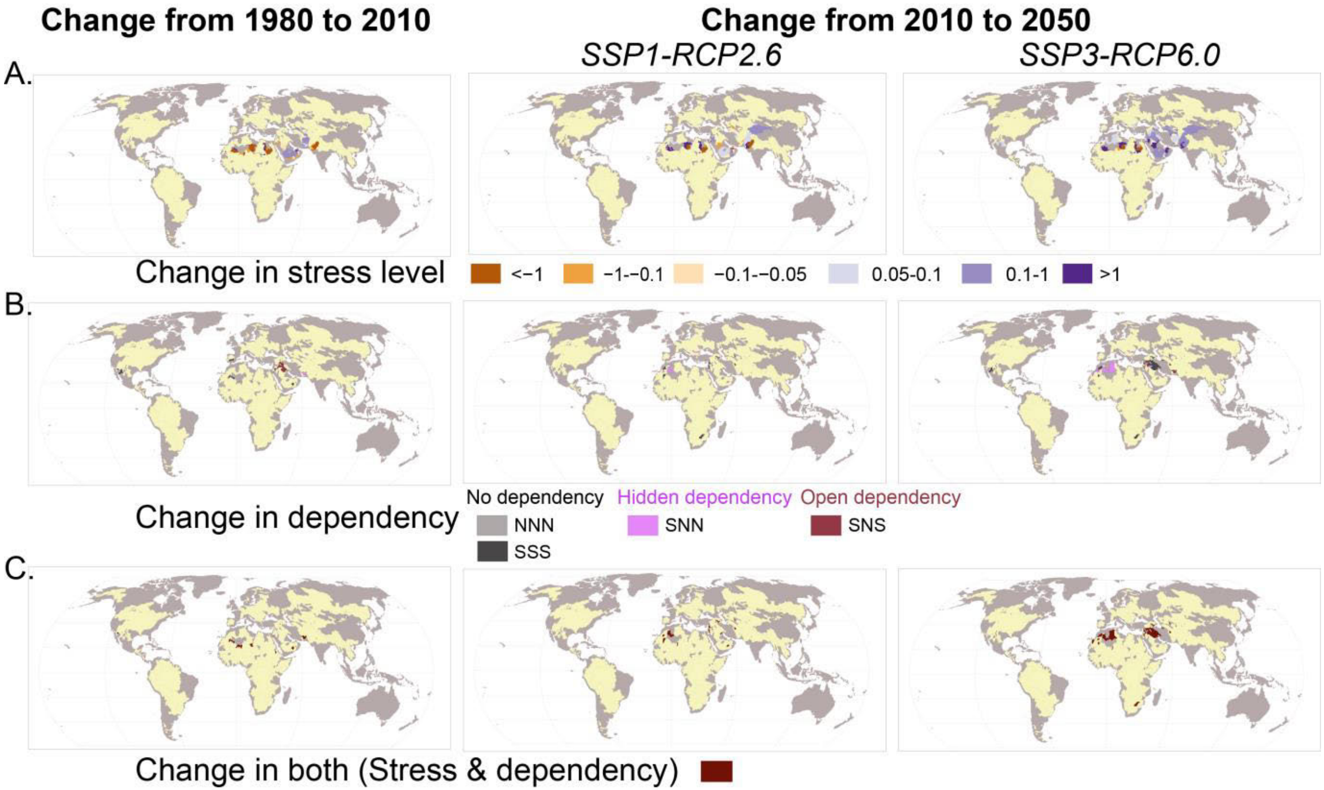

Figure 6 Changes in (A) stress level, (B) dependency categories (calculated using water stress threshold value of 0.2), (C) both stress and dependency from past to present (1980 to 2010) and from present to future (2010 to 2050). For the future changes, results for two extreme scenarios are presented here, namely SSP1-RCP2.6 and SSP3-RCP6.0.

5 Discussion

The key findings of this dissertation, presented in the previous chapter, extend and improve the general understanding of the causes of water scarcity in the transboundary context. While increased pressure in water demand has been widely recognized before for increased water scarcity in transboundary river basins (e.g. Degefu et al., 2018, 2019; Veldkamp et al., 2017; Wada and Heinrich, 2013), its connection with upstream–downstream dynamics has not been systematically analyzed. In addition to the existing research, the findings of this dissertation show that water scarcity in global transboundary river basins is primarily due to overuse of local water in most of the cases (Publication **I**). The analysis identified about 33–51% of the population in transboundary river basins currently facing water stress only because of their own water use.

