EVALUATING WATER SECURITY ACROSS SCALES: DIAGNOSTICS AND TRENDS

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ABSTRACT

Water security is a concept that accounts for multiple types of water-related risks and their societal impacts. It has proved to be a complex concept, which is difficult to frame and even more challenging to evaluate. This thesis aims to evaluate water security across scales and to begin to disentangle the concept's complexity by looking at trends and relationships between water security indicators.

The foundation of this thesis is the development of a water security framing and diagnostic methodology. The framing is built upon previous water security framings and metrics. It is comprised of seven key categories of information or dimensions of water security: (1) drivers, (2) historical and cultural context, (3) the water resource system, (4) system performance, (5) outcomes, (6) actions, and (7) trends. These seven categories encapsulate a pragmatic view of water security, which is shaped by the possibility of obtaining meaningful metrics as well as by theoretical considerations. The diagnostic method used to assess water security and developed herein draws its inspiration from the medical field. The evaluation begins with an information gathering phase that entails a brief overview of the status and trends of the relevant data in order to develop an initial diagnosis.

This water security framing and diagnostic methodology are applied to a case study of Pakistan. A dashboard tool comprised of 52 indicators is developed to act as a visual aid for the case study. The dashboard's utility is in its ability to consolidate information across five of the seven dimensions of water security and to aid in the first step of the diagnostic methodology: information gathering. This case study shows that a dashboard tool can be used to quickly highlight potential water security problems within a country. Four additional dashboards are generated for Afghanistan, Tajikistan,

Turkmenistan, and Uzbekistan in order to conduct a regional comparative analysis allowing for the provisional detection of patterns between indicators.

One of the flaws in a national water security assessment is the inability to account for sub-national heterogeneity. Therefore, following the country analysis, a multiscale water security analysis is conducted, with the United States serving as a case study. This analysis generates a water security index at the state and county levels. This index is created based on the system performance and outcome dimensions of the overall water security framing to highlight areas of water insecurity. This study demonstrates how larger scales of analysis can conceal areas of water insecurity, whilst also providing a systematic methodology to compare water security across administrative boundaries.

The final section of this thesis examines indicator trends and relationships to begin to better understand the relationships between water security indicators. Trend analysis and econometric methods are used to empirically test the relationship between water productivity and water stress using 166 countries. A negative relationship is found between the two indicators. In addition, potential drivers of water stress are analysed. It is found that the relationships between indicators vary when looking at changes within a country versus looking at the relationships across countries. Within a country, water stress is associated with water productivity, population, cultivated land area, and political stability, whereas gross domestic product (GDP) and precipitation are related to variations of stress across countries.

The findings of this thesis, as well as the developed methods and tools, have the ability to impact academic audiences and policymakers. This study expands upon the academic literature by developing an updated framing and a diagnostic methodology. The dashboard tool and systematic creation of a sub-national water security index highlight key water security challenges and hotspots that can be used by policymakers across scales

to inform potential interventions. The thesis also sheds light on relationships between water security indicators. Ultimately, this thesis develops novel ways to evaluate water security, advances the discussion around the concept, and can help to focus future water security analyses.

Key Words: Water security; Diagnostic method; Spatial heterogeneity; Composite indicator; Water stress; Water productivity

PUBLICATIONS

The work presented in Chapters 3 through 5 has been submitted or accepted to the following peer-reviewed journals:

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1 INTRODUCTION

1.1 Background and Rationale

Water-related risks are of global concern. Risks include hydrological shocks, such as flooding, which in 2019 alone caused over 5,000 deaths and 35 billion USD in damages worldwide (Guha-Sapir, 2019). In contrast to flooding, between 1996 to 2005, it was estimated that around 4 billion people worldwide were subjected to "severe water scarcity at least one month of the year" (Mekonnen and Hoekstra, 2016). Humans also continue to face risks from inadequate service provisions, and as of 2017, 30% of the world's population still lacked access to a safely managed drinking water source (WHO/UNICEF, 2019). In addition to human and economic losses, ecosystems are being threatened due to man-made infrastructure, land-use change, and increased pollution. Flooding, water scarcity, inadequate service provision, and environmental degradation are only a few of the water-related risks that span the globe cutting across scales. More importantly, many areas may be subjected to more than one type of risk. For example, Pakistan faces several water-related challenges, including flooding, drought, water stress, and inadequate services (Young et al., 2019b).

Water security emerged in the early 1990s, and it has morphed into an all-encompassing concept for water-related risks. One of the broadest definitions summarizes it as a "tolerable level of water-related risk to society" (Grey et al., 2013). This all-inclusive definition is useful, as it offers a way to account for all risks across all dimensions, scales, and potential time periods. Yet, it leaves the framing and evaluation of the concept up for a variety of interpretations. Even though an agreed-upon definition proves to be elusive, several concepts can be drawn from the water security literature. First, water security is influenced by phenomena such as the climate and anthropogenic forces (Conway, 2013). Secondly, water security involves risks that originate from the water resource system and impact three primary actors: people, the economy, and the environment (Grey and Sadoff, 2007). Third, water security can be managed through the application of infrastructure and institutions (Briscoe, 2009). Each of these concepts could be thought of as multiple dimensions of the overall water security concept. Finally, each of these dimensions (drivers, the three primary actors, the water resource system, and management) interact through time and across scales, making water security both complex and dynamic.

Regardless of its conceptual difficulties, water security has come to be known as the goal of effective water management (UN, 2000). Achieving water security has thus been added to policy agendas across NGOs, governments, and multi-lateral organizations (Staddon and Scott, 2018). One of the first steps to achieving water security is to assess the water security status of a given area. Given the above-mentioned complexly, operationalizing the concept for this purpose can be challenging. Therefore, this thesis aims to enhance the methods and techniques used for three different types of assessments: national, multiscale, and relational.

Nations are frequently chosen as the analysis scale for water security assessments, both in policy discourse (ADB, 2013; Whittington et al., 2013; ADB, 2016) and academia (Cook and Bakker, 2012). This focus on national water security is useful, as the nation is a common scale of decision-making in terms of investments in hard or soft infrastructure (Garrick and Hall, 2014). Yet, there is still no consensus on how to gather appropriate information, measure, and communicate national water security. Since security is highly context-specific (Baldwin, 1997), setting a specific value or an ideal level of water security for all countries would be futile. Alternatives that allow for a more objective assessment of performance include cross-country comparisons or benchmarking (Helgason, 1997). Benchmarking is useful as it is believed that "comparison can be a driver of performance" (Helgason, 1997), as well as increase the dialogue around complex concepts and facilitate learning (De Stefano et al., 2014).

There have thus been several water security cross-country comparisons (Lautze and Manthrithilake, 2012; ADB, 2013, 2016; World Bank, 2017). Yet, these assessments are either not comprehensive or not replicable. For example, Lautze and Manthrithilake (2012) fail to assess potential economic outcomes, which are useful for understanding water insecurity in its entirety (Garrick and Hope, 2013). The Asian Development Bank (ADB) (2013, 2016) studies do not explicitly quantify drivers of change, which are also useful (Garrick and Hope, 2013), but they do highlight the importance of urbanization as a possible driver. A study carried out by the World Bank (2017) is fairly comprehensive, but the final country-level assessments of water security do not incorporate drivers. Finally, none of these studies incorporate trends, which are useful given that water security is dynamic, and past trends can help improve future projections. The ADB (2013, 2016) studies may have the possibility of developing a trend analysis in the future, but the two studies conducted thus far incorporate different sub-indicators.

Young et al. (2019b) provide an example of a comprehensive assessment of water security at the national level. The report references the use of a diagnostic process to highlight key challenges and opportunities in terms of Pakistan's water security (Young et al., 2019b). While the report's overall structure could be replicated (e.g. focus on outcomes, resource endowment, etc.), the exact steps used in the diagnostic process are not reported, and indicators to assess water security were generated directly for this study, limiting its replicability (Young et al., 2019b). The diagnostic process is nonetheless useful, as it offers a method for problem identification and the ability to investigate causal relationships (Edquist, 2011). Similarly, diagnostics have been employed in the study of socio-ecological systems (SES) (Ostrom, 2007), with the focus on both measuring outcomes (health) and their causes (symptoms) (Cox, 2011). Diagnostics have also been applied in other water security studies (Garrick et al., 2013; Penn et al., 2017; World Bank, 2017).

Given the complexity of water security, communicating relevant information can be challenging. At the national level, there are typically two approaches: a composite index (Lautze and Manthrithilake, 2012; ADB, 2013, 2016) or systematically listing indicators (World Bank, 2017; Young et al., 2019b). Composite indices are useful, as they allow for multiple types of information to be synthesized into a single value (OECD, 2008). This can be useful as water security is comprised of multiple dimensions, i.e. drivers, the resource itself, and outcomes across actors. However, composite indices can obscure the importance of individual indicators (OECD, 2008). An alternative to a composite index is to systematically discuss relevant indicators, but this can be a lengthy process (Young et al., 2019b). In terms of communicating an area's water security status, two studies have attempted to circumvent the drawbacks of each of these methods. The World Bank (2017) generated single-page country summaries at the end of their report,

which quickly and succinctly communicated the key challenges for each country. In a similar vein, van Ginkel et al. (2018) developed a dashboard tool to visualize urban water security. Both provide examples of options for visually communicating the multi-dimensionality of water security and allow for comparisons.

The discussion has thus far been focused on national water security, and this is a frequent spatial scale of choice (Cook and Bakker, 2012). However, water security can be assessed from the individual to the global level. This has led national studies to be questioned due to their ability to obscure sub-national heterogeneity, as seen in finer resolution global studies (Vörösmarty et al., 2010; Gain et al., 2016). Thus, there has been a call in the literature for multiscale water security assessments (Cook and Bakker, 2012; Wheater and Gober, 2013). Several recent studies have attempted to examine water security across scales, such as Sadoff et al. (2015). Yet, this is not a tiered analysis of a single location, but rather an evaluation of multiple unrelated basins, cities, and aquifers (Sadoff et al., 2015). The lack of tiered analyses within the literature could primarily be driven by the lack of data availability across boundaries, in addition to the uncertainty that arises from the upscaling and downscaling of data (Wheater and Gober, 2013). It could also be due to the types of methods applied across scales. For example, household water security studies tend to employ interviews and surveys to focus on individuals' access to water services and their perceptions of water (Jepson et al., 2017b). In contrast, global studies tend to be more comprehensive in terms of the dimensions evaluated and use composite indices to display results (Vörösmarty et al., 2010; Gain et al., 2016).

Given the multi-dimensionality of water security and its multiple scales, one way to cut down on this complexity is to narrow the focus of analysis. For example, this could be done through a relational assessment that studies the interactions between dimensions of water security. When attempting to frame and measure water security, it becomes

apparent that many of the evaluation metrics are connected and influence each other in a myriad of ways, such as the complex and uncertain relationship between climate and water resources (Conway, 2013). Some relationships have previously been tested. For example, Brown and Lall (2006) demonstrated that precipitation variability could impact economic growth, and Landis et al. (2017) revealed a complex relationship between hydrological variability and political violence. However, other relationships are simply intuited, such as the assumption that an increase in water productivity will result in a decrease in water stress (Mekonnen and Hoekstra, 2016; Scheierling and Treguer, 2016; Khair et al., 2019).

The relationship between stress and productivity is only one of many potential relationships that exist within the concept of water security. Yet, this relationship is of particular interest as these two indicators are the focus of target 6.4 of the Sustainable Development Goals (SDGs) (UN Water, 2019).[1] This target assumes that the way to reduce scarcity is to increase productivity (UN Water, 2019). Since water scarcity is a prominent water-related risk, this assumption affects an area's overall water security (UNESCO, 2019). Again, this is just one of the many relationships within the concept of water security that could possibly be explored.

In summary, water security has evolved since its early conception in the 1990s. This has resulted in numerous conceptual framings and a variety of evaluation techniques. Yet, there is still room for improvement as there is no standardized process to comprehensively assess national water security. There is also the issue of clearly communicating national water security, with the application of a dashboard tool at the urban scale offering a potential solution (van Ginkel et al., 2018). Further, multiscale

[1] The UN classifies SDG indicator 6.4.1 as a measure of water-use efficiency (FAO, 2019b). However, this thesis refers to SDG 6.4.1 as a measure of productivity. For a full justification, please see Chapter 5.

assessments are not common, and there is still a rich area of research when it comes to looking at the relationships between water security indicators and dimensions. This thesis attempts to address these limitations through: (1) generating a diagnostic methodology that can be applied across countries and a dashboard tool to communicate results, (2) developing a systematic methodology to conduct water security analyses across scales, and (3) empirically testing the relationship between water productivity and water stress to further the understanding of complex relationships within the concept of water security.

1.2 Aims and Objectives

This doctoral thesis aims to operationalize the concept of water security in a way that both furthers the academic literature and has practical applications for a range of stakeholders such as policymakers and water resource managers. This thesis seeks to generate new techniques for evaluating water security to account for drivers of water security, the water resource system, the outcomes of water security, and the institutions and infrastructure that are used to manage the resource, as well as trends. Given the heterogeneity of water security, this research is conducted across scales, with the primary focus being on national water security. The overall aim is broken down into three primary questions, each with subsequent research objectives:

1. Is there a way to standardize the evaluation of national water security to allow for replicability across countries? (Chapter 3)
    - Develop a comprehensive framing of water security
    - Develop a replicable methodology to operationalize water security
    - Develop a way to quickly visualise and compare the multiple dimensions of water security

2. How can one evaluate and compare water security across scales, and is it a useful endeavor? (Chapter 4)
    - Develop a multiscale assessment of water security
    - Map water security across scales to determine if spatial heterogeneity is present
3. Is there a negative relationship between water stress and water productivity? (Chapter 5)
    - Calculate a time series for water productivity
    - Utilize econometrics to examine the relationship between water stress and water productivity through time

1.3 Chapter Outline

Chapter 2 of this thesis is a review of the relevant water security literature. This includes a brief background and overview of the concept's creation, along with a discussion regarding the approaches used to achieve water security and critiques of the concept. This review emphasises fundamental concepts that can be found both in water security definitions and framings and explores how past evaluations vary across scales in terms of scope and methodologies. The review concludes with potential paths forward and an overview of the methodological approach used in this thesis.

In Chapter 3, a comprehensive framework of water security is constructed to act as a foundation for the evaluation of national water security. This framework is based on an initial framing set out by John Briscoe (2009) and focuses on the primary types of information needed to assess water security. Additional knowledge is pulled from the SES framing set out by Elinor Ostrom (2009). This combination results in a framing built around seven key categories of information: (1) historical and cultural context, (2)

drivers, (3) the water resource system, (4) system performance, (5) outcomes, (6) actions, and (7) trends. A diagnostic method is then proposed to operationalize the framing, with a dashboard tool illustrating the first step of the methodology. Pakistan is used as the primary case study, but dashboards are generated for four additional countries to allow for a regional cross-country comparative analysis.

Sub-national heterogeneity is often obscured in national analyses, and yet few multiscale assessments of the topic exist. Chapter 4 begins by acknowledging four primary considerations encountered during the selection of scale in any water security analysis. A multiscale analysis is then prepared, with the United States as a case study. This is done through the creation of a water security composite index, which is comprised of ten sub-indicators that focus on system performance and outcomes. These ten sub-indicators are collected at three scales: the United States and its constituent states and counties. The resulting water security index is then mapped at the state and county scales. Both maps show the presence of sub-national spatial heterogeneity, indicating the importance of multiscale assessments of water security.

Chapter 5 once again brings the national scale to the forefront and aims to understand the relationships between water security dimensions. This chapter's focus centres on the relationship between drivers of insecurity and the performance of the water resource system. This is done through an emphasis on water stress and water productivity. To proceed with the analysis, a time series is generated for water productivity. This study then employs econometrics to test the relationship between stress and productivity through time for 166 countries.

Chapter 6 houses the concluding remarks. It includes a thesis summary, methodological contributions, and practical recommendations. Finally, future research directions are discussed.

2 A REVIEW OF WATER SECURITY

Given the breadth of the water security literature, this is not a complete concept review, which can be found in Cook and Bakker (2012) or Gerlak et al. (2018). Rather, this review focuses on key concepts found both within water security definitions and complementary framings. These key concepts are then used as a basis to compare past water security studies, along with each study's respective scale of analysis and methodology. In addition, approaches used to achieve water security are discussed, as well as several of the concept's primary critiques. Before proceeding, this review opens with a brief background of the evolution of water resources management and security studies, which have both influenced the creation of water security.

2.1 Background

Humans have always been and will always be intertwined with water. This relationship is quite capricious, as water proves essential for life, while also having the ability to take it away. This relationship can be observed in the development of civilizations across the globe, with many of the most prosperous societies being located near waterways (Ball, 2000). This includes Mesopotamia, literally meaning "between two rivers" (Ball, 2000). Whereas, the lack of water has been attributed to the decline of a number of civilizations, such as the Harappan, circa 1500 B.C., which was located in present day Pakistan (Giosan et al., 2012). Our attempts to manage water may have been relatively tame in the early days, starting with basic agricultural practices, such as

seasonal planting, to take advantage of flood patterns (Strang, 2015). Yet, through the years, the world has become increasingly complex. This increased complexity is caused by a myriad of factors not limited to a growing population, globalization, and new knowledge that has resulted in several scientific revolutions (Kuhn, 1962). In terms of our relationship with water, the modern era saw it reframed as a 'resource', which is accompanied by the belief that it is something that can be controlled (Schmidt, 2017). Some now use the expression 'harnessing' water, realizing our inability to control something as powerful as mother nature (Ball, 2000). However, according to Schmidt (2017), through a common philosophical view of water management, our hubris remains, even given several large man-made catastrophes, such as the Teton Dam failure (Reisner, 1987).