An important highlight of this thesis is identifying upstream dependency based on the novel concept (Publication **II**) that a basin area is dependent on upstream inflows if it requires those inflows to avoid water scarcity (e.g. stress, shortage) and its associated impacts under past, present, and future water use and water availability conditions (Publication **III**). Those sub-basin areas where local water demand is higher than the threshold for self-sufficiency with locally originated runoff are significantly dependent on upstream inflows to secure their water availability (Publication **II**). Upstream withdrawals lead to less available water for downstream, resulting in socio-economic and environmental disparities among the sharing countries (Degefu et al., 2016). When and where basins become water-stressed is particularly important for managers to understand whether they can do something about it themselves or whether collaboration is needed. For example, what is the prevailing driver of their basin turning into hidden or open water stress (as discussed in Publication **II**)? This may provide insights into various adaptation strategies combating water scarcity.

Analysis of the water stress drivers over time revealed that increasing availability has a smaller effect on a basin's stress level than increasing water use, unless water use is high relative to availability (see Publication **III**, Section 3.1.2). Our study explains that this is partly because the stress indicator (use-to-availability ratio) places a strong emphasis on consumption. Therefore, the analysis highlights that if the stressed SBAs, or those approaching to it, want to avoid stress, the single most powerful driver is nearly always local water management. Nevertheless, water availability is a crucial driver determining water scarcity, especially in the case of transboundary water, where any changes in upstream (either due to changing climate or changes in water use) directly impact downstream water availability. Depending on the dominant drivers, different adaptation strategies are required to cope with transboundary water scarcity, as outlined in Publication **III**. The dissertation highlights that to make sound decisions for transboundary water, a well-rounded understanding of the drivers of water scarcity indicators is needed.

5.1 Adaptation to transboundary water scarcity

According to the UN Watercourses Convention (1997), "*utilization of an international watercourse in an equitable and reasonable manner requires taking into account all relevant factors and circumstances, including: (a) geographic, hydrographic, hydrological, climatic, ecological and other factors of a natural character; (b) the social and economic needs of the watercourse States concerned; (c) the population dependent on the watercourse in each watercourse State; (d) the effects of the use or uses of the watercourses in one watercourse State on other watercourse States.*"

Transboundary water management requires water allocation mechanisms that take into account all these characterizing features of a water-sharing problem in transboundary river basins. In a transboundary sub-basin, water can be considered either as "local," within the control of the country the sub-basin belongs to, or flowing from upstream and therefore potentially influenced by others (upstream use). It has often been claimed that the benefits obtained through upstream water resource developments are achieved at the cost of downstream impacts on the environment and on communities making direct use of that environment (Brown and King, 2006; Goldsmith and Hildyard, 1984). Veldkamp et al. (2017) identified that upstream water interventions push scarcity downstream. At the same time, local overuse of water is identified as one of the main reasons for the development of water scarcity for the past, present, and future (Publication **III**). Therefore, to achieve sound management of transboundary water, riparian countries need to share their water, which requires an allocation scheme to determine who is able to use water resources and how, when, and where.

The main reasons for the lack of an internationally accepted and standardized mechanism for allocating water in border crossing river basins are the socio-economic and environmental disparities among the riparian countries (Degefu et al., 2016). The effect of climate change versus socio-economic developments can take place differently locally and upstream. This will require different adaptation strategies to cope with the problem at hand. Therefore, scarcity drivers identified in this analysis can be impacted either by global or regional actions. When water availability is impacted by climate change (without considering upstream water consumption), local decisions cannot have much effect other than through climate change adaptation, and of course, doing their share to reduce CO_2 emissions. On the other hand, changes in demand would require regional strategies to deal with the scarcity. When local water demand increases, the sub-basin itself needs to be prepared to deal with dependencies and potential scarcity. If upstream withdrawals are stable, it can be argued that any conflict is effectively of the downstream basin's own making, therefore changes in local water demand can be solved by local actions. On the other hand, if upstream demand changes, negotiation is required. When upstream withdrawals increase, downstream regions can easily consider the upstream country responsible for this situation, even though scarcity and dependency only emerge as a problem when local demand in the downstream country crosses a threshold (Publication **II**). This requires a negotiation approach, where existing water needs and water use are taken into account. The UN Watercourses Convention of 1997 also refers to the no-harm principle (Article 7), which works in tandem with the consideration as to whether a given water use is reasonable and equitable (United Nations, 1997). These examples illustrate the close connection between water allocation and different views on responsibility for adapting to water scarcity (Publication **II**).