Over the years, water management has become increasingly complicated and has turned into a wicked problem. Rittel and Webber (1973) propose ten characteristics that make a problem 'wicked' rather than 'tame', with several characteristics especially relevant to water management and planning: issues with fully knowing the problem given its complexity, the problem having no perfect solution, and that each problem is unique. Given these characteristics, there is no set methodology or panacea that can be used to solve wicked problems. The paper even goes so far as to criticize the systems-based approach used during the time and to advocate for more iterative and participatory planning processes (Rittel and Webber, 1973). Yet, the work that originated in the Harvard Water Program, from the early 1950s through the 1970s, profoundly influenced the field of water resources management and made progress in the applications of water resource systems research, specifically in terms of multi-objective planning (Reuss, 2003). This multi-objective approach sought to balance the competing concerns of water

resource managers, such as societal needs versus feasibility (Reuss, 2003). This has also come to include environmental concerns (Reuss, 2003; Loucks et al., 2005).

This multi-objective understanding of water resources management merged into Integrated Water Resources and Management (IWRM) in the 1980s (Loucks et al., 2005). This was highlighted in The Dublin Principles set out in 1992. These principles can be summarized as: (1) water is finite and needed for both people and the environment, (2) water resources management should be a participatory process and include a range of stakeholders, (3) gender plays a role in water management, and (4) "water … should be recognized as an economic good" (ICWE, 1992). These would become the guiding principles of the Global Water Partnership, which was established in 1996 (GWP, 2019) and went on to become one of the leading organizations on IWRM. The creation of the Dublin Principles and the need to manage water effectively arose partially out of concerns of water scarcity (ICWE, 1992). The concept of water scarcity was not new (Falkenmark, 2013), and in 1989, water security was contextualized by creating classifications of water stress in terms of availability per person (Falkenmark et al., 1989).

During the evolution of water resources management, another field was undergoing a transformation. In 1991, the Cold War was coming to an end, and there was an increased interest in new security threats. Security studies, a sub-discipline of International Relations, traditionally focused on the balance of power, deterrence theory, arms control, alliance theory, national security, and war and peace (Caballero-Anthony, 2016; Krause and Williams, 2018). Seeds of dissent with the traditionalist view of security can be found as early as the 1950s (Krause and Williams, 2018), when Wolfers (1952) acknowledged the ambiguity of the term 'security' when used on its own and proposed criteria to be used to contextualize the term. Yet, intellectual strides in the concept's expansion did not occur until the 1980s and 1990s (Krause and Williams,

2018). This expansion has come to be known as the 'broadening' and 'deepening' of the security concept (Krause and Williams, 2018). Through broadening, the concept was expanded to include not just militaristic security, but environmental, economic, and food security, to name a few (Krause and Williams, 2018). Security was deepened to not only include the nation-state, but also the individual (Krause and Williams, 2018).

2.2 Creation of Water Security

In 1984, the Director of the United Nations Environmental Program stressed that water scarcity was a concern for both "national and global security" (Clarke, 1991). This concern regarding water scarcity, coupled with the broadening of security studies, led to the creation of water security. Some of the first uses of the term can be traced to the early 1990s. Starr (1991) viewed water security in terms of the potential national security threat the United States of America could face from growing water scarcity in the Middle East. Another early work acknowledged this national threat from scarcity, but also stressed that rural populations needed "security – the confidence that they can survive the dry years …" and that this could be done by increasing supplies and availability as well as improving access (Clarke, 1991). By the latter half of the decade, the concept of water security still heavily focused on availability, but it also started to expand to include health and gender concerns as well as management (Biswas, 1999).

The concept of water security was further solidified within the global agenda with the Ministerial Declaration of The Hague on Water Security in the 21st Century. The declaration defined water security as a 'goal' to "protect ecosystems; promote sustainable development & political stability; access to enough safe water; protection from risk" (UN, 2000). This multi-dimensional conceptualization was the first to recognize the need to protect against water-related risks. Another key development from this forum was that

water security became viewed as a 'goal' of water resources management. If water security was the goal, then Integrated Water Resources Management (IWRM) was the way to achieve it. For the rest of the decade, water security on the global agenda focused on identifying key challenges of water security and the promotion of IWRM to reach it (GWP, 2000; USAID, 2009). There was an additional focus on water security and the poor that came out of the 4th World Water Forum (Grey and Sadoff, 2006), and this issue continues to be a focus of both development organizations (OECD, 2013; UN Water, 2013) and academics (Grasham et al., 2019; Hoque and Hope, 2019).

From 2000 onwards, the number of water security publications rose dramatically along with an increase in content diversity (Cook and Bakker, 2012; Gerlak et al., 2018), making it challenging to give a detailed historical account past this point. Before proceeding, it is useful to note that the diversity within the literature is due, in part, to water security being a wicked problem (Grafton, 2017), but also to the subjectivity of the concept of security. Wolfers (1952) deemed security subjective and case specific since security relates to values, which change based on the decision maker. There have been several attempts to bypass this subjectivity in the security studies literature, with Baldwin (1997) suggesting a broad framing that could be tailored to a given study based on a set of 'specifications.' Similarly, in the water security literature, Cook and Bakker (2013) suggested that broad framings of the concept could be complemented with narrower framings that would lead to more "precise identification ... of specific issues of concern." Yet, this inherent subjectivity still leaves the concept open to wide-ranging interpretations.

2.3 Definitions and Key Concepts

Several commonly used definitions of water security can be found in Table 2-1. Given the aforementioned subjectivity, these definitions remain rather vague. A fundamental element open for interpretation is scaling. The only definition that sets a spatial scale is Norman et al. (2013), while WaterAid (2012) mentions smaller scales of analysis, such as “local ecosystems”, but is not specific. None allude to a temporal scale. An acceptable quantity and quality of water are also mentioned across multiple definitions, but the acceptable values are not given. This ambiguity can be useful, as it allows for the concept to be applied across a range of situations. Thus, instead of trying to explicitly define water security, this brief conceptual review attempts to highlight several of the key concepts found within these definitions. Concepts that can be drawn from complementary framings are also reviewed, along with how these conceptualizations of water security are subject to change based on spatial scale, discipline, or subject.

Table 2-1: Definitions

Author(s)	Definition
Witter and Whiteford, 1999	"a condition where there is a sufficient quantity of water at a quality necessary at an affordable price to meet both the short-term and long term needs to protect the health, safety, welfare, and productive capacity of a population"
UN, 2000	"…ensuring that freshwater, coastal and related ecosystems are protected and improved; that sustainable development and political stability are promoted, that every person has access to enough safe water at an affordable cost to lead a healthy and productive life and that vulnerable are protected from risks of water-related hazards."
GWP, 2000	"at any level from the household to the global, means that every person has access to enough safe water at affordable cost to lead a clean, healthy and productive life, while ensuring that the natural environment is protected and enhanced."
Grey and Sadoff, 2007	"the availability of an acceptable quantity and quality of water for health, livelihoods, ecosystems, and production, coupled with an acceptable level of water-related risks to people, environments, an economies"
WaterAid, 2012	"reliable access to water of sufficient quantity and quality for basic human needs, small-scale livelihoods and local ecosystems, coupled with a well-managed risk of water-related disasters."
Grey et al., 2013	"a tolerable level of water-related risk"
Norman et al., 2013	"sustainable access, on a watershed basis, to adequate quantities of water of acceptable quality to ensure human and ecosystem health.
UN Water, 2013	"the capacity of a population to safeguard sustainable access to adequate qualities of acceptable quality water for sustaining livelihoods, human well-being, and socio-economic development, for ensuring protection against water-born pollution and water-related disasters, and for preserving ecosystems in a climate of peace and political stability."
Scott et al., 2013	"constitutes the sustainable availability of adequate quantities and qualities of water for resilient societies and ecosystems in the face of uncertain global change."

There appears to be a general acknowledgement of risk in a number of the definitions in Table 2-1, with several definitions specifically using the term (UN, 2000; Grey and Sadoff, 2007; WaterAid, 2012; Grey et al., 2013). If water security is viewed from the standpoint of the minimization of water-related risks (Grey et al., 2013), then two key types of risk emerge from the definitions in Table 2-1: those arising from (1) the inability to meet needs and (2) water-related shocks. Across the definitions, there are generally three actors subjected to these risks: people, the environment, and the economy.

In terms of water needs, one of the first definitions, set out in 1999 (Witter and Whiteford, 1999), focuses solely on how water affects humans. This focus on a human's need for water is explicitly mentioned in all of the other definitions, with the exception of Grey et al. (2013), yet one could argue that even here, it is implied. The same could

also be said of environmental needs, with all definitions from 2000 onward explicitly mentioning the environment or ecosystems, again with the exception of Grey et al. (2013), and where again it could be inferred. However, the economy is only specifically mentioned in two definitions (Grey and Sadoff, 2007; UN Water, 2013). One could argue the economic concerns are implied in other definitions, such as a prosperous economy being part of a "resilient society" (Scott et al., 2013). One reason for the direct lack of reference to economic concerns could be that the first two actors' (people and the environment) water requirements are typically referred to as 'needs', while water for economic production can be referred to as a 'demand', i.e. a want, but not essential (Feitelson, 2012).

Then there is exposure to water-related shocks, referred to as hazards (UN, 2000) or disasters (WaterAid, 2012; UN Water, 2013). Water-related shocks also fall under the water-related risks in several definitions (Grey and Sadoff, 2007; WaterAid, 2012; Grey et al., 2013; UN Water, 2013). Grey and Sadoff (2007) specifically state that people, the economy, and the environment all require protection from water-related risks. Thus, three key dimensions of water security can be viewed as mitigating the risks faced by people, the economy, and the environment in terms of adequate supply as well as protection from water-related shocks.

Finally, there is the underlying theme of the resource itself, with each risk to the three actors stemming from the water resource system with which they interact. For example, poor water quality, which has been referenced as an environmental outcome (Mason and Calow, 2012; Sadoff et al., 2015), actually can affect the ability to meet the needs of all three actors. Thus, the water resource system is considered to be a key dimension of the concept of water security.

2.3.1 Key concepts found in definitions

The concepts found in the definitions listed in Table 2-1 can be categorized into five dimensions: (1) risk; the impact this risk has on (2) people, (3) the economy, and (4) the environment; and (5) the water resource system. Each of these dimensions is expanded upon below.

2.3.1.1 Risk

The concept of risk is often defined as "the exposure to a chance of injury or loss", with what constitutes an injury or loss being determined by both an individual's perception and method of evaluation (Morgan, 1990). Even given this subjectivity, risk is considered to be measurable and is not to be confused with uncertainty (Knight, 1921), which now includes "aleatory, epistemic and ontological uncertainty" (Squair, 2009). Risk is comprised of multiple dimensions: potency, rate of action, exposure, and impact (Stedinger, 2016). These dimensions can be illustrated through a hypothetical drought situation: a severe drought (potency) occurred for 8 months (rate of action), affected 1,000 individuals (exposure), and resulted in 2 deaths and 5 million USD in crop damages (impact). Impacts can be represented either in terms of total impact (e.g. number of deaths) or relative impact (e.g. percent of deaths), with the way an impact is reported potentially influencing perceptions of risk (Stedinger, 2016). Risk can be simplified by simply thinking of the question of risk from what and to whom, which in terms of water security is considered the risk emanating from the resource system that then impacts three primary actors: people, the economy, and the environment (Hall and Borgomeo, 2013).

2.3.1.2 People

When it comes to people and water, one of the fundamental concerns is access to adequate supplies of safe drinking water and improved sanitation. There have now been

two United Nations (UN) International Decades on Water, one from 1980 – 1990 and the other from 2005 – 2015, with the primary purpose of each being to increase global access to water and sanitation (UN Water, 2016). The concern for individuals' access was validated in 2010 when the UN declared access to drinking water and sanitation a human right (UN, 2014). Access to water and sanitation has also appeared in both the Millennium Development Goals (MDGs) and the Sustainable Development Goals (SDGs) (UN, 2015, 2016). Access entails not only connectivity rates, but also the reliability and affordability of service (Hope and Rouse, 2013). Reliability can be measured in terms of continual service (Pierce and Jimenez, 2015), but affordability is slightly more challenging to measure (Hoque and Hope, 2019). Finally, people also require water for spiritual or religious purposes (Feitelson, 2012). According to Finney (2015), "water, then is important for our souls as well as for keeping us alive." This is not specifically referenced in the definitions in Table 2-1, but it has been discussed in the water literature, along with how cultures use and interact with water (Briscoe, 2009; Priscoli, 2012; Strang, 2015; Koehler et al., 2018).

People are at serious risk from water-related shocks. Between 1980 to 2016, there were over 240,000 hydrological (flooding, flash floods, and landslides) related deaths (Munich RE, 2020). Future projections are uncertain, but one population-based method estimates over 1.4 billion people will be at risk from a 1/100 year riverine or coastal flood by 2050 (Jongman et al., 2012). There is also the impending threat of rising sea-levels, with a conservative estimate of 190 million people being at risk by 2100 (Kulp and Strauss, 2019). In terms of drought, societal impacts are much harder to quantify (Van Loon et al., 2016). Yet, the EM-DAT database monitors natural disaster impacts and reports over 550,000 drought-related deaths between 1980-2016 (Guha-Sapir, 2019).

Finally, one definition in Table 2-1 made specific mention of vulnerable populations (UN, 2000), which is a recurring theme within the literature. This includes females, as it is suggested that they may be more vulnerable in rural settings, as they typically bear the burden of water retrieval (Hope, 2017). Poverty also plays an important role in water insecurity, with poorer populations facing higher flood and drought risk, especially in urban areas (Winsemius et al., 2018). Poverty plays a role in low service provision as well (Hutton and Chase, 2017), once again, especially in urban areas (Grasham et al., 2019). There is also the notion of countries being stuck in a self-reinforcing cycle of poverty, also known as a poverty trap (Sadoff et al., 2015), which can occur across spatial scales (Barrett et al., 2016; Dadson et al., 2017).

2.3.1.3 The economy

The economy is impacted by water in several ways. First, there must be an adequate amount of water to sustain production. According to Feitelson (2012), this revolves around three primary sectors: agricultural (not including subsistence farming), industrial, and services. The economy is also exposed to the same exogenous shocks, such as floods and droughts. Between 1980 and 2016, hydrological disasters (flooding, flash floods, and landslides) caused over 1 trillion USD in damage (Munich RE, 2020). By 2050, approximately 168 trillion USD will be at risk from 1/100 year riverine or coastal flooding (Jongman et al., 2012). Again, quantifying drought impacts can be challenging, but drought damages between 1980 and 2016 are estimated to have totalled near 203 billion USD (Guha-Sapir, 2019). There is also an economic toll in terms of inadequate access to water and sanitation since poor services impact worker health (Sadoff et al., 2015).

In the literature, there has been an interest in water security's relationship with a country's economic development (Grey and Sadoff, 2007). Grey and Sadoff (2007)

proposed that countries "hampered by hydrology" are typically underdeveloped, have high hydrological variability, and have been unable to invest sufficiently in water management. In contrast, developed countries have less hydrological variability and were thus more likely to finance water infrastructure and, therefore, "harness" their hydrology (Grey and Sadoff, 2007). This notion of being 'hampered by hydrology' also relates to the discussion regarding poverty traps, with poorer countries unable to effectively "harness" their hydrology and thereby unable to develop fully (Dadson et al., 2017). Additional studies have attempted to validate this thinking by finding a negative relationship between GDP per capita and hydro-climatic variability (Brown and Lall, 2006; Brown et al., 2013).

2.3.1.4 The environment

The environment also requires a portion of water in order to maintain healthy ecosystems. Molle and Mollinga (2003) go so far as to say that environmental needs also include "aesthetic" purposes. Thus, the quantity and quality of water needed is highly context specific (Feitelson, 2012) and can be hard to measure. Yet, there have been preliminary calculations on global environmental flow requirements (Sood et al., 2017). Attempts have also been made to measure biodiversity threats (Vörösmarty et al., 2010), including SDG indicator 6.6.1, which seeks to capture the "change in water-related ecosystems over time" (UN Water, 2018). However, this indicator is only focused on measuring the land area change of habitats and changes in water quality and quantity (UN Water, 2018). The International Union for the Conservation of Nature (IUCN) is making strides in monitoring species loss with their Red List (IUCN, 2019), along with the Convention of Biological Diversity's (CBD) Aichi Biodiversity Targets (CBD, 2020).

Water-related shocks also directly affect the environment. One key difference from the previous two dimensions is that flooding may not always have detrimental

impacts. Seasonal flooding can actually be beneficial, as it is necessary for ecosystem health (Gardiner, 1994). Thus, drought can impact the environment not only by directly impacting aquatic species and plants, but also by limiting seasonal flooding (Bond et al., 2008).

2.3.1.5 The water resource system

The concept of the water resource system is separated into a dimension, as it has the ability to affect each of the three primary actors. The water resource system is characterized by the hydrological cycle, which is responsible for global water reserves and changes in precipitation (Conway, 2013). The hydrological cycle is a part of the global climate system, which results in a complex and dynamic system that is characterized by uncertainty (Conway, 2013). Climate change, along with anthropogenic forces, will continue to interact with the hydrological cycle, affecting water-related shocks and availability (Conway, 2013). The complex dynamics that lead to water-related shocks are not specifically discussed here, given the extensive literature on both flooding and drought, as well as their general complexity.

In terms of availability, limited supply or poor water quality not only affects people, but also ecosystem health and economic production. The importance of availability is specifically referenced in all definitions, with the exception of Grey et al. (2013), and can be measured in many ways. Typically, water is reported in terms of renewable fresh surface and groundwater (FAO Aquastat, 2019), also known as blue water. Groundwater values are challenging to estimate, but estimates have improved due to advances in remote sensing (Solander et al., 2017). The significance of green water, the water that is taken in by vegetation and then evaporated into the atmosphere (Hoekstra et al., 2011), is also growing, especially in terms of food production (Rockström et al., 2009; Kummu et al., 2017).

In addition to the issues of a changing climate and broad anthropogenic forces, such as land-use change, two issues that affect supply are degradation of quality and overuse of supplies. Coastal freshwater supplies are subject to salinization from reduced recharge, sea-level rise, or subsidence (Oude Essink et al., 2010). There is also increasing salinization of agricultural land further inland, partially due to the damming of rivers, which eliminates the periodic flooding and their essential nutrients (Reisner, 1987). Poor water quality from salinization, as well as from increased global pollution (Damania et al., 2019), limits the amount of useful water across all users. Lastly, water use has been on the rise since 1960, and an increase in usage is expected to continue (Wada and Bierkens, 2014).

These issues can lead to water scarcity. According to Damkjaer and Taylor (2017), there are over 150 indicators for water scarcity. These include more comprehensive and social based indicators, such as a water poverty index (Sullivan, 2002). It also includes indicators concerned with physical scarcity, such as the UN SDG 6.4.2 measuring water stress (FAO, 2018a), with stress typically measuring some version of the amount of usage compared to availability. In terms of stress, Wada and Bierkens (2014) conducted a comprehensive study of global water usage and created a blue water sustainability indicator (BlWSI) for both surface water and groundwater stress. They found high areas of stress in the American Southwest, Northern Africa, the Middle East, and Central Asia, with stress in these regions expected to grow (Wada and Bierkens, 2014).

A growing population and the need to provide future food security has prompted an interest in exporting food to food insecure regions (Kummu et al., 2017). This then brings into question virtual water, the embodied water in products that are imported and exported globally (Mekonnen and Hoekstra, 2011). This is especially important when

water scarce regions actually export water, such as an increase in virtual groundwater exports during drought years in California (Marston and Konar, 2017).

Mitigating water-related shocks and ensuring a sufficient supply of water is of vital importance. This has typically been done by investing in hard infrastructure to increase supply, such as the construction of dams and flood control measures (Gleick, 2000, 2002; Schmidt, 2017). However, there has been a shift in water planning and management towards alternative supplies, such as water reuse or desalinization (Gleick, 2000). In addition, there has been a push to pursue 'soft path' solutions to water security issues, such as improvements in efficiency or productivity and demand management strategies (Gleick, 2000, 2002).

2.3.2 Concepts from complementary framings

According to McGinnis and Ostrom (2014), "a framework provides the basic vocabulary of concepts and terms that may be used to construct the kinds of causal explanations expected of a theory." Given the ambiguity and the varied interpretations of water security, multiple framings exist. Additionally, more established frameworks can be applied to water security in order to enhance understanding of the concept and provide additional techniques for evaluation (Garrick and Hope, 2013). These additional framings include, but are not limited to: risk; systems-based framings, such as socio-ecological systems (SES) and socio-hydrology; cultural theory; and philosophical framings.

A widely-used framing is that of risk (Hall and Borgomeo, 2013; Hope and Rouse, 2013; OECD, 2013). A risk framing of water security is useful in several ways. First, risk is one of the key concepts identified in the water security definitions found in Table 2-1, making a risk-based framing a natural fit. Second, risk has been closely linked to water resources management (Loucks et al., 2005; WWAP, 2012). Third, a risk-based framing

includes several concepts that are beneficial to the understanding of water security, such as drivers of change, impacts to multiple actors (as discussed above), and the likelihood of an event's occurrence (Garrick and Hope, 2013; Hall and Borgomeo, 2013). A risk-based framing of water security can also incorporate uncertainty (Mason and Calow, 2012), which is useful, seeing as the water resource system is characterized by uncertainty (Loucks et al., 2005). These characteristics have led risk-based framings of water security to be called a "unifying framework to link across multiple water security challenges" (Garrick et al., 2012). It also has been said to "provide the potential to link the current policy-oriented discourse on water security to a new and rigorous science-based approach to the description, measurement, analysis and management of water security" (Grey et al., 2013). Despite these benefits, risk-based framings of water security have been critiqued for their ability to be too reductionist (Zeitoun et al., 2016). This is a valid critique, and it will be discussed more fully in Section 2.6.

Two examples of systems-based framings are an SES framing (Garrick et al., 2013; Hoque et al., 2019) and the application of socio-hydrology (Srinivasan et al., 2017). A key concept of these systems-based framings is the coevolution of humans and resource systems (Srinivasan et al., 2017; Hoque et al., 2019). Specifically, an SES approach focuses on how the resource interacts with users and governance systems to produce outcomes, which are subject to change based on contextual factors (Ostrom, 2007). A systems-based framing of water security is not mutually exclusive to a risk-based framing, but can be complementary (Hoque et al., 2019).

In addition, a "moral and political philosophical" framing has been used through a "capabilities approach", which motivated the authors to suggest a shift in the framing of water security to a concept more concerned with ensuring human well-being through their relations to water (Jepson et al., 2017a). Cultural theory has also offered a lens

through which to understand water security (Koehler et al., 2018). This framing allowed the authors to identify how drinking water risks were observed and perceived across four waterpoint management cultures (Koehler et al., 2018). The two framings expand the dialogue of water security by incorporating approaches that account for individual well-being.

Two concepts that stand out within these complementary framings, as they relate directly to the water resource system, are drivers of change and management of the water resource. The concept of drivers of change is drawn from a risk-based approach, while management comes from the systems-based approach. These two items stand out, as they were alluded to in Section 2.3.1.5 when describing the water resource system. For example, water resources are understood to be influenced by the broader climate system as well as anthropogenic forces (Conway, 2013). Drivers may not indicate the given status of an area's water security, but they do offer an indication of how water security may change in the future. Here, management is broadly interpreted as the range of infrastructure and institutions that can be employed to manage the water resource system, such as hard infrastructure and demand management policies. This was referred to in Section 2.3.1.5, since water management directly influences the amount of supply as well as demand. Thus, both drivers and management are vital to understanding water security.
Interpretations by scale, disciplines, and subjects

2.3.3 Interpretations by scale, disciplines, and subjects

Even though several key concepts can be found in water security definitions and complementary framings, it is useful to note that conceptualizations of water security vary by spatial scale, research discipline, and subject (Cook and Bakker, 2012). As discussed above, most water security definitions do not reference a desired spatial scale

of analysis. Thus, water security can be applied from the individual all the way up to the global level, and the spatial scale of analysis can influence the framing of water security. For example, household water security emphasizes individual access and elevates the importance of individuals' interactions with water, such as the psychological effects of water insecurity (Jepson et al., 2017b; Turley and Caretta, 2020). Whereas, transboundary water security typically includes some mention of management and allocation (Sadoff and Grey, 2005; Mirumachi, 2013; Ganoulis and Fried, 2018).

Disciplinary interpretations of water security can range from an anthropologist's interest in the "cultural or lifestyle dimension of water insecurity" (Stevenson et al., 2012), to the international lawyer's interest in defining national rights for equitable usage (Tarlock, 2008). Cook and Bakker (2012) suggest that disciplines also have spatial scale preferences, making a full breakdown of framings by discipline challenging. Thus, Cook and Bakker (2012) chose to sort framings by subject matter rather than by discipline. For example, it was found that engineering framings tended to focus more on the supply-side and hydrological risks, whereas agriculture-based framings tended to focus more on how water fits into food security (Cook and Bakker, 2012). In addition to spatial scales and discipline, Gerlak et al. (2018) concluded that interpretations can vary based on: "users' institutional agendas, programmatic objectives, …, theoretical leanings, political preferences, views of justice and equity, and … geographic settings."

2.4 Water Security Evaluations

In this section, past water security evaluations are reviewed based on spatial and temporal scales, the primary methodology, and whether the five dimensions outlined in section 2.3.1 are included, along with management and drivers. These review criteria were chosen over others, such as a review based on disciplinary approaches, as they

directly relate to the thesis. As there have already been two in-depth concept reviews (Cook and Bakker, 2012; Gerlak et al., 2018), this is not a complete review of past water security evaluations. Rather, the primary purpose of this review is to determine the changing scope and methods applied to evaluate water security across scales and is intended to be a small review across eight spatial scales (household, rural, urban, nation, region, basin, global, and multiscale). Thus, this is not an exhaustive list of water security evaluations, and it predominately includes studies cited elsewhere in this thesis to explore how they incorporate dimension(s) of water security. However, since this thesis is primarily focused on the national level, additional studies were selected for review to represent smaller spatial scales, e.g. household and urban, with a target of having three to four studies to review per scale. However, some scales had more evaluations to review (household, urban, national), whereas others had fewer studies available (global and multiscale). For a step-by-step explanation for the study selection, as well as examples of the different types of classifications in terms of methods and dimensions, please see Table 2-2.

Table 2-2 Review Criteria and Classifications

Study Selection	
Criteria	
A	Evaluate water security in a comprehensive way, i.e. more than one dimension
or	
B	Evaluate one aspect of water security, i.e. drinking water security
Process for Selection	
1	First, studies that are cited elsewhere in the thesis were included in the review
	i. These studies were included only if they met either Criteria A or Criteria B
2	Since this thesis primarily focuses on the national scale, studies at other scales were not fully represented
	i. Therefore, a search was run in The University of Oxford's online library repository (SOLO)
	ii. The search included journal articles with either "water security" or "water insecurity" in the title between 2010 - 2020
	iii. This search returned 647 peer-reviewed articles
	iv. The following terms were then applied to find studies across scales with one of the following in their title: "household", "rural", "urban", "basin", "global", "multi(-)scale", and several options were used for regional studies, including "Central Asia"
	v. No additional multiscale studies were found, so a minimum of two studies per spatial scale was set
	vi. To be included, studies had to meet either Criteria A or Criteria B
	vii. In the case that there were many studies that met the criteria (household level), studies were selected that expanded the variety of methods and geographical locations reviewed
	viii. Studies found through a search in SOLO are indicated by an (*) following the (Author, Year) in Table 2-3

Classification of Study Methodology	
Category	**Description**
Qualitative	Interpreted as use of the following methods: Interviews, Stakeholder Engagement, and Case Studies (primarily narrative/discussion based studies, but still may include empirical data)
Quantitative	Interpreted as use of the following methods: Indicators (systematically discuss relevant indicators), Diagnostics, Survey, Questionnaire, Composite Index, and Statistics
Mixed	Any mixture of the methods listed as qualitative or quantitative

Classification of 7 Dimensions		
Category	**Description**	**Potential Indicator(s)**
Risk	Engage with the concept of risk	not necessarily measuring risk, but acknowledge that risk is connected to water security
People	Whether needs are being met and impact from shocks	access, cultural values, perceptions of risk, health, affordability, and reliability
Economy	Whether needs are being met and impact from shocks	economic losses, productivity, cost of service provision, cost recovery, and economic growth
Environment	Whether needs are being met and impact from shocks	ecosystem health and flow requirements
Resource	Revolving around the endowment and usage	quality, quantity, availability, withdrawals, and stress
Management	Any indication of management or governance of the resource	institutions, infrastructure, laws, policies, operations, maintenance, and financing options
Drivers	Items that may affect the water security of a given area	population, hydrology, climate, financial constraints, and socio-demographics

The use of ‘evaluation’ in the study selection criteria in Table 2-2 refers to water security studies that have assessed a specific dimension of water security, measured the water security status of an area, and or assessed relationships between water security indicators. Thus, conceptual framings that simply list potential indicators of water security without providing empirical data (Romero-Lankao and Gnatz, 2016; James and Shafiee-Jood, 2017) are not included. Also, evaluations in this sense should not be confused with planning and or management techniques employed to achieve water security, which are discussed in Section 2.5.

Based on the process set out in Table 2-2, thirty-one articles were selected to be reviewed and can be found in Table 2-3. Before proceeding, there are several important clarifications to make about the process for selection, along with the classification procedure. A search was not run for additional national evaluations, as seven were initially included through Step 1 of the selection process. A search was conducted in SOLO for studies at the “global” or “multi(-)scale” spatial scales. Yet, the one global study that met the criteria (Bolognesi et al., 2018) expanded upon a water security index already included in the review (Gain et al., 2016), so it was not included. No results were found when searching for multiscale studies.

In terms of the classification of studies, the primary spatial scale for each study is listed in Table 2-3. For example, the household scale is listed for a study conducted by Young et al. (2019a), even though they assess households across countries. The basin scale includes river and lake basins. The temporal scale is also listed in Table 2-3 when available, and if this is left blank, the scale is not specified within the study. Oftentimes, the studies listed water quality as a metric for the environment. This was not counted under the ‘environment’ dimension since water quality is viewed as a component of the resource, as discussed in Section 2.3.1.5.

Table 2-3: Past evaluations

#	Study (Author, Year)	Spatial Scale	Temporal Scale	Methodology	Risk	People	Economy	Environment	Resource	Management	Drivers
1	Kuijinga et al., 2014	Household	2011-2012	Mixed: Interview/Survey		x			x	x	x
2	Molden et al., 2016*	Household	2014	Mixed: Interview/Survey		x			x	x	
3	Deitz and Meehan, 2019	Household	2016	Quantitative: Statistics		x			x		x
4	Young et al., 2019a*	Household	2017 - 2018	Quantitative: Survey/Composite Index		x			x		
5	Turley and Caretta, 2020	Household	2018	Qualitative: Interviews	x	x			x		
6	Norman et al., 2013	Rural	2008 - 2012	Mixed: Stakeholder Engagement/Indicators	x	x		x	x	x	
7	Penn et al., 2017*	Rural	2014 - 2016	Qualitative: Case Study/Interviews/Diagnostics		x			x	x	
8	Koehler et al., 2018	Rural	2013 - 2014; 2015; 2016	Mixed: Interview/Survey	x	x			x	x	
9	Hoque et al., 2019	Rural	2017 - 2018	Mixed: Interview/Survey	x	x			x	x	
10	Padowski, Carrera, and Jawitz, 2016*	Urban		Quantitative: Indicators		x			x	x	x
11	Jensen and Wu, 2018*	Urban	2001 - 2017	Mixed: Stakeholder Engagement/Indicators	x	x	x		x	x	
12	van Ginkel et al., 2018	Urban		Quantitative: Indicators/Questionnaire	x	x	x	x	x	x	x
13	Assefa et al., 2018*	Urban	2013 - 2017	Quantitative: Composite Index		x			x		
14	Empinotti et al., 2019*	Urban	2013 - 2015	Qualitative: Case Study					x	x	x
15	Khan et al., 2020*	Urban		Quantitative: Composite Index/Questionnaire	x	x	x		x	x	
16	Lautze & Manthrithilake, 2012	Nations		Quantitative: Composite Index	x	x		x	x	x	x
17	Asian Development Bank (ADB), 2013	Nations	2013	Quantitative: Composite Index	x	x	x	x	x	x	
18	Brown et al., 2013	Nations	1901-2003	Quantitative: Statistics	x	x	x				x
19	Asian Development Bank (ADB), 2016	Nations	2016	Quantitative: Composite Index	x	x	x	x	x	x	
20	Sadoff et al., 2017	Nations		Mixed: Case Study/Statistics	x	x			x	x	x
21	World Bank, 2017	Nations		Quantitative: Indicators/Diagnostics	x	x	x		x	x	
22	Young et al., 2019b	Nation		Quantitative: Indicators/Diagnostics	x	x	x	x	x	x	x
23	Zakhirova, 2013*	Region		Qualitative: Case Study		x	x		x	x	
24	Cashman, 2014	Region		Qualitative: Case Study	x	x	x	x	x	x	x
25	Petersen-Perlman et al., 2012	Basin		Qualitative: Case Study	x			x	x	x	x
26	Garrick et al., 2013	Basin		Quantitative: Indicators/Diagnostics	x			x	x	x	x
27	Landis et al., 2017*	Basin	1997 - 2012	Quantitative: Statistics	x	x					x
28	Vörösmarty et al., 2010	Global (Gridded)		Quantitative: Composite Index	x	x		x	x		x
29	Gain et al., 2016	Global (Gridded)		Quantitative: Composite Index	x	x			x	x	x
30	Hope and Rouse, 2013	Multi-Scale	Case Specific	Mixed: Case Study/Statistics	x	x	x		x	x	x
31	Sadoff et al., 2015	Multi-Scale	Case Specific	Mixed: Case Study/Statistics/Indicators	x	x	x	x	x	x	x

* represents a study that was found through a SOLO search

2.4.1 Spatial scale

There do appear to be patterns in the methodology and categories based on spatial scale. Yet, the resource category is prevalent across all studies regardless of scale. Since these are all water security studies, thus having some interest in water, this was anticipated. The mention of risk is relatively prevalent across studies, with the exception of households. People are also the focus in all but two studies. The economy and the environment are not considered in any of the household analyses (again, this is not considering water quality) and infrequently in rural or urban studies. Management is included in all rural studies. There are four comprehensive studies (those including people, the economy, the environment, the resource, management, and drivers): 1 multiscale (Sadoff et al., 2015), 1 regional (Cashman, 2014), 1 national (Young et al., 2019b), and 1 urban (van Ginkel et al., 2018).

2.4.1.1 Household

Studies at this scale are primarily interested in the relationships between people and water. Only two studies are categorized as assessing drivers (Kujinga et al., 2014; Deitz and Meehan, 2019). However, the Deitz and Meehan (2019) study could be classified as looking more into the contextual factors linked to a given outcome: socio-demographics related to rates of access to plumbing (Deitz and Meehan, 2019). This study is one of two strictly quantitative studies, with the other using survey data to create a composite index of household water security (Young et al., 2019a). The qualitative study (Turley and Caretta, 2020) relied strictly on a narrative format, whereas mixed methods studies (Kujinga et al., 2014; Molden et al., 2016) relied on narratives, but also incorporated tables to display data. Risk is under-represented at this scale, as it is only mentioned in one study (Turley and Caretta, 2020).