Finally, Publication **I** identifies some sub-basins where water disputes were not reported even though their water stress increased significantly as the result of upstream water use. Even in some of the river basins, water stress seems to be leading riparian countries to cooperation rather than conflict. The results of this dissertation challenge the "scarcity induces disputes" contention and proposes that the potential cause of dispute over transboundary water resources is not only the physical scarcity of the resource; it is the result of complex and dynamic socio-economic and political interactions—thus reinforcing the existing literature (e.g. Mirumachi, 2015; Tayia, 2019) . However, this result may change if focus is placed on drought or dry season conditions – but even in this case, the lack of correlation of conflict with annual water scarcity means that inter-seasonal or inter-annual water storages would play an important role in whether a dispute occurs, i.e. economic scarcity is an important factor.

5.2 Limitations and future opportunities

The analyses presented in this thesis aim to provide an understanding of the causes and factors of transboundary water scarcity. This dissertation assessed transboundary water scarcity using data from different global models. The analysis is naturally subject to the uncertainties originating from the used datasets. Due to varying model output availability, data needed to be collected from different sources, for example in the case of Publication **III**. The scenarios used in Publication **III** are plausible representations of future climate and socio-economic changes based on current understanding (Wada et al., 2016; Winsemius et al., 2016), and it would be useful to repeat the analysis on new scenarios as they emerge.

Additionally, water availability is highly variable over space and time, such that the annual assessment of water stress may underestimate the total impact of upstream water use impacts, which might also be seasonal (van Beek et al., 2011).

Thus, the evolution of scarcity and dependency for a given climate can be categorized into different transition pathways. An early attempt at this was made in the "discussion paper" where interannual variability of water scarcity was considered (Munia et al., 2017). Some subsequent studies (e.g. Degefu et al., 2018, 2019; Veldkamp et al., 2017), have considered seasonal variation to estimate water scarcity and upstream influence of water scarcity in transboundary basins in current conditions. Seasonality and interannual variability of available water under future climate and socio-economic scenarios would provide more precise information, but accuracy is reliant on adequate information about storage infrastructure to assess what volumes of water can realistically be kept from wet to dry times. Therefore, including seasonal variation of water availability and water used, as well as spatially explicit environmental flow requirements (i.e., EFR) in the calculation of water stress would provide additional information for the analysis of upstream–downstream relationships. The stress indicator used in the analysis includes EFRs, assuming 30% of the water is needed to satisfy the EFRs (Falkenmark et al., 2007).

The analysis does not take groundwater explicitly into consideration. In various regions, such as South Asia, groundwater is often a more important source of water supply than surface water and due to climate change, groundwater demand is expected to grow even further due to the increasing temporal variability of surface water flows (Herbert and Döll, 2019). With groundwater, there may not be clear upstream or downstream regions. Yet one water-user state could well be dependent on actions and control by another state, even if it is not "downstream." Also, in some aquifers most of the groundwater recharge may occur in one country, whereas the groundwater may be extensively abstracted in the other countries (Wada and Heinrich, 2013). Nevertheless, such global analyses accounting for groundwater have been previously attempted (e.g. Wada and Heinrich, 2013; Herbert and Döll, 2019). In the future, including groundwater in addition to surface water in consideration of transboundary water scarcity will provide further insights, especially in regions where conjunctive water use of surface water and groundwater is predominant.

Water stress indicators are used for publications **I**, **II**, and **III** and water shortage indicator for Publication **II** to estimate water scarcity. There also exist other indicators for water scarcity that could be used to understand how physical water scarcity in transboundary river basins interacts with social aspects when impacting transboundary relationships. To determine whether water stress or shortage occurs, the thresholds of 0.2 and 1000 m^3/capita/yr were used, respectively, as defined by Falkenmark et al. (2007). Besides the fact that different studies apply different indicators and threshold values to define water shortage and stress, the use of thresholds can cause abrupt increases and decreases in the population exposed to scarcity events, disguising more subtle changes in water scarcity over time. The scarcity criteria could also be revisited using other indicators, such as food self-sufficiency (Gerten et al., 2011; Kummu et al., 2014) or sustainability of water withdrawals (Wada and Bierkens, 2014) to understand more broadly the development of water scarcity in transboundary basins.

Identifying upstream and downstream parts of a basin was also difficult for some cases, particularly in very dry basins. There are many riparian countries that do not have any clear upstream/downstream relationship. Difficulties also arise from complex border geometries and boundaries that follow rivers. Given these challenges, there are opportunities for improving the transboundary sub-basin dataset constructed within the thesis.