2.4.1.2 Rural

When looking at the rural scale, all studies look at people, management, and the resource. However, none specifically measure drivers of change, and the environment is only included in one instance (Norman et al., 2013). Individual financial risk was mentioned in Koehler et al. (2018), and this was considered under the 'people' category. Whereas, Hoque et al. (2019) incorporated discussion regarding different financing options for infrastructure (e.g. public versus private), which was considered under the 'management' category. There is no standard methodology used at this scale. A narrative format is used in the one qualitative assessment (Penn et al., 2017). Whilst the other three studies incorporate quantitative information (Norman et al., 2013; Koehler et al., 2018; Hoque et al., 2019).

2.4.1.3 Urban

At the urban scale, all but one study (Empinotti et al., 2019) focus on humans and water. Rather, Empinotti et al. (2019) are interested in evaluating the effect of drought on governance, with drought being considered a 'driver' of change. Management is also frequently studied, except by Assefa et al. (2018), who focus solely on a framework around access and availability. The environment is once again underrepresented, with only one study incorporating environmental concerns (van Ginkel et al., 2018). One of the more interesting insights that can be ascertained at this scale is the gradual shift away from interviews and an increased interest in indicator assessment. Two studies still continue to incorporate comments, one through a management performance questionnaire (van Ginkel et al., 2018), and the other employs feedback from pertinent stakeholders (Jensen and Wu, 2018). The only study to employ a strictly narrative format was carried out by Empinotti et al. (2019), with the rest taking a step back from the narrative format to give more weight to the presentation and discussion of indicators.

2.4.1.4 National

Only one study included in this review is based on a single country (Young et al., 2019b), whereas the other six measure water security across several countries. Risk is mentioned in all studies, and economic and environmental concerns become more prevalent at this scale. Young et al. (2019b) incorporate all categories into their assessment. The World Bank (2017) and the Asian Development Bank (ADB) (2013, 2016) do not specifically report on drivers. However, the World Bank (2017) report does include one graphic on future socio-economic and climate drivers of water scarcity, but does not include drivers in their overall country summaries. Even though not specifically calculating drivers, the ADB (2013, 2016) studies do incorporate the notion of drivers, as they are referred to indirectly in their assessment of urban water security. Lautze and Manthrithilake (2012) do not include economic concerns. There is one study that is more qualitative in nature, with a focus on water security and fragility (Sadoff et al., 2017). The rest of the studies are of a quantitative nature in terms of indicator development, but two also incorporate lengthy narratives to accompany the indicators used (World Bank, 2017; Young et al., 2019b). Finally, Brown et al. (2013) use econometrics to assess the relationship between hydrological variability and economic growth.

2.4.1.5 Regional

The two regional studies (Zakhirova, 2013; Cashman, 2014) included are both qualitative assessments and offer a narrative account of water security for a given area. Cashman (2014) employs a Strengths, Weaknesses, Opportunities, and Threats (SWOT) format to highlight water security in the Caribbean. In the process, the study touches on all six dimensions. Zakhirova (2013) discusses the management dimension of water security in Central Asia.

2.4.1.6 Basin

Each of the three basin level studies includes information on water and drivers of change, but only two include management (Petersen-Perlman et al., 2012; Garrick et al., 2013). Garrick et al. (2013) offer a diagnostic approach to highlight federal rivers at risk, whereas Petersen-Perlman et al. (2012) use a narrative case study to highlight water security across three basins, with a focus on "resilience and vulnerability." Landis et al. (2017) look at hydrological variability and climate change impacts on political violence in the Niger River basin, while controlling for socio-economic effects.

2.4.1.7 Global

The two global studies are applied at a gridded level (Vörösmarty et al., 2010; Gain et al., 2016). Both use a composite indicator to measure multiple water security dimensions, but neither use all of the review criteria. Vörösmarty et al. (2010) do not include management or economic concerns. Whereas, Gain et al. (2016) do not include environmental or economic concerns.

2.4.1.8 Multiscale

There are two multiscale assessments. First, Hope and Rouse (2013) use case studies to operationalize their risk-based framing and to discuss drinking water security at both the rural and urban scales. Sadoff et al. (2015) evaluate a variety of different scales, including the country, aquifer, and city. However, these scales are all studied separately, i.e. a tiered analysis is not conducted. This study also incorporates all the review criteria, but it is done through a variety of different methodologies across different scales.

2.4.2 Temporal scale

These studies were all generated in the last seven years. Several do not list a specific temporal scale, since data was collected from a variety of sources, such as in van Ginkel et al. (2018). It is interesting that the mention of a temporal timeframe for analysis seems to decrease with scale. As studies become more comprehensive in nature, the ability to find data for all indicators across a given year may become rarer, such as in the study by van Ginkel et al. (2018). Even when a temporal scale is listed, most studies do not incorporate trends. This includes studies, such as Empinotti et al.'s (2019) assessment of drought in São Paulo, Brazil, from 2013 to 2015. The ADB (2013, 2016) studies may eventually allow for the assessment of trends, but this currently is not possible, as several of the sub-indicators have changed between assessment periods. Koehler et al. (2018) rely on a survey that was taken for three separate time periods, and thus a trend or seasonality could be assessed. Assefa et al. (2018) compile data from 2013 – 2017, but they only compare several of the individual indicators and not their final water security index through time. Young et al. (2019b) discuss trends of certain indicators and future projections. The pathways analysis included in Sadoff et al. (2015) discusses changes through time for several case studies. Jensen and Wu (2018) produce one of the only studies to specifically measure trends across all indicators, doing so from 2001 to 2017. Finally, two studies use econometric methods to assess relationships over time (Brown et al., 2013; Landis et al., 2017).

2.4.3 Methodology

Each of the studies in Table 2-3 employs qualitative, quantitative, or mixed methods to evaluate either an aspect of water security or its totality. The methods used across the 31 studies are often applied for different purposes: a focus on specific

dimensions, a more comprehensive status assessment, or the study of relationships between indicators. As mentioned above, the majority of these evaluations took a case study approach, being applied to a specific area, such as Pakistan (Young et al., 2019b). Qualitative methods included interviews, which typically focused on assessing specific dimensions of water security, such as people or management. There were also several qualitative based case studies. Quantitative methods were applied for several purposes and included composite indices, surveys, a focus on indicators, and statistical techniques. Mixed methods typically used some form of a narrative case study or interviews in combination with surveys.

Given the diversity of methods, there does not appear to be a clear methodology that offers a comprehensive water security assessment, since both the narrative approach (Cashman, 2014) and the focus on quantitative indicators (van Ginkel et al., 2018) have produced comprehensive assessments. Yet, none of these comprehensive case studies are easily replicable across their given scale. This is either due to data not being reproducible (van Ginkel et al., 2018; Young et al., 2019b) or the context-specific nature of the study (Cashman, 2014; Sadoff et al., 2015).

2.4.3.1 Qualitative

Qualitative methods include interviews (Penn et al., 2017; Koehler et al., 2018; Hoque et al., 2019; Turley and Caretta, 2020) and narrative case studies (Petersen-Perlman et al., 2012; Zakhirova, 2013; Cashman, 2014; Empinotti et al., 2019). Interviews are frequently used for the purpose of capturing individuals' perceptions and values regarding water (Penn et al., 2017; Koehler et al., 2018; Hoque et al., 2019; Turley and Caretta, 2020). The narrative case study format can be used either to discuss specific dimensions of water security, such as management and drivers (Empinotti et al., 2019), or multiple dimensions (Petersen-Perlman et al., 2012; Cashman, 2014).

2.4.3.2 Quantitative

There were several different quantitative methods applied and for a variety of purposes. They can be broken down into three threads: relational studies, surveys, and a focus on indicators. The relational studies found in Table 2-3 look to explain relationships between water security indicators, and all employ statistical methods. Deitz and Meehan (2019) use regressions to determine socio-demographics related to low plumbing access. Brown et al. (2013), Landis et al. (2017), and Sadoff et al. (2015) all employ econometric techniques to elucidate relationships between water security dimensions through time. Surveys are often employed to capture the people or management dimensions of water security. Thus, the majority of surveys involve questions regarding people's experience with water in terms of perception of insecurity (Koehler et al., 2018), levels of access (Kujinga et al., 2014), and the strength of institutions (van Ginkel et al., 2018). Surveys can also be run across multiple time periods (Koehler et al., 2018).

Several studies simply list a set of indicators to quantify water security (Norman et al., 2013; Sadoff et al., 2015; Assefa et al., 2018). Yet, two studies come up with interesting ways to view this data that could be classified as dashboards (World Bank, 2017; van Ginkel et al., 2018). The World Bank's (2017) study includes country profiles for 20 countries in the Middle East and North Africa (MENA), and van Ginkel et al. (2018) generate a sample dashboard for Sao Paulo, Brazil, to visualize 56 indicators of water security. These standardized visualizations serve as a way to compare countries in terms of their water security. The interest in dashboards as a way of communicating complex information is not new, with dashboards being utilized as a way to communicate the UN 2030 Agenda (UNDP, 2017).

In terms of indicator selection, several approaches were used. This includes basing the indicator selection on the dimensions of the water security framework

employed in the study. For example, Sadoff et al. (2015) highlight information based on four headline risks. There was also the use of pressure-state-impact-response (PSIR) (Padowski et al., 2016) and the process analysis method (PAM) (Jensen and Wu, 2018). In addition, diagnostics were used in several studies to highlight water security challenges (Garrick et al., 2013; World Bank, 2017; Young et al., 2019b). The diagnostic process is useful in the context of water security, as it not only can be used to systematically process information to identify problems, but can also be used to investigate the causes of said problems (Edquist, 2011). Essentially, the diagnostic process allows for the systematic evaluation of outcomes and their causes (Cox, 2011). A diagnostic process has been implemented across disciplines, such as the diagnostic approach pioneered by Eleanor Ostrom (2007) to analyse socio-ecological systems.

In contrast to listing indicators, there are studies that create a water security composite index (Vörösmarty et al., 2010; Lautze and Manthrithilake, 2012; ADB, 2013, 2016; Gain et al., 2016; Khan et al., 2020). A composite index is an alternative to the listing of indicators, as it merges multiple metrics into one value. This allows for a rapid understanding of the total water security status for a given area. However, there are some negatives to composite indicators, as their creation involves a level of uncertainty (Saisana et al., 2005), and changes in individual indicators can be overlooked (OECD, 2008).

2.4.3.3 Mixed methods

Mixed methods occur across analysis scales and for different purposes. These mixed methods typically come in the form of survey data accompanied by interviews to include people's water-related experiences (Kujinga et al., 2014; Molden et al., 2016; Koehler et al., 2018; Hoque et al., 2019). Mixed methods are also used to evaluate specific dimensions of water security, such as combing several concise case studies with statistical

insight to evaluate drinking water security (Hope and Rouse, 2013). Similarly, statistics are combined with a narrative discussion to evaluate the relationship between water security and fragility (Sadoff et al., 2017). Finally, Sadoff et al. (2015) employ case studies to analyse historical pathways, a statistical analysis to test relationships, and indicators for a status assessment.

2.5 Achieving Water Security

The methodologies incorporated in the studies discussed above can be used to assess water security. These past evaluations have enhanced the understanding of a specific dimension of water security, captured the water security status of a set locale, and or illuminated complex relationships between indicators. Yet, this is separate from the processes employed to actually achieve water security. Thus, the evaluation of water security is just one step in a broader approach.

As previously mentioned, water security is the goal of effective water management (UN, 2000). Thus, when looking at larger scales of analysis (city, country, or river basin), specific approaches to achieve water security are typical of water resources management, such as Integrated Water Resources Management (IWRM) (GWP, 2000). IWRM and other approaches, such as adaptive pathways (Sadoff et al., 2015), offer ways to turn the information gained from water security studies into useful investments and policies. IWRM is an integrative framing that includes setting goals, resource assessment, planning, plan implementation, and monitoring of progress (GWP, 2009). Similar steps can be found in the process of medical diagnosis, which has expanded in recent years. This diagnostic process attempts to gather as much information as possible, evaluate the information, make a working diagnosis, and then continue to assess until a final diagnosis is made (Graber, 2015). Based on this diagnosis, treatment

is prescribed and monitored (Graber, 2015). New steps in the diagnostic process now account for the evaluation of the treatment outcomes, as well as the efficiency and effectiveness of the process itself (Graber, 2015). The underlying principles of this diagnostic process are effective communication, continual learning, and a desire for improvement (Graber, 2015). Thus, diagnostics may offer not just offer a methodology for highlighting relevant water-related risks, but also provide a broader process to achieve water security.

These processes do not have to be mutually exclusive, but rather concepts from each of these approaches can be used in conjunction. For example, decision-making techniques categorized under the pathways approach, such as dynamic adaptive policy pathways (Haasnoot et al., 2013), could be used as a technique in the long-term planning step of an IWRM approach. Thus, these approaches (IWRM, pathways, diagnostics) offer a variety of tools that can be added to a water manager or policymaker's toolkit to make effective decisions in order to achieve water security.

Even though approaches to achieve water security exist, actually achieving water security is no easy feat. Putting aside the lack of consensus on the conceptualization and measurement of the concept, there are still abundant challenges faced when trying to achieve water security. First, there is the issue with the effectiveness of the approaches mentioned above. For example, IWRM has been criticized for its lack of success (Wichelns, 2017), which partially stems from institutional failures (Medema et al., 2008; Schreiner, 2013). Second, even though systems-based techniques to cope with wicked problems have improved, such as decision-making under uncertainty (DMDU) (Kwakkel et al., 2016), turning findings into actionable interventions or policy is "not guaranteed" (Wichelns, 2017). One explanation for this could be a misalignment between the optimal solution versus the politically feasible solution. Allan (1999) describes how water

management is influenced by an area's political economy in the sense that "economically and environmentally logical policy priorities" are often at odds with the "politically feasible policy priorities." Essentially, the "political prices" to implement strategies are often too high, and thus less optimal solutions may be favoured among policymakers (Allan, 1999).

Thus far, the discussion has largely revolved around the use of institutions and infrastructure to manage water security. Yet, the issues with implementing water security briefly mentioned above touch on something broader: water governance. Governing bodies implement approaches, such as IWRM, to achieve water security, as well as make use of their respective tools and techniques. Thus, the need for effective governance and institutional capacity predicates any effort to achieve water security (Bucknall et al., 2006). This entails the need for robust frameworks to enact laws and uphold accountability; institutions; investments not only in hard infrastructure, but also in information and new technology; and political will (Bucknall et al., 2006). Effective governance is challenged in many ways, such as by the multiple scales of water governance (global to the local) and their different motives and objectives (Gupta and Pahl-Wostl, 2013); the siloing of policymakers and government bodies, leading to a lack of comprehensive governance (Pahl-Wostl et al., 2013a); and through power and political dynamics (Bakker and Morinville, 2013). Thus, even with integrative approaches (IWRM) and improved techniques (DMDU), well-intended interventions may not yield water security in practice.

2.6 Critiques

Criticism of water security is summarized and categorized into three fundamental critiques. First, the work on water security and economic growth has been criticized due

to its promotion of investment in hard infrastructure to mitigate water security issues in developing countries (Merrey, 2009; Zeitoun, 2011). The approach taken by Grey and Sadoff (2007) has been viewed as focusing too heavily on the supply-side of water security. Merrey (2009) debated whether water security was even necessary for economic growth and cautioned against investment in large scale infrastructure. Zeitoun (2011) also questioned the findings of this study, as well as the underlying methods. In terms of Merrey's (2009) criticism, and somewhat to a degree Zeitoun's (2011) as well, the water security literature has expanded since 2007 to take heed of these criticisms. The general dialogue of water security has stressed that there are no panaceas when it comes to water security (Pahl-Wostl et al., 2016), and there is now a broader interest in suites of investments in "infrastructure, institutions, and information" to combat water insecurity (Sadoff et al., 2015).

This first critique ties into a second and much broader critique of water security that stems from the concept's inherent subjectivity. As seen in sections 2.3 and 2.4, this has led to a range of concept interpretations, framings, and evaluation methodologies. Zeitoun et al.'s (2016) critique of reductionist approaches to water security is included in this broad category. This critique is included here for two reasons: (1) this is just one interpretation of water security, and thus illustrates its fluidity, and (2) the methods suggested are more context-specific, which could decrease subjectivity by focusing on a given locale (Zeitoun et al., 2016). Zeitoun et al. (2016) criticize research that "seeks to reduce the complexity through quantified risk-analysis and simplifying assumptions about national economy, hydro-climatology, and society." They counter with the need for more context-specific studies regardless of the scalability of their findings (Zeitoun et al., 2016). This is a justified critique of water security studies and can be addressed in several ways. First, there is a need for pluralistic methods to understand water security,

which includes risk-based approaches to understand certain facets of insecurity so long as they are robust and do not overly simplify complexity (Zeitoun et al., 2016). Second, top-down analyses can be accompanied by bottom-up approaches (Loucks et al., 2005). These approaches can work together to create a more nuanced understanding of water security (Loucks et al., 2005). The need for merging these approaches has appeared in the water security literature (WWAP, 2012; Dadson et al., 2013; Garrick et al., 2020), and the climate adaptation literature has begun to look at ways to achieve this integration (Conway et al., 2019). Pluralistic methods or a mixture of bottom-up and top-down approaches may do nothing to remove the concept's inherent subjectivity, but they may offer a better way to incorporate said subjectivity.

Lessons can be learned from the security studies field as a whole, as security is acknowledged to be a value-laden concept imbued with subjectivity (Baldwin, 1997). As early as 1952, Wolfers suggested a set of contextual criteria (questions) to be included with every security study (Wolfers, 1952). This idea was later adopted by Baldwin (1997) and summarized into seven key questions: (1) "security for whom", (2) "security for which values", (3) "how much security", (4) "from what threats", (5) "by what means", (6) "at what cost", (7) "in what time period." Essentially, any study should start from a broad definition and framing of the concept and then can be narrowed based on the seven questions above (Baldwin, 1997). This has also been echoed in the water security literature through the need for a broad framing that could be narrowed to gain more useful insights (Cook and Bakker, 2012). Again, this does not diminish the overall subjectivity, but it allows the concept to be applied across a variety of situations.