The approach used for the thesis is completely focused on blue water, and green water was not taken into account. Green water increases the amount of locally available water by including soil water in addition to runoff. This can affect scarcity, as the need for blue water typically varies in response to changing green water availability. For example, when there is less green water available, more blue water is needed, for irrigation. Again, decreases in blue water availability may also push a region to be become more dependent on green water use. In future studies, it would be very important to link the green water to existing blue water scarcity analysis. Related to this point, the analysis also did not account for virtual water imports and exports, which could illustrate how the impacts of water scarcity propagate towards other parts of a country or other countries (Dalin et al., 2012; Hoekstra et al., 2012b; Islam et al., 2007).

Considering the limitations mentioned above, this dissertation can be considered as a first step towards understanding the causes and factors involved in global transboundary water scarcity. The analyses performed for this dissertation can hopefully be used as a stepping stone for future studies, considering the above-mentioned limitations and opportunities. Particularly, transboundary water disputes mostly come from complex socio-economic and political interactions (Mirumachi, 2013, 2015). Therefore, the interaction of physical water scarcity with social aspects and its impact on scarcity and conflict would be an interesting and important subject for future research. There is great potential for the use of global water models and data to further understand water scarcity in transboundary basins, and this thesis has just started to scratch the surface.

6 Conclusion

The objective of this doctoral dissertation was to increase the understanding of transboundary water scarcity and the role of upstream in it. This objective was examined by looking at the following research questions:

RQ1: What are the dominant drivers of transboundary water scarcity indicators across the globe?

RQ2: How can we quantitatively characterize upstream dependency in transboundary water basins?

RQ3: How and where has water scarcity in global transboundary river basins developed?

To answer the first research question, the analysis looked at the role of local vs. upstream in water scarcity. The analysis identified that the dominant driver of transboundary water scarcity in most basins is the local overuse of water, being the first new scientific finding of the thesis. This indicates that managing local demand is the key strategy to alleviate water stress.

The second research question was addressed by developing a novel framework to identify upstream dependency and its development (Publication **II**)—the second new scientific contribution of the thesis. The analysis identified that those sub-basins where local water demand exceeds the locally originated runoff are significantly dependent on upstream inflows for securing water availability to meet demand. The typology developed in the analysis provides guidance which may assist in improving water management in transboundary basins.

To address the third research question, the concepts and methods developed in Publications **I** and **II** were used to analyze the past, present, and future situation of transboundary water scarcity. This resulted in global maps highlighting how water scarcity has developed and the potential hotspots under changing climate and socio-economic conditions—the third new scientific finding of the thesis. The analysis found that over the past decades water scarcity in the transboundary basins has intensified and developed mainly over the basins which are heavily irrigated and densely populated, e.g. Central and South Asia, China, southern Europe, the USA, Mexico, and the MENA" region (Middle East and North Africa) (Publication **III**). Future changes will mainly intensify the water stress in basins which are already under stress. Under changing climate and socio-economic conditions, the analysis has investigated the drivers of water stress indicators in a transboundary context (i.e. local vs upstream water availability or use) and distinguished their role for these trends.

In the case of transboundary rivers, it can be tempting to assign blame to others, but this is not usually useful. While upstream withdrawals reduce the available water downstream, upstream dependency occurs because the downstream region wants to use more water than they have locally available. Therefore, both local and upstream water use and action can influence water allocation.

There is an international consensus that transboundary water resource sharing problems should be resolved through negotiation (Qin et al., 2019). It is a fairly normal part of basin-scale planning to look at water availability scenarios under climate change and water consumption projections/scenarios. Managers therefore already have some information about the key issues they are facing. In this dissertation, the aim was to explore this at the global scale. The focus on annual water stress will shed light on the significance of water allocation problems in shared basins and add nuance to the existing understanding of water stress drivers. This analysis contributes to transboundary management in places lacking the capacity to obtain more reliable data and perform such analyses themselves. Global scale analysis also provides a common view of the problem, shaping how people approach this problem. In this way, this analysis provides information that has a more indirect rather than direct effect on management, with more general insights into transboundary water scarcity adaptation and water allocation.

An understanding of the drivers of water scarcity in transboundary basins and the dependency category of an SBA has important policy implications for improving water management in transboundary basins.

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Aalto-DD 31/2020

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ISBN 978-952-60-8960-7 (printed)
ISBN 978-952-60-8961-4 (pdf)
ISSN 1799-4934 (printed)
ISSN 1799-4942 (pdf)

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