The third and final critique comes from the broader security studies literature. This critique posits that fields have been over-securitized. Over the last two decades, the expansion and diversity of security studies has continued. The Copenhagen School

emerged during this time and became known for its theory of securitization (Šulovič, 2010). The Copenhagen School was originally a proponent of the 'broadening' and 'deepening' of security studies (Šulovič, 2010). Yet, now, there is a focus on 'desecuritization' and a perception that certain topics may have been elevated to an unneeded level of urgency (Šulovič, 2010).

In the water security literature, there is also cause for concern as water security can still evoke militaristic notions. For example, Mason and Calow (2012) state that "even if understood broadly, there is an argument that the word 'security' will always carry militaristic overtones… ." According to Staddon and Scott (2018), there are two ways that securitization occurs, with one being a political process that promotes resource hoarding and military confrontation. Thus, the concept of desecuritization has been mentioned through the lens of desecuritizing water, such as to achieve improved outcomes in water negotiations (Fischhendler, 2015). Yet, given its drawbacks, the securitization of water has been able to elevate the concept to "high-politics" and "politically prioritize" water issues (Fischhendler and Nathan, 2016). This can be seen through the concept's adoption in the policy sphere (UN, 2000; USAID, 2009; OECD, 2013). The concept of water security is thus likely to remain prominent in the policy arena, at least for the near future.

2.7 Moving Forward

In order to achieve water security, one first needs to have an understanding of the current water security situation of a given area. Though there is a mature and ever-growing literature regarding the appropriate framing and operationalization methodology of water security, there are still several significant gaps. First, work can still be done on methods to assess national-level water security and the communication of indicators. Few

analyses incorporate trends, and of the 31 water security evaluations reviewed in Section 2.4, there are only two that use multiple scales, with neither being a tiered analysis. Finally, there is still room to improve upon the knowledge of relationships between water security indicators and dimensions.

Thus far, national cross-country comparisons of water security typically do not include drivers or trends (ADB, 2013, 2016; World Bank, 2017). A fully comprehensive study has been conducted on Pakistan's water security, but it is a case specific study (Young et al., 2019b). Yet, the diagnostic approach used was thorough and focused on highlighting key "challenges and opportunities" for water security (Young et al., 2019b), which could be a useful methodology for comparing water security across countries.

There are currently few studies that look at trends in water security, and still fewer that evaluate water security across scales. Both are important, given the spatial and temporal variability of water. It is especially important to evaluate how water security has changed in the past in order to help calculate future projections as well as for decision-making and planning. Multiscale tiered analyses of water security would prove useful, as national water security assessments have the ability to obscure sub-national heterogeneity (Cook and Bakker, 2012). A tiered analysis of water security would allow for the identification of hotspots of insecurity at sub-national levels.

Finally, several studies have explored the relationships between water security dimensions. This includes hydrological variability and economic growth (Brown et al., 2013), the effect of hydrological and climate drivers on political instability (Landis et al., 2017), and how socio-demographics interact with access to plumbing facilities (Deitz and Meehan, 2019). In addition to these studies, there is a broad body of research outside of water security that could be applicable, such as socio-economic drivers of water stress (Chenoweth, 2008; Fant et al., 2016; Mekonnen and Hoekstra, 2016). Even when drawing

upon the literature outside of water security, there is room to improve knowledge of the relationships between indicators, as these can change based on scale and location (Deitz and Meehan, 2019). This is an area of research that should continue in the future, as knowledge about the relationship between water security indicators serves not only to inform policy, but also to improve our models of water insecurity and improve future projections.

2.8 Methodological Approach

This thesis aims to fill the research gaps discussed above in Section 2.7 by improving upon methods and techniques used for three types of water security assessments: national, multiscale, and relational. The first step to achieving the thesis's goal is the formation of a water security framing found in Chapter 3, which establishes how water security is viewed and interpreted throughout this thesis. This systems-based framing was built upon a comprehensive framing of water security by John Briscoe (2009), whose framing targeted water managers. This framing is further strengthened by concepts from a widely cited systems framing (Ostrom, 2007). This thesis first strives to fully utilize all aspects of the framing (Chapter 3) and then subsequently focuses on certain aspects (Chapters 4-5), i.e. starting with a comprehensive framing and then narrowing to gather more insight into relationships. This was done through three primary methods: a diagnostic dashboard, a composite indicator, and an econometric analysis.

In Chapter 3, a diagnostic methodology was adapted from the medical literature to operationalize the water security framing at the country scale. Diagnostics were chosen over other methods, given their ability to explore outcomes and potential causes (Cox, 2011). The methodology laid out in Chapter 3 could potentially offer a process by which to achieve and maintain water security. Yet, given the lack of consensus on useful

indicators as well as the amount of information that could potentially be reviewed, only the first step of the diagnostic method is operationalized in Chapter 3. A dashboard was chosen as the interface through which to communicate the data, as dashboards have been used to communicate water security indicators (van Ginkel et al., 2018) and are being employed for several SDGs (UNDP, 2017). The indicators and format of the dashboard are based on the water security framing. However, two categories of information, historical and cultural context and actions, were not included as they do not easily translate into indicators or a dashboard format. The dashboard does allow for the potential linkage between indicators; however, specific relationships and feedbacks between information categories or indicators are not included. Data for the indicators were largely chosen from publicly available datasets (e.g. World Bank, FAO, UN), with the goal of having a harmonized dataset for as many countries as possible. Pakistan was chosen as a case study to illustrate the usefulness of the dashboard since it is included in several water security studies (Lautze and Manthrithilake, 2012; ADB, 2013, 2016) and is the subject of a recent and thorough report on national water security (Young et al., 2019b). These past studies offer a method by which to compare the usefulness of the dashboard. In addition, four other countries were selected in order to show how the dashboard can be generated for multiple countries, but also act as a regional cross-country comparative analysis. This includes Afghanistan, Tajikistan, Turkmenistan, and Uzbekistan due to their geographical proximity to Pakistan.

Through the creation of the water security dashboard, it became apparent that national water security assessments could leave knowledge gaps in regard to sub-national heterogeneity. Thus, in Chapter 4, a multiscale analysis is conducted. Ideally, this analysis would have continued with a case study of Pakistan. However, due to data limitations, the United States of America (USA) was chosen as the case study location.

The USA collects similar data across multiple administrative boundaries, thus allowing for a multiscale comparison. The multiscale analysis included ten separate sub-indicators, nine of which came from publicly available data sources. The indicator selection was driven by the system performance and outcome categories of the water security framing from Chapter 3. It became apparent that including other items in a composite index, such as drivers, would not be as useful, given that the dynamics between drivers and insecurity cannot be assumed to hold across scales. The ten sub-indicators were mapped at the country, state, and county scale, whilst the composite index was mapped at the state and county levels. Thus, the index created is not comparable across countries, as the sub-indicators used will likely differ by country.

Through the creation of the dashboard in Chapter 3, a large number of water security indicators were gathered. This offered a dataset for exploration into the potential relationships between drivers, the water resource system, system performance, and outcomes. Descriptive statistics were run for the indicators used in Chapter 3, and an interesting relationship emerged, that of the relationship between water stress and water productivity. Initial correlations showed a negative relationship between the two indicators. This correlation supports an assumption that increased productivity is related to a decrease in stress (Mekonnen and Hoekstra, 2016; Scheierling and Treguer, 2016; Khair et al., 2019), which is also the basis of SDG 6.4 (UN Water, 2019). Therefore, this relationship was chosen as the focus of Chapter 5, along with the analysis of additional drivers of water stress, such as hydroclimatic and socio-economic variables. Again, the framing laid out in Chapter 3 offered a guide to the type of drivers selected. Since data was available for a large number of countries (166) and across five timesteps, the analysis utilized a fixed effect regression model to analyse the panel dataset. The majority of data

in this study came from publicly available datasets, and the complete dataset is publicly available (Doeffinger and Hall, 2019).

This thesis focuses on the evaluation of the current water security status of a given area and does not attempt to study future steps that could be used to achieve water security, such as the 'treatment' phase or potential monitoring options. This includes different investment alternatives, their subsequent effects, and the tradeoffs that may result from their selection. Since this thesis focuses on utilizing secondary empirical data to understand water security, the biggest hindrance is data quality and availability. In terms of data quality, the FAO Aquastat (2019) database was frequently utilized, but has several limitations. For example, the total renewable freshwater availability for each country has remained constant for each timestep available since 1958 (FAO Aquastat, 2019). This data point, therefore, does not incorporate any interannual or intrannual variability. In terms of data availability, many indicators could not be included due to the lack of data, such as information on the affordability of services. Also, as mentioned above, several fundamental categories of information were lacking from this thesis, partially due to data availability and also as some do not easily translate into an indicator format. These gaps include an analysis of public versus private water utilities, different financing options, historical and cultural context, and a more thorough and nuanced understanding of the governance mechanisms in place along with the political economy. Ultimately, this thesis sets out several methodologies that can be followed to evaluate water security across scales, with the potential to (1) update indicators as information becomes more accurate, (2) substitute indicators for ones of better quality, or (3) add additional indicators, such as affordability, as information becomes available.

3 A DIAGNOSTIC DASHBOARD TO EVALUATE WATER SECURITY

Abstract: While water security is widely regarded as an issue of global significance and concern, there is not yet a consensus on a methodology for evaluating it. The difficulty in operationalizing the concept comes from its various interpretations and characteristics at different spatial and temporal scales. In this paper, we generate a dashboard comprised of 52 indicators to facilitate a rapid assessment of a country's water security and to focus the first step of a more comprehensive water security diagnostic assessment. We design the dashboard around a conceptualization of water security that builds upon existing framings and metrics. To illustrate its usefulness, we apply the dashboard to a case study of Pakistan and a regional cross-country comparative analysis. The dashboard provides a rapid view of the water security status, trends, strengths, and challenges for Pakistan. The cross-country comparative analysis tentatively identifies relationships between indicators such as water stress and the transboundary dependency ratio, with countries exhibiting high values in both variables being especially vulnerable to transboundary water risk. Overall, this dashboard (i) provides quantitative information on key water-related variables at the country level in a consistent manner and (ii) helps to design and focus more in-depth water security diagnostic studies.

3.1 Introduction

Water security has emerged in international policy and academic debate as an overarching concept to encompass the multiple dimensions of water. Water security, like any other form of security, evokes varied meanings. A definition that attempts to capture all of these connotations is a "tolerable level of water-related risk to society" (Grey et al., 2013). This broad definition does not specify a spatial or temporal scale. It applies to a city such as New York or the entirety of China. It refers to water-related risk today and in the future. This definition does not elaborate on the types of water risk. It could refer to risks that arise from natural hazards such as flooding, drought, storm surge, or tsunamis. It could refer to people's access to safe drinking water supplies, such as a general lack of access, poor quality, or supply system unreliability and unaffordability. It could also refer to threats to water resources, such as groundwater overuse or transboundary conflicts. Given the breadth of scale and types of risk, it is understandable that there is no consensus on an evaluation methodology.

There have been multiple attempts to operationalize the concept of water security (Lautze and Manthrithilake, 2012; Norman et al., 2013; Gain et al., 2016; van Ginkel et al., 2018). Zeitoun et al. (2016) criticize previous approaches that use risk to attempt to quantify water security. Instead, they suggest the concept would benefit from a more holistic evaluation process that allows for case-specific understandings along with the ability to incorporate the overlap of water security with additional security concerns (Zeitoun et al., 2016). Yet, they do not lay out a methodological approach to achieve this. In this paper, we are alert to the critique of reductionism, so adopt a broad and holistic understanding of water security. Nonetheless, we argue that there needs to be some standardization and measurement involved if we are to track progress and compare different situations and contexts.

There are several options available for communicating complex concepts with multiple data dimensions, such as visualization software and the use of composite indices. Dashboard tools are one such option and offer a way to communicate and visualize an array of socio-economic and environmental indicators, such as monitoring biodiversity (Han et al., 2014). By monitoring data that are relevant to water security and placing them in a dashboard, one can approach some comparable process of data reporting (van Ginkel et al., 2018). Dashboards can also help countries comprehend their water security progress, aid in policymaking, help with monitoring water security (Han et al., 2014), and are increasingly being promoted in the context of the 2030 Agenda (UNDP, 2017). This also allows for the possibility of comparisons across countries.

Given that the concept of water security has proved to be so challenging to conceptualize and evaluate, its usefulness has been questioned (Pahl-Wostl et al., 2016). However, it is widely used in policy circles both within governments, NGOs, and multi-lateral development organizations to draw attention to water-related issues and challenges (Staddon and Scott, 2018). Given this wide uptake, it's important for researchers to engage with the concept, even if this proves to be conceptually and operationally challenging. This paper proposes, describes, and applies a diagnostic dashboard for policymakers and water management practitioners to quickly and efficiently attain a picture of a country's water security. This dashboard contributes to the literature by structuring diverse data relevant to water security into a single page. We focus on the country level due to the availability of data and to support country-level decisions by governments and international agencies. This perspective also allows for cross-country comparisons.

The paper starts by taking stock of past conceptualizations and empirical studies of water security. Next, we lay out our methodology that consists of three parts: (1) a

water security framing built from previous conceptualizations, (2) a diagnostic methodology, and (3) a conceptual dashboard that can be used as an aid in the first step of the diagnostic method. Then we focus on the dashboard and use a case study of Pakistan to test its accuracy and usefulness, along with a regional cross-country comparison. Finally, the results are discussed, along with concluding remarks.

3.2 Current approaches to water security

3.2.1 Framings

The term water security was first used in the early 1990s amid growing concerns that water scarcity could be a threat to national security (Clarke, 1991; Starr, 1991, 1992). By the latter half of the decade, the concept expanded beyond water availability and became part of the broader academic and global agenda with the Ministerial Declaration of The Hague on Water Security in the 21st Century at the 2nd World Water Forum in 2000. The declaration called for the provision of water security and to ensure

> *"that freshwater, coastal and related ecosystems are protected and improved; that sustainable development and political stability are promoted, that every person has access to enough safe water at an affordable cost to lead a healthy and productive life and that the vulnerable are protected from the risks of water-related hazards" (UN, 2000).*

This multi-dimensional framing was the first to recognize the need to protect against water-related risks and viewed water security as a 'goal' of water resources management (UN, 2000). This 2000 framing is one of many. There are numerous conceptualizations of water security, generating the need for several periodic reviews of the literature (Cook and Bakker, 2012; Garrick and Hall, 2014; Gerlak et al., 2018).

A long-standing problem in the field of water security is what to include in its conceptual framing, i.e. focus on specific water-related issues or try to cover all possible

dimensions. Studies have focused solely on water security and economic growth (Brown et al., 2013); water security and fragility (Sadoff et al., 2017); drinking water (Hope and Rouse, 2013); and institutional capacity (Bakker and Morinville, 2013). The advantages of these studies are in-depth analyses of a specific aspect of water security that provide vital information to policymakers. However, they do not cover the full scope of a concept that is widely regarded as being multi-dimensional (Gerlak et al., 2018). Furthermore, water security intersects with broader inter-related assessment frameworks, including assessments of ecosystem services (Russi et al., 2013; GWP, 2016) and of adaptive capacity (Lemos et al., 2016).

John Briscoe (2009) created one of the earliest multi-dimensional framings. He designed his framing around what types of information a country 'water tsar' would need to achieve water security. This framing focused on four types of information: (1) historical and cultural context, (2) exogenous drivers (3) endogenous tools, and (4) outcomes concerning people, economy, and the environment (Briscoe, 2009). Briscoe (2009) emphasized the need for 'information' rather than specific indicators. This allows for his framing to be applied across a range of situations. This framing was only laid out in theory and not operationalized within the scope of the 2009 paper, but additional studies by Briscoe and co-researchers provide applied examples (Briscoe and Qamar, 2006). Scholars have continued to propose multi-dimensional framings of water security (Mason and Calow, 2012; Romero-Lankao and Gnatz, 2016; James and Shafiee-Jood, 2017; Srinivasan et al., 2017). Nonetheless, a consistent multi-dimensional framework has proved to be elusive. The fundamental question of how to go about measuring or gathering the consistent information needed and then generating a useful recommendation from it still stands.

3.2.2 Evaluations

There are several water security evaluations, and they range from the local to the global scale. Local studies tend to focus on stakeholder engagement and attempt to tie research insights to local policies. One example of this is the study conducted by Norman et al. (2013) in a small town in British Columbia. They focus on stakeholder engagement in their indicator formation with the intent to inform policy decisions (Norman et al., 2013). On the city scale, a recent study evaluated ten cities using pressure-state-impact-response (PSIR) to create a dashboard of 56 different indicators (van Ginkel et al., 2018). It also develops a single index value of water security for each city (van Ginkel et al., 2018). This study is one of the most comprehensive to date as it accounts for various climate and socio-economic drivers, system state variables, outcomes, and adds in the additional response indicators that essentially capture government effectiveness (van Ginkel et al., 2018). Nonetheless, the study is limited in that data to quantify some of the proposed indicators are not readily available, and it does not incorporate trends.

At the country scale, several studies have been conducted specifically in Asia and the Pacific. The first being by Lautze and Manthrithilake (2012), who look at water security in terms of "basic needs, agriculture production, the environment, risk management, and independence" for 46 countries. This study was for a single year, and only 27 of the 46 countries had data in all five components. The Asian Development Bank (ADB) (2013, 2016) continued with this focus by releasing two water security reports for 49 countries in Asia and the Pacific. The ADB (2013, 2016) studies are comprehensive, covering five areas of water security: household, economic, urban, environment, and resilience to water-related disasters. They also generate a single index value of water security for each country (ADB, 2013, 2016).

On a global scale, Gain et al. (2016) created a map of water security by aggregating data from a 0.5° spatial resolution, country-level data, as well as river basin data. This aggregate value of water security was based on a multi-criteria analysis that included "water availability, accessibility to services, safety and quality, and management" (Gain et al., 2016). Finally, Sadoff et al. (2015) evaluated water security across scales: cities, river basins, and aquifers. In addition, the study reported on several indicators based on country information: costs of insecurity, floods, access to services, and ecosystem impacts (Sadoff et al., 2015).

The majority of these studies only focus on a snapshot of data from one year. The ADB (2013, 2016) is beginning to formulate a time series with their two separate reports, and the GWP/OECD report (Sadoff et al., 2015) used time series data for several of their water security indicators. One can see that each of the above analyses focus on somewhat similar issues, but they measure water security with different indicators. For example, they measure some form of accessibility to water and environmental degradation. However, when focusing specifically on adaptability to water security, there were multiple approaches, such as risk management (Lautze and Manthrithilake, 2012), resilience (ADB, 2013, 2016), or management (Gain et al., 2016). Zeitoun et al.'s (2016) argument of reductionism is relevant for some of these studies, as they have tended to reduce the complexity of water security to a single indicator (e.g. ADB's National Water Security Index Score). However, this has begun to be addressed both through a focus on context and pathways (Sadoff et al., 2015), but also through the implementation of diagnostic studies (Garrick et al., 2013; Hydrosystems Research Group, 2017; World Bank, 2017, 2018a; Young et al., 2019b). This study builds upon this line of work to develop a water security diagnostic approach and applies the approach to construct a dashboard to evaluate country water security.

3.3 Methodology

3.3.1 Water security framing

An overall framing of water security is established before proceeding to develop a diagnostic methodology since "a framework provides the basic vocabulary of concepts and terms that may be used to construct the kinds of causal explanations expected of a theory" (McGinnis and Ostrom, 2014). We focus on the framing by John Briscoe (2009) and expand upon it. We chose Briscoe's (2009) framing due to its comprehensive nature, its focus on both qualitative and quantitative data, its recognition of the subjectivity of water security, and its ability to allow for an iterative decision-making process. Based on this framing, we propose seven types of information needed to assess and understand water security. These information categories are (1) drivers, (2) historical and cultural context, (3) the water resource system, (4) system performance, (5) outcomes, (6) actions, and (7) trends. The majority of these criteria are reminiscent of the four laid out by Briscoe (2009), with the main difference being (3), (4), and (7). Having a separate category for the water resource system and understanding its performance was alluded to by Briscoe (2009), but never explicit in his framework. The trends category was added because it helps to interpret the future state of water security, which is naturally the focus of water management actions. The reasoning behind each of these information categories is summarized below, with several categories being compared to Ostrom's (2007) theoretical framing of social-ecological systems (SES) as it is a widely accepted framework to understand complex systems.

(1) Drivers are factors that may contribute to changing the status of water security. Drivers appear in different forms in Briscoe's (2009) framing and Ostrom (2007). In Briscoe's (2009) framing, drivers are exogenous factors that are influencing

the water resource system and its governance. For example, an increase in population could increase the pressure on the resource and change usage patterns. Meanwhile, Ostrom (2007) referred to these factors as "social, economic, and political settings" plus the "related ecosystems", as well as mentioning the technological environment. Ostrom (2007) acknowledges that the SES can be influenced as well as influence these factors. In this line, we separate our drives into five categories: social, economic, political, technological, and environmental.

(2) As well as acknowledging exogenous influences, Briscoe (2009) also emphasizes the importance of **historical and cultural context**, which is more endogenous in nature, recognizing how this can affect the types of institutions and policies that could be put in place to manage water. For example, people's coping mechanisms to floods can evolve due to changing social or cultural norms. These attributes are more aligned with the cultural representations of water discussed in Veronica Strang's (2015) book, in which she points to several well-known cases of historical significance. This includes the Nile in Egypt, where water's place in society has evolved over the centuries (Strang, 2015). Historical and cultural context will be predominantly qualitative, highly case-specific, and, like many aspects of water security, may vary over different spatial and temporal scales.

(3) The **water resource system** incorporates the variables that describe the state of water resources, recognizing that the system is, for the most part, modified by human activity. So, understanding the status of the system must include the water endowment and how water is allocated. Thus, this set of state variables includes: (1) how much water is available, (2) how the water is allocated, and (3) the infrastructure and institutions that are in place to manage the previous two elements. While these are not explicit categories of Briscoe's (2009) framing, he does express the need for a "broad, integrated conceptual

understanding of the water challenge." Briscoe (2009) also references the importance of measuring drivers as they have the ability to determine the "quantity and quality of water available." Our water resource system category overlaps with three of the primary components of Ostrom's (2007) overall framing of an SES. The water endowment roughly maps onto Ostrom's (2007) characterization of the resource system. This endowment component captures surface and groundwater, how much of this water originates within the country, and unconventional supplies such as desalination and recycled water. Our usage component picks up on the users in Ostrom's (2007) framing and can be broken down further into different usage types such as agricultural, industrial, and municipal. The infrastructure and institutions currently in place are included here because they have alignment with Ostrom's (2007) governance system, and as managed systems, they are difficult to separate from the previous two components. For example, hard infrastructure such as dams affects the quantity of the water endowment (by changing the amount of water that is evaporated), the timing of its availability, and where it is located. Soft infrastructure such as wetlands also influence processes such as evapotranspiration and groundwater recharge. Institutional policies can affect the allocation of the resource as well as the operation of the infrastructure.

(4) System performance indicators report on how the water resource system is operating as far as users of water are concerned, where this also includes environmental users. The system performance category is also an addition to Briscoe (2009). Briscoe (2009) does discuss how technological advancement can improve the performance of infrastructure. Thus, alluding to the monitoring of performance metrics. In this case, system performance incorporates the overall quality of the water available, the stress on the resource, and whether the resource is being used productively and efficiently. It also includes the performance of infrastructure and institutions. These system performance

indicators represent an intermediate step between the system state variables in (3) and the outcomes in (5), which are the values that are associated with and aggregated over system performances. For example, water quality affects the social, economic, and environmental outcomes of the system.

(5) Outcomes are the attributes of a system that are valued by people and decision makers (Hall and Borgomeo, 2013). Outcomes appear in Briscoe's (2009) framing, although Briscoe uses the term interchangeably with impacts. In keeping with the 'triple bottom line' definition of sustainability, Briscoe (2009) breaks this information category into social, economic, and environmental outcomes. SES theory also includes outcomes, and they are subdivided into social, ecological, and additional SES externalities (Ostrom, 2007). These two interpretations illustrate the need for subfields within this category, and we choose to use those set out by Briscoe (2009) because they align with other risk-based water security framings that focus on outcomes (Sadoff et al., 2015; ADB, 2016).

(6) Actions are the interventions at the disposal of stakeholders in the system, which may change the state of the water resource system and hence, its performance and outcomes. This may include policy and operational reforms or investments in infrastructure and technology. Thus, this encompasses a broad decision space. Briscoe (2009) refers to these items as 'endogenous tools' and references the following: institutions, infrastructure, and technology. These actions differ from the infrastructure and institutions that are already a part of the water resource system mentioned above, as they have yet to be implemented. These actions vary across an array of decision makers from the farmer deciding whether to add drip irrigation to a river basin manager trying to implement water quality regulations. These actions also vary across temporal scales. If we take the example of the farmer, his/her decisions may be implemented from one

growing season to the next, while some strategies, such as increased storage capacity, may take longer to implement, given their high cost and construction timeline.

(7) Trends in all of the above indicators provide information on the evolution of water security, which informs future management actions. Trends are an addition to the Briscoe (2009) framing, but Briscoe does reference the need to acknowledge changes that may occur in the future due to climate change or technological advancement. Trends in any of the above categories may be informative, though data on some (e.g. population drivers) are much easier to obtain than others (e.g. water quality or outcomes for aquatic organisms). Few water security trend analyses have been conducted, mainly due to a lack of data.

3.3.2 Diagnostic method

To demonstrate the framing of water security described in Section 3.3.1, we set out a diagnostic approach to evaluate the multiple dimensions of water security. Figure 3-1 shows a method for diagnosing water security, inspired by an analogy from the medical diagnostic approach (Graber, 2015). The diagnostic process starts by gathering high-level information about water security as a whole, assessing the data, and then generating an initial diagnosis. This initial diagnosis would highlight the main water challenges and opportunities within a country. Once this initial diagnosis is reached, Step 2 involves gathering additional information and running further tests, such as looking at a specific species decline or assessing flood risk. Once this initial diagnosis is reached, Step 2 involves gathering additional information and running further tests, such as looking at a specific species decline or assessing flood risk. Once all available information is gathered and has been assessed, a final diagnosis is reached. Based on this diagnosis, a treatment plan can be constructed. Step 4 in the process is labelled as

'treatment', given the medical analogy of the term 'diagnostic.' Treatment includes the planning and decision-making phase, and examples could be generating a policy to regulate pollution discharge or enhancing the financial stability of urban water utilities. After the treatment stage, there is a need for periodic reviews of the outcomes of the treatment. This is illustrated through the red arrows in Figure 3-1. Based on this evaluation, one should determine if the treatment was successful or not, and if the diagnosis or treatment needs to be re-assessed. This is illustrated through the blue arrows in Figure 3-1. Finally, this is an iterative method that takes into account stakeholder feedback during each step of the process.

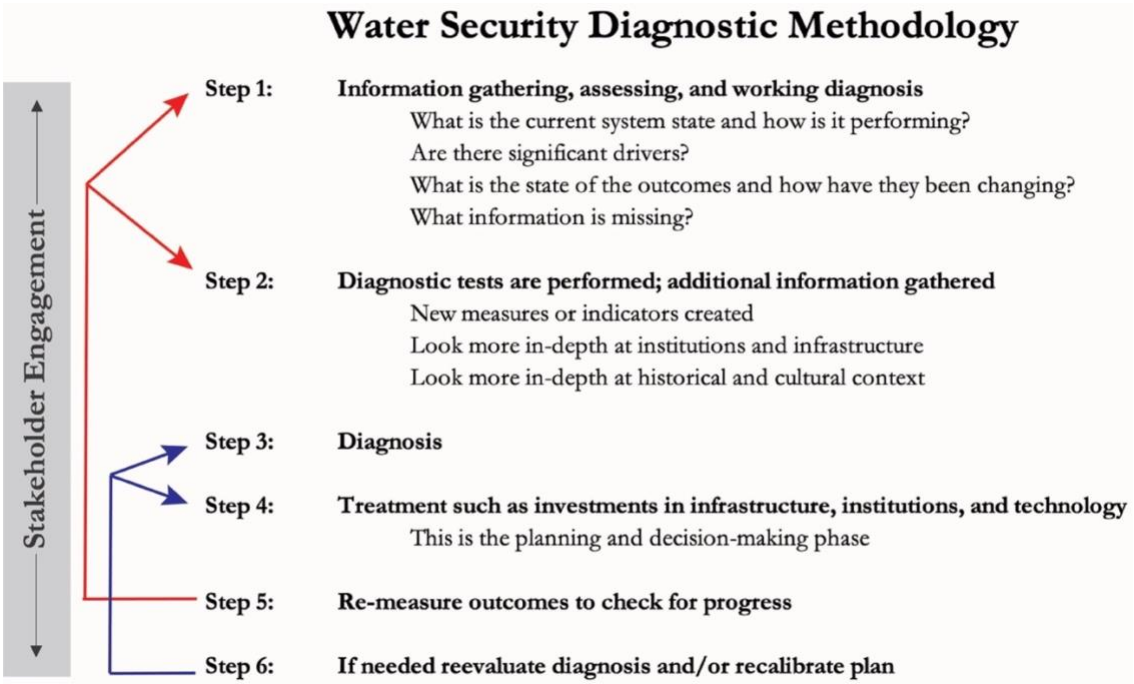


Figure 3-1: Water security diagnostic methodology based on a medical diagnosis process (Graber, 2015).

3.3.3 Water security dashboard: a tool for initial diagnosis

The dashboard that we have created facilitates a rapid approach to Step 1 of the diagnostic methodology and thereby assists the process of reaching a working or initial diagnosis. The dashboard is generated based on the framework set out above. Thus, it

seeks to look at a variety of indicators in order to highlight multiple water security challenges. A single-page dashboard helps to focus the analysis and visualize the current status and trends of relevant information. It also helps to identify potential connections between indictors and dimensions to understand how water-related risks may arise. Though water security may be assessed at many scales, we have focused on the national scale. By using globally and publicly available data at this scale, the dashboard tool can be used for cross-country comparisons and enable ranking of performance across countries.

Even though the framework above was used as a basis for the dashboard, two categories were not compatible with a dashboard format: (2) historical and cultural context and (6) actions. Historical and cultural context typically are found in a narrative format. However, diagrammatic timelines have been used to highlight historical events relating to water (Sadoff et al., 2015). General context is reported at the beginning of the Results section, though this does not provide a complete historical and cultural analysis. Data on the 'actions' category is also not included, as these relate to the 'treatment' step in the diagnostic process and require creative input from decision makers. Ultimately, fifty-two variables were selected for the dashboard (Table 3-1). This represents a pragmatic choice of data that are available for most countries. In the discussion below, we note limitations with these datasets.

Based on this data, we can make an initial diagnosis and recommend items to be pursued in Step 2, such as additional data to be gathered and tests to run. This format also lends itself to cross-country comparative analysis. However, this is only the first step in the overall diagnostic methodology. Even though a standardized set of variables are used to create a working diagnosis, Steps 2-6 of the method allow for tailoring and stakeholder engagement.

Table 3-1: Items included in the Dashboard along with unit, time scale analysed, and data source.

Variable Name	Unit	Timescale	Source
Drivers			
Social			
Population	-	1990 – 2017	World Bank Databank, 2019; projections UN, 2017
Urban population	% of population		World Bank Databank, 2019; projections UN, 2017
Net migration		1990 – 2017	World Bank Databank, 2019
Human Development Index	0-1 (0 worse)	1990 – 2017	UN, 2019b
Gini coefficient	0-100 (100 worse)	1990 – 2017	World Bank Databank, 2019
Gender gap in wages	0-1.5 (1 is equality)	2000 - 2016	UN, 2019a
Employment in agriculture	-	1990 – 2017	World Bank Databank, 2019
Economic			
Gross domestic product (GDP)	2010 USD	1990 – 2017	World Bank Databank, 2019; projections from IMF, 2019
GDP per capita	2010 USD/person	1990 – 2017	World Bank Databank, 2019
Agriculture value added	% of GDP	1990 – 2017	World Bank Databank, 2019
Industry value added	% of GDP	1990 – 2017	World Bank Databank, 2019
Services value added	% of GDP	1990 – 2017	World Bank Databank, 2019
Political			
Fragile states index (FSI)	0-120 (120 worse)	2006 – 2018	The Fund for Peace, 2019
Technological			
Technology Development	No. of water-related patents	2000 – 2016	OECD, 2020
Environmental			
Average yearly temperature	° Celsius	1990 – 2017	Harris et al., 2014; projections World Bank CCKP, 2019
Interannual temperature variability (CV)	-	1990 – 2017	**Calculated**: Harris et al., 2014
Total yearly precipitation	mm	1990 – 2017	Harris et al., 2014; projections World Bank CCKP, 2019
Interannual precipitation variability (CV)	-	1990 – 2017	**Calculated**: Harris et al., 2014
The Water Resource System			
Conventional Water Endowment			
Total renewable freshwater	10^9 m^3/year	1990 – 2017	FAO Aquastat, 2019
Renewable groundwater	10^9 m^3/year	1990 – 2017	FAO Aquastat, 2019
Renewable surface water	10^9 m^3/year	1990 – 2017	FAO Aquastat, 2019
Transboundary dependency ratio	%	1990 – 2017	FAO Aquastat, 2019
Water availability per capita	m^3/inhab/year	1990 – 2017	**Calculated**: FAO Aquastat, 2019; World Bank Databank, 2019
Unconventional Water Endowment			
Desalinated water produced	10^9 m^3/year	1990 – 2017	FAO Aquastat, 2019
Direct use of treated wastewater	10^9 m^3/year	1990 – 2017	FAO Aquastat, 2019
Net virtual water imports	10^9 m^3/year	1996 – 2005	Mekonnen and Hoekstra, 2011
Usage			
Agriculture	10^9 m^3/year	1990 – 2017	FAO Aquastat, 2019; Liu et al., 2016
Industry	10^9 m^3/year	1990 – 2017	FAO Aquastat, 2019; Liu et al., 2016
Municipal	10^9 m^3/year	1990 – 2017	FAO Aquastat, 2019; Liu et al., 2016
Environmental	10^9 m^3/year	1990 – 2017	FAO Aquastat, 2019
Renewable groundwater	10^9 m^3/year	1990 – 2017	FAO Aquastat, 2019
Renewable surface water	10^9 m^3/year	1990 – 2017	FAO Aquastat, 2019

Table 3-1 Continued

Infrastructure			
Cultivated land equipped for irrigation	%	1990 – 2017	FAO Aquastat, 2019
Treated wastewater	%	2018	Wendling et al., 2018
Total storage capacity	10^3 m^3	1990 – 2017	FAO Aquastat, 2019
Institutions			
Government institutions	-	At Present	FAO, 2019a
International freshwater treaties	-	As of 2007	Oregon State University, 2007
System Performance			
Number of recorded droughts	-	1990 – 2017	Guha-Sapir, 2019
Number of recorded floods	-	1990 – 2017	Guha-Sapir, 2019
Water stress	%	1990 – 2017	SDG 6.4.2 **calculated**: FAO Aquastat, 2019; Liu et al., 2016
Water productivity	2010 USD/m^3	1990 – 2017	SDG 6.4.1 **calculated**: FAO Aquastat, 2019; Liu et al., 2016
Water quality index - pollution	0-1 (1 worse)	2014	Sadoff et al., 2015
Continuity of Service	0-24 hours	1995 – 2019	IB-NET, 2020
Degree of IWRM implementation	0-100 (0 worse)	2018	SDG 6.5.1 from UN Environment, 2018
Outcomes			
Social			
Access to improved water	%	2000 – 2017	WHO/UNICEF, 2019 (by service level)
Access to improved sanitation	%	2000 – 2017	WHO/UNICEF, 2019 (by service level)
Deaths from flood	-	1990 – 2018	Guha-Sapir, 2019
Economic			
Agriculture value added	2017 USD	1990 – 2017	World Bank Databank, 2019
Total cost of flood damage	2017 USD	1990 – 2017	Guha-Sapir, 2019
Total cost of drought damage	2017 USD	1990 – 2017	Guha-Sapir, 2019
Environmental			
Biodiversity index	0-1 (1 worse)	2014	Sadoff et al., 2015
Environ flow violations index	0-1 (1 worse)	2014	Sadoff et al., 2015
Maps for Dashboard Tool			
Country & Admin level shapefiles	-	Current	Natural Earth, 2019
World's major rivers	-	Current	Natural Earth, 2019
HydroSHEDS basin rivers	-	2013	Lehner and Grill, 2013
World Cities	-	2019	ArcGIS Hub, 2019

Socio-demographic drivers include population, urbanization, net migration, the human development index (HDI), the Gini coefficient, the gender gap in wages, and the percentage of employment in agriculture. Population and the urbanization rate provide basic demographic context. The net migration value is a sum of the total emigration and immigration within the country. The HDI is a multi-dimensional indicator and incorporates life expectancy, education level, and gross national income (GNI) per capita (UN, 2019b). GNI includes all income for citizens regardless if it was earned abroad, whereas GDP only includes revenue from production within the country's boundaries (World Bank Databank, 2019). The Gini coefficient is a measure of economic distribution

within society measuring equality on a scale of (0-100), with 0 being total equality and 100 being absolute inequality (World Bank Databank, 2019). We incorporate the gender gap in wages (UN, 2019a). This is the gap in average wages across all income categories with a value of 1 indicating equality in wages and a value less than one indicating that males are earning more than females (UN, 2019a). The data for this indicator is currently only available for Pakistan and not the additional four countries used in our cross-country comparison analysis. Finally, we include the percentage of employment in the agricultural sector, as this could indicate the percentage of the workforce relying on water intensive actives. While this is not an exhaustive list of demographic or equity-based indicators, they give us a general idea as to changing population dynamics and socioeconomic status through time.

Variables for economic drivers include GDP per capita and a breakdown of a country's economic makeup in terms of the overall GDP as well as agriculture, industry, and service sectors. Knowing whether a country has transitioned or is in the process of transitioning to a manufacturing or service-based economy can help to understand how water withdrawals could change in the future, i.e. in some countries, such as the United States, agricultural water withdrawals have decreased following industrialization (Siddiqi and Anadon, 2011). To quantify political stability within a country, we use the Fragile States Index (FSI). This indicator measures state vulnerability across twelve different dimensions, making it a comprehensive index of overall country stability (The Fund for Peace, 2019). Ostrom (2007) recognized that the technological, along with the social, economic, and political, environment are important factors that contribute to outcomes. The technological environment is expressed through the OECD's (2020) technology development indicator. In this case, this indicator is comprised of the number of water-related patents developed or partially developed (indicated by a fraction) by a given

country between 2000-2016, which includes “water pollution abatement” and “water adaptation technologies” (OECD, 2020). Technology development is used as one of the OECD’s indicators on Green Growth and gives some indication to the value placed on innovation within the country (Haščič and Migotto, 2015). Finally, information on climate drivers includes temperature and precipitation data. The coefficient of variation (CV) for temperature and precipitation represents the interannual hydroclimatic variability, which is associated with more challenging conditions for water management as it means that rainfall is not predictable from one year to the next (Hall et al., 2014).

The water resource system is broken down into the water endowment, water usage, infrastructure, and institutions. The water endowment is further separated into the conventional endowment and unconventional endowments. The conventional endowment includes renewable groundwater and surface water, as well as data on the transboundary dependency ratio, and total renewable freshwater is put in relative terms by reporting on the water availability per capita. The conventional water endowment only considers renewable freshwater, so it would benefit from the additional information on slow-recharge aquifers. The data was acquired from FAO Aquastat (2019), but there are some limitations since country renewable freshwater remains constant from 1958 – 2017. Also, groundwater and surface water may not sum to the total renewable freshwater, as FAO Aquastat’s (2019) total renewable freshwater includes values that could be considered both groundwater and surface water. We also highlight a country’s dependency ratio, which refers to the amount of renewable freshwater that originates outside the country’s borders. A low dependency ratio (0%) indicates that all of a country’s water is generated within the country, whereas a high dependency ratio of (100%) would suggest that all of the country’s water is generated elsewhere and flowing into the country. We recognize the importance of green water in a country’s water

endowment; however, given the lack of country-level data on green water, we excluded it for now. Unconventional endowments include net virtual water imports, the amount of desalinated water produced, and the direct use of treated municipal wastewater. If we think of the water endowment as the water available for different uses, then the virtual water imported is water that effectively becomes available to use (e.g. in the form of the imported agricultural products). Thus, importing water effectively expands a country's resource endowment. Desalinated water and recycled wastewater are also ways in which countries can effectively enhance their resource base.

FAO Aquastat (2019) database is the primary resource on country-level water withdrawals. However, data is reported in five-year windows. A value can be reported for each country for any of the years within these five-year windows, and there are frequent data gaps. Liu et al. (2016) attempted to fill in FAO Aquastat data gaps through interpolation and inverse distance weighting. The result was a complete country-level dataset for water withdrawals on a five-year time step from (1973-2013) (Liu et al., 2016). For this analysis, we use Liu et al.'s (2016) dataset and update it based on current FAO data. The environmental usage is based on the environmental flow requirements found in FAO Aquastat (2019). Thus, the most recent value for water usage is from 2013. We additionally report on the amount of surface water and groundwater withdrawn, as we try to capture the importance groundwater plays in water security (Gleeson et al., 2012). This data comes from the FAO Aquastat (2019) database and may not directly align with sectoral water withdrawal data.

Several relevant indicators are used to characterize the current infrastructure and institutions. The cultivated land area equipped for irrigation, the amount of wastewater treated, and storage capacity are used to measure the scale of water infrastructure (Gaupp et al., 2015). Elaborating on the current status of water-related institutions is more

challenging, as the type of institutions, along with their roles and capacity, are highly context specific. Currently, the FAO (2019a) reports on the number of water-related governmental institutions, and Oregon State University (2007) reports on international freshwater treaties every country is a party. These are not perfect indicators, but sometimes the "mere presence of governance instruments" is all that is available (Woodhouse and Muller, 2017). We recognize that these available indicators give limited perspective on infrastructure and institutional complexity within a country, but unfortunately, are amongst the only indicators for which data is available for cross-country comparisons. We believe that they represent a reasonable starting point at the initial diagnostic phase of a water security assessment.

Water system performance includes how well the system is operating, i.e. if it is being sustainably managed. First, the recorded number of floods and droughts are listed as these values provide knowledge on how the overall hydrological regime is performing. Water stress is calculated based on the water withdrawals versus the total renewable freshwater (including environmental flow needs), using the equation for UN SDG 6.4.2 (FAO, 2019c). Water productivity is a metric that captures the amount of money gained from a unit of water used and is calculated based on the UN SDG 6.4.1 indicator for water-use efficiency (FAO, 2019b; Doeffinger and Hall, 2020). The calculation excludes the proportion of rainfed agriculture from the equation and does not include green water (FAO, 2019b). Also, the agricultural gross value added for this calculation includes forestry and fisheries, as these items are typically included as part of the agricultural sector (FAO, 2018b). Both of these system performance metrics were calculated with the water withdrawal data discussed above, and come with limitations inherent in this data. Water quality is a crucial system performance attribute which can affect each of the outcomes. For example, poor water quality can affect the health of both people and the

environment (Damania et al., 2019). Due to the lack of information on country-level water quality, we use the country-level pollution indicator from the GWP/OECD report (Sadoff et al., 2015). This indicator has no time series, so we are not able to quantify how water quality has changed over time. In terms of infrastructure performance, we include information on the reliability of water service delivery in terms of the continuity of service (IB-NET, 2020). We also include new data from SDG indicator 6.5.1, "degree of integrated water resource management implementation" (UN Environment, 2018), which is a qualitative measurement. Ideally, an indicator for the affordability of water services would be included, but it is not currently reported on in a consistent way across countries and, as Hoque and Hope (2019) point out, is a challenging metric to measure effectively.

Outcomes are reported with indicators for social, economic, and environmental impacts. Social outcomes include access to improved water and sanitation as well as flood-related deaths. For economic outcomes, we focus on the value of agriculture as well as flood and drought costs. The agricultural sector GVA is used to help understand the scale of economic dependence on water. This value also provides insight into the implications of changes in agricultural production. Flood and drought costs were originally given in US dollars in the year the event occurred, so the values were adjusted to 2017 US dollars using the US Inflation Calculator (2019). In regards to determining the outcomes of drought, these outcomes are much more challenging to account for than those of flooding (Hall and Leng, 2019). The EM-DAT dataset is based on reporting by governments and NGOs, so the criteria for including floods and droughts are variable (Guha-Sapir, 2019). In addition to the variation in the qualification of a drought, measuring the direct human and economic impacts can be challenging (Van Loon et al., 2016). Finally, for environmental outcomes, we look at the biodiversity index and environmental flow violation index. Data for both of these indicators are taken from

Sadoff et al. (2015). The biodiversity index represents the strength of the area's biodiversity, while the environmental flow violation index relays if enough water if flowing through a country's waterways.

3.3.3.1 Generating the dashboard

The dashboard was generated to communicate and act as a visualization for the fifty-two variables in a single place and within one sheet of paper to streamline the process of water security diagnostics. We highlight trends in the indicators for which a time series is available. We focused on an overall period of 1990 to the present for trend detection, since the majority of the data was available for this time period. The data is also more robust during this time period, i.e. not as many interruptions in datasets. For exact date ranges used for each indicator, see Table 3-1. The direction of the arrows in the dashboard signifies an increasing or decreasing trend, while a horizontal line indicates no positive or negative trend over the time period. Trends were calculated using ordinary least squared (OLS) regression. Additionally, the average annual rate of growth was calculated for each indicator for which a time series was available. This is indicated based on the size of the trend arrow in the dashboard. Finally, future projections were available for population, GDP, annual precipitation, and average temperature.

In addition, we ranked the majority of the fifty-two indicators across countries. The overall water endowment and the number of current institutions were not ranked, since they are intended to provide context. The majority of the indicators were ranked from highest to lowest. However, several were ranked from lowest to highest: the HDI, GDP per capita, total GDP, technology development, total precipitation, water availability per capita, net virtual water imports, cultivated land equipped for irrigation, treated wastewater, water productivity, continuity of service, degree of IWRM implementation, and access to improved water and sanitation. These specific indicators

were ranked from lowest to highest, as a lower score is of more cause for concern. Highlighted indicators within the dashboard are those that fall in the top 75th percentile of the aforementioned ranking scheme. These rankings provide a simple mechanism to highlight potential water security challenges, particularly when looking across the system performance and outcome categories.

3.3.3.2 Case study selection

To test the validity of this dashboard, we use Pakistan as a case study because its water security has been examined in several studies (Lautze and Manthrithilake, 2012; ADB, 2013, 2016; Young et al., 2019b). This literature gives us a way to validate our findings and test whether or not the dashboard is capable of correctly and accurately indicating key water security challenges. Four further case studies were conducted, and their dashboard printouts are in the Supplementary Information. The countries studied were Afghanistan, Turkmenistan, Uzbekistan, and Tajikistan. We selected these countries due to their geographical proximity to Pakistan to allow for regional cross-country comparisons.

3.4 Results

3.4.1 Pakistan case study

Management of the waters of the Indus Valley in what is now Pakistan has been a challenge for civilization since ancient times. Some attribute the fall of the Harappan civilization in around 1500 B.C., which had "a highly sophisticated system of water management and sanitation" (Strang, 2015), to a decrease in precipitation (Giosan et al., 2012). By the 19th century, "the Indus irrigation system became the largest contiguous irrigation system in the world" (Briscoe and Qamar, 2006). Management of this irrigation

scheme was complicated when Pakistan was partitioned from India in 1947 (Briscoe and Qamar, 2006). The Indus Water Treaty, signed in 1960, made great strides in the joint cooperation of the Indus (Briscoe and Qamar, 2006). However, there are continuing political tensions between the countries that threaten this cooperation (Ranjan, 2016; Williams, 2019). Over the years, there has been continued expansion of storage and channel infrastructure (Briscoe and Qamar, 2006). Large flooding still occurs along the Indus, with the 2010 floods claiming approximately 1,985 lives and causing 9.5 billion USD in economic damages (Guha-Sapir, 2019). Some future projections suggest that around 11 million people are expected to be at risk from fluvial flooding by 2044 (Willner et al., 2018).

Following the concise summary to provide context, a dashboard was generated based on the methodology described above. The result can be seen in Figure 3-2. The country has data available for the fifty out of fifty-two variables. Data were not reported for the amount of desalinated water produced or water reuse in terms of the direct use of treated wastewater. Also, no data is available for Pakistan's GDP projections (IMF, 2019). This dashboard, coupled with the brief historical summary above, is used to generate an initial or working diagnosis of water security for Pakistan. If trends are available, they are shown to the right of the related indicator. The highlighted indicators are in the 75th percentile based on the ranking system described above.

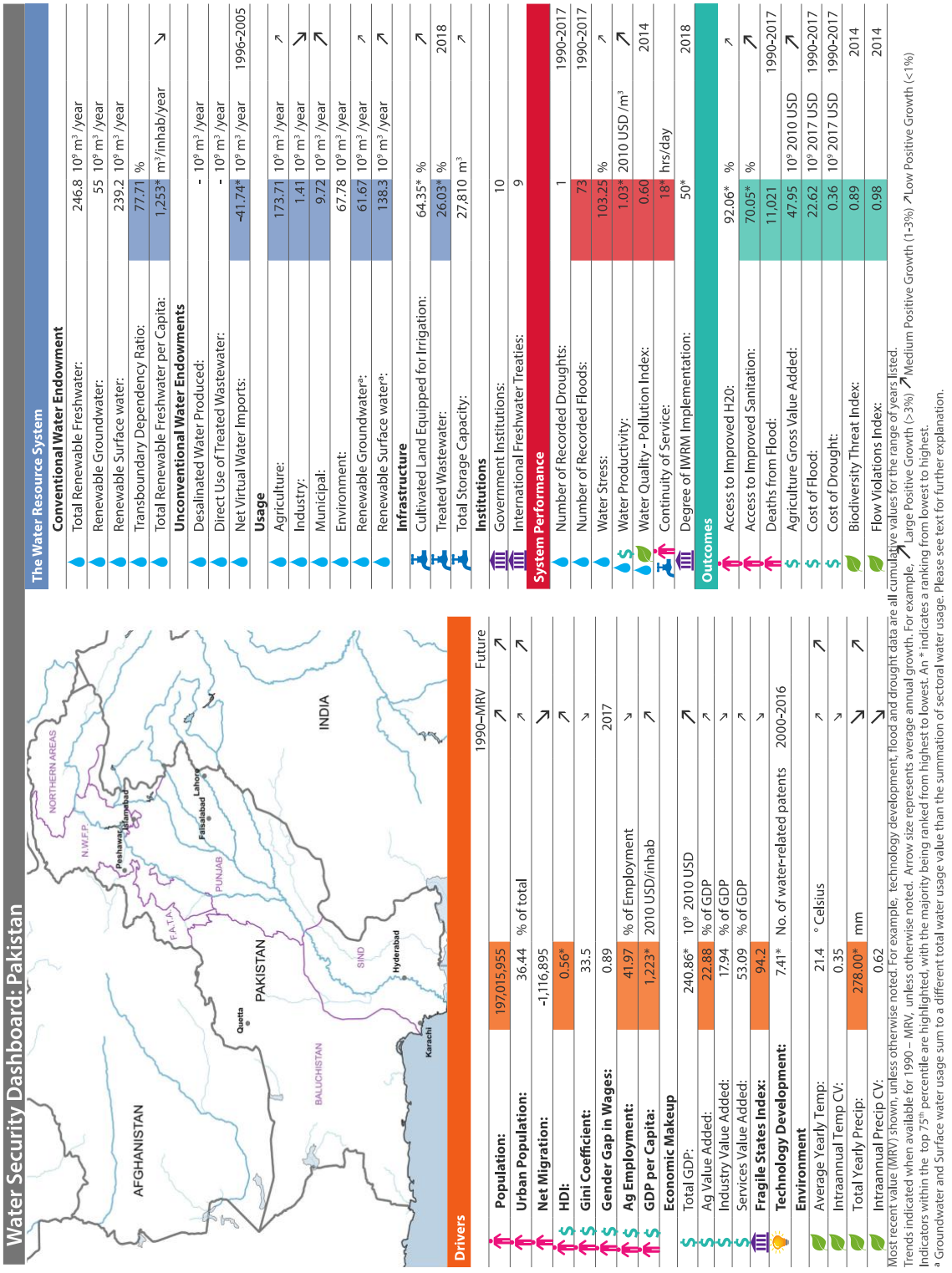


Figure 3-2: Water security dashboard for Pakistan

The dashboard in Figure 3-2 highlights several of Pakistan's water-related issues. First, looking at the Water Resource System section, we see that 78% of the country's water comes from outside the country. This transboundary dependency ratio is a

substantial proportion of the country's water, with the majority flowing into Pakistan from India. However, the Indus Water Treaty is in place and thus reduces the transboundary risk. The water stress in the country is 103%, signalling that Pakistan is either relying on non-renewable groundwater (since the amount is over 100%) or not leaving enough water for environmental flows. The latter is illustrated in the Outcomes section, with the high incidence of both biodiversity threats and environmental flow violations.

By looking at the socioeconomic drivers, we can see that the country has a large GDP and is expected to see an increase in population despite the large negative net migration rate. The urban population is expected to increase from 36% to over 50% by 2050. The municipal withdrawals have seen a rapid upward trend, which corresponds to the increase in population. The country's service sector has been growing. However, the industrial sector has shown a decline, and the agriculture sector still accounts for around 23% of the GDP and has remained relatively constant over the last 30 years. This signals an overall rise in economic output from agriculture since the percent of GDP from agriculture has remained relatively constant, but the GDP has grown. There has also been a steady rise in agriculture water withdrawals, with the most recent estimate being 94% of all withdrawals. On top of this, the country's total water productivity is extremely low, albeit improving. However, this improvement in total water productivity could be associated more with the large increase in GDP rather than water efficiency improvements. Finally, the agriculture sector accounts for 42% of employment within the country, but this has declined slightly since 1990.

Yearly precipitation has been declining over the last 30 years, while the annual mean temperature has been increasing. When looking from 1901 to 2017, temperature has exhibited an increasing trend and is expected to continue rising (World Bank CCKP, 2019). However, looking over this longer time period, precipitation has actually increased

slightly and is expected to continue to increase, although projections have high uncertainty. Regardless, by looking at current values, the country is trending towards an increase in water stress. Alone this is a cause for concern, but since water productivity is also low, it could be seen as an opportunity to strengthen productivity and efficiency improvements, such as in the agricultural sector.

There are two additional issues: access to improved sanitation and flooding. The country has comparatively low sanitation rates even though access has been improving over the last 17 years. Couple this with the low installed wastewater treatment (only 26% as of 2018), and the sanitation sector emerges as a key priority area for improvement. Yet, the country does have a higher rate of access to an improved drinking water source at 92%. In addition to sanitation issues, the country also has seasonal precipitation fluctuations and yearly flooding, with 73 floods occurring between 1990 and 2017. These floods have cost the economy around 20 billion USD over the last 30 years, with thousands of lives lost.

Finally, the dashboard is useful to not only highlight challenges, but also opportunities and strengths. As mentioned above, one opportunity for improvement is through increasing agricultural efficiency and or productivity. As far as strengths, the country appears to be performing poorly across the majority of outcome and system performance indicators. However, when taking into consideration the country's status as a Fragile State, Pakistan appears to be doing an acceptable job of water management in terms of their degree of IWRM implementation (when comparing to other countries).

3.4.2 Cross-country comparisons

The country dashboard also allows for cross-country comparisons. Four additional dashboard printouts for Afghanistan, Tajikistan, Turkmenistan, and

Uzbekistan can be found in Appendix A. Overall, the regional comparisons (Figure 3-3) show that these five countries have similar water security issues, but with varying intensities. All countries have high levels of water stress, with the majority of water going toward the agricultural sector. The highest water stress occurs in Turkmenistan at 199%. Turkmenistan also has the highest dependency ratio at 97%. Countries with a high dependency ratio and high water stress are particularly vulnerable to the joint management of transboundary water bodies. Turkmenistan and Uzbekistan have the lowest scores on the Fragile States Index (FSI) in the region, and both of these countries have the highest rates of access to improved drinking water and sanitation sources. Afghanistan has the highest FSI score out of the five countries, and the lowest rates of access to improved drinking water and sanitation services. The variations in these indicators across the five countries, as well as a world average, can be found in Figure 3-3.

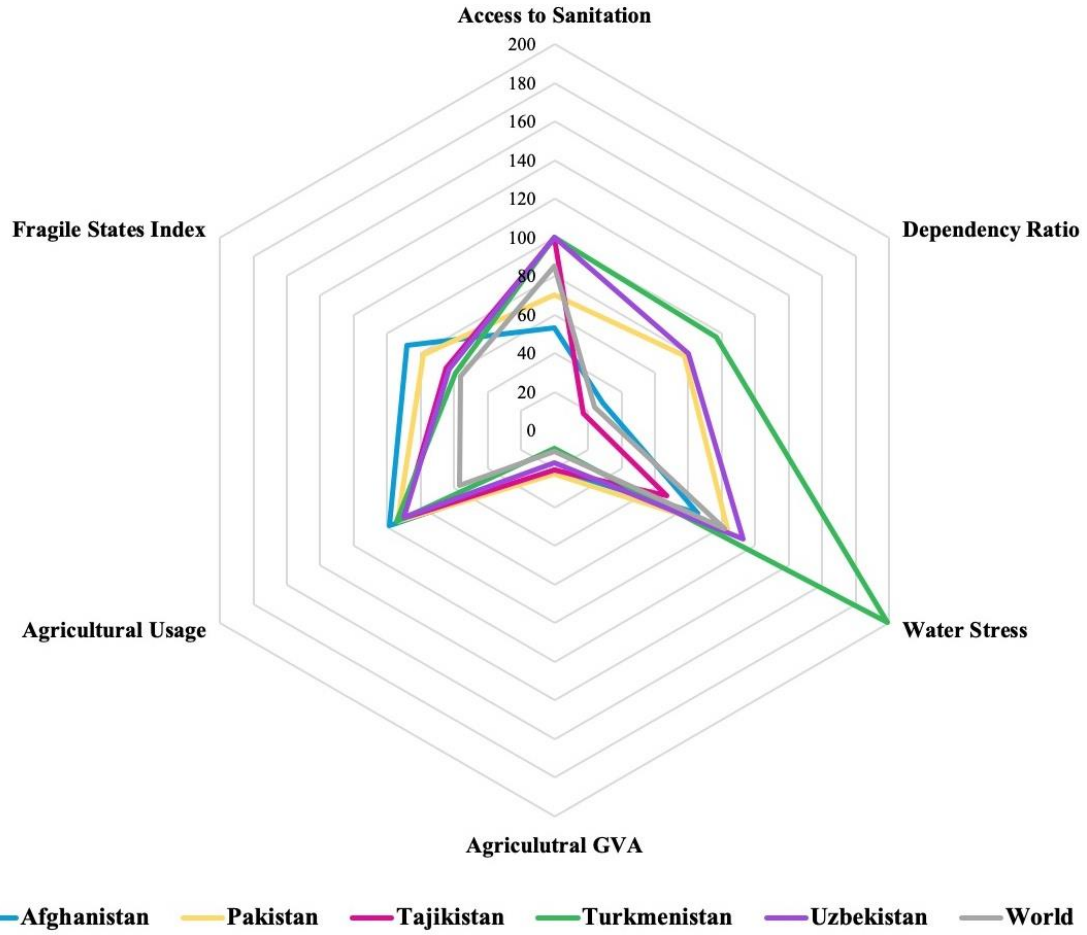


Figure 3-3: Variation of key water security indicators by country. Access to Sanitation refers to access to an improved sanitation source, FSI stands for Fragile States Index, Water Stress is calculated based on SDG 6.4.1, the Dependency Ratio refers to the percentage of renewable freshwater originating outside the country, Ag GVA stands for the agricultural gross value added, and Ag Usage stands for agricultural water usage. All indicators are in percentage. The FSI is taken as the percentage of the observed value out of the possible total score of 120.

The countries all face high seasonal variations in precipitation and have seen an increase in average yearly temperature since 1990. The rise in temperature is expected to continue. However, the degree of future change in the region's precipitation is uncertain. Given this high hydrological variability, several countries have issues with floods and droughts. Only Turkmenistan has no record of drought, based on the broad definition laid out by the EM-DAT database: "an extended period of extremely low precipitation…" (Guha-Sapir, 2019). Turkmenistan also only has one recorded flood since 1990, and Uzbekistan has only experienced one flood and one drought in the same time frame. In

addition, all countries have a biodiversity index over 0.6 (on a scale from 0-1), indicating an elevated threat to the countries' biodiversity.

3.5 Discussion

The Pakistan water security dashboard highlights the status, trends, and water challenges and strengths within the country. These findings correspond to the issues found in a recent World Bank report on the water security of Pakistan (Young et al., 2019b), but the report goes into much more depth including institutional and management structures, expands upon each of the challenges faced in Pakistan, and includes recommendations for enhancing water security. This dashboard could serve as a first step in the evaluation of a country's water security and potentially help to structure and direct a more comprehensive analytical study. The dashboard picks up on several additional items that other indicator-based assessments of water security have not exposed. Lautze and Manthrithilake (2012) do not include items such as water quality or economic outcomes. The ADB (2016) had similar findings, but did not specifically report on the water stress within a country. This is an essential piece of information that needs to be emphasized since the country's water stress is over 100%. The ADB (2016) also rates the water security of specific economic sectors on a scale from 1 to 5, with 5 being the best possible score. Pakistan receives a 3 in the agricultural economic category, equating to essentially average economic water security in the agricultural sector (ADB, 2016). The ADB (2016) agricultural score "describes the degree to which water is secured to enable agriculture in the country" and includes "water productivity in agriculture and self-sufficiency of agricultural production." When looking at the individual sector productivity calculated within our database for 2013, agricultural productivity was extremely low at \$0.25/m^3 and ranking 132nd out of 141 countries. It is hard to compare

these values since we are comparing a categorical value with a specific value, but it is interesting that the ADB (2016) scores Pakistan as average in agricultural water security when we find the country to have such low agricultural water productivity.

This dashboard differs from previous analyses of water security for three key reasons. First, it provides a quick assessment of water security that can be applied to all countries of the world based on a harmonized dataset. For example, a World Bank (2017) report is centred around the Middle East. The ADB (2013, 2016) studies focus on Southeast Asia. Second, two key global studies on water security do not incorporate all of the categories of information shown in the dashboard (Vörösmarty et al., 2010; Gain et al., 2016). For example, Gain et al. (2016) do not incorporate environmental uses of water or several potential drivers of water insecurity, such as population growth, climate change, and economic shifts. Whereas, Vörösmarty et al. (2010) do not incorporate economic outcomes. Third, this work expands upon a previous water security dashboard (van Ginkel et al., 2018), as we incorporate trends. Thus, our study incorporates additional information that is vital in understanding the totality of water security challenges and opportunities and can be applied across countries.

The dashboard is only the first step of the overall diagnostic methodology, and we are only able to arrive at a working diagnosis. From here, additional information would need to be gathered, and tests run to reach a final diagnosis by which to begin prescribing solutions. Based on the findings for Pakistan, we would recommend the following possible actions in the next diagnostic step. First, the inclusion of studies on the climate regime and how it will change in the future, including glacial melt in the Himalayas (e.g. Jury et al., 2020). Second, we recommend additional analysis of country water usage as well as a better understanding of the water balance, especially the significant surface-groundwater interactions (e.g. Foster and MacDonald, 2014). FAO

Aquastat (2019) estimates that in 2012, approximately 60 billion cubic meters of groundwater were withdrawn compared to the 55 billion cubic meters of renewable groundwater available. Much of the groundwater withdrawal is canal irrigation recharge, complicating the water balance (Young et al., 2019b). A discussion around these issues, as well as a basin and provincial groundwater balances, can be found in Young et al. (2019b). We also find that the agricultural sector accounts for 23% of the GVA and uses around 174 billion cubic meters of water per year, but a recent report shows that 58% of the agricultural GDP derives from livestock, which requires less blue water than crops (Young et al., 2019b). We also report a wastewater treatment rate of 26% (Wedling et al., 2018), which appears to be higher than other estimates (Young et al., 2019b). This difference could be due to the reported value in the dashboard being normalized by data on connectivity rates (Wedling et al., 2018). Also, there is no information reported on the reuse of treated wastewater. These items would need to be studied more in-depth to gain a better understanding of water usage impacts and productivity. In addition, the country has several hot-spots of potential water insecurity that are only expected to be exacerbated by climate change. The Indus delta is experiencing rapid biodiversity loss (Young et al., 2019b), and Karachi, one of the country's most populated cities, is at risk from rising sea levels (Dasgupta et al., 2011). Finally, anyone evaluating water security will need a thorough understanding of the political system and the institutional frameworks within the country, such as water service delivery and resource management (Mustafa, 2001). These items are by no means an exhaustive list, but they illustrate potential further steps in the diagnostic process.

The cross-country comparisons can help policymakers learn lessons from other countries while recognizing the differences that exist. They can also allow us to begin to recognize regional patterns like the ones seen above. For example, four out of five of the

countries have a declining contribution of the agricultural sector to overall GDP. However, this is not fully reflected in their water withdrawals, with over 90% of withdrawals in these countries going towards their agricultural sector, compared to a world average is 57% (Doeffinger and Hall, 2019). Like the example above, some patterns are more noticeable and highlight areas of concern, whereas other observations are more hypothetical in nature. For instance, we can observe that the fragile countries are exhibiting lower rates of access to improved sanitation.

3.5.1 Limitations

Given our focus on datasets that cover most countries, there are inevitable limitations. First, the specific indicators used may or may not be useful for each country. For example, indicators on drought may be more useful for Pakistan than Turkmenistan. Then there are issues with the underlying data. In terms of quality, there are obvious issues such as a country's renewable freshwater remaining constant since 1958, according to FAO Aquastat (2019). Thus, the dashboard has the potential to be improved by an increasing amount of new data being generated, such as data on water quality (Damania et al., 2019).

There is also the issue of actual data availability. Whilst we include metrics on institutions and their performance, we recognize that these are rather crude metrics of the quality of water governance, which is recognized as being fundamental to the sustainable management of water resources. The number of government institutions only provides basic context, but SDG Indicator 6.5.1, which specifically looks at the level of implementation of IWRM within a country, is a useful performance indicator. Once more data is collected on this indicator, trends could be included. We would also wish to include metrics for information availability, as good system monitoring is an essential

prerequisite for good governance. In addition, information on the affordability of water services is vital to the understanding of the ability of a country to meet its citizen's needs. This indicator is currently unavailable across the majority of countries, but an affordability indicator is under development (WHO/UNICEF, 2019). We were also unable to determine whether needs are truly met based on the current data. The drinking water use category outlined by Molle and Mollinga (2003) could be incorporated in future iterations of the dashboard as more disaggregated data becomes available on municipal usage. As we are unable to capture water needs in this version of the dashboard, we are also unable to distinguish between water needs versus water demands (Feitelson, 2012).

At this stage, the database underlying this dashboard is static, i.e. it is not linked to online databases such as FAO Aquastat (2019) or the World Bank Databank (2019). This means that the database does not capture the periodic updates of information from these sources. The dashboard also does not take into consideration any sub-national heterogeneity. This means that it does not pick up on any hotspots of water insecurity within a country. This is primarily due to the lack of data at smaller spatial scales, and the differences in reporting mechanisms and indicators across countries. This is an important area of future research as a multiscale analysis would offer a more accurate picture of a country's water security.

Finally, the current version of the dashboard does not show relationships between the indicators, whether they be causal or in the form of a feedback mechanism. The dashboard also does not include two out of the seven information categories of the framing in Section 3.3.1 (e.g. historical and cultural context and actions). Historical and cultural context is excluded due to its narrative format and country specificity. We do try and incorporate this information category through a brief historical and cultural narrative for the Pakistan case study, but acknowledge that this is not a full analysis. In the future,

a more robust historical analysis could be conducted in Step 2 of the diagnostic methodology. The action's category represents the actions available to a decision maker. These actions, whether they be an investment in information gathering or the investment in a new storage facility, represent a broad decision space, so this category does not lend itself to the dashboard format. This information would become available in the treatment stage of the methodology or Step 4. Thus, these two categories will have to be included in additional steps of the diagnostic methodology.

3.6 Conclusions

Combined with a general understanding of the water resources system within a country, the dashboard that we have proposed highlights key water security challenges and opportunities. We have found that the dashboard format can act as an initial diagnostic tool for the status and trends of water security in a country. The ability to rapidly generate the dashboard printout and evaluate it quickly also increases the usefulness of the tool. By conducting a case study in Pakistan, we were able to compare our dashboard to several other water security evaluations of the country. This allowed us to provide some validation of the robustness of the dashboard and its ability to provide information on country water security. It also allowed us to show its added value in terms of its comprehensiveness and its global replicability. By adding in trends, we can begin to understand how water security indicators have changed in relation to one another and could potentially change in the future. The comparative analysis across five countries also highlights several potential relationships that could be studied further. Additional comparative analyses have the potential to identify new patterns.

The application of the dashboard needs to be followed by additional data collection and analysis. Nonetheless, this dashboard could serve as the first step or an

introductory overview of country-level water security. The dashboard was generated at the country level and, due to a harmonized dataset, allows for cross-country comparisons. There is the potential for this dashboard to be applied at other scales, such as the city or district level. Yet, the actual indicators used may vary by scale as data and monitoring of drivers, the water resource system, system performance, and outcomes will vary by scale. For example, data on outcomes may be available at a smaller scale, but there could be issues with the downscaling of drivers or water resource system data.

The dashboard is designed for policymakers and water management practitioners and provides a quick and efficient way to rapidly assess and communicate a country's water security. We envision a version of this dashboard being incorporated into a global online database. This type of uptake would also improve the dashboard by linking the underlying database to the original data sources as well as allowing some level of interaction by the user. It could also help in structuring more in-depth analyses of a country's water security and could encourage early stakeholder engagement around water security issues.

APPENDIX A: SUPPLEMENTARY INFORMATION TO CHAPTER 3

Contents of this file

Supplementary Figures 3-1 to 3-4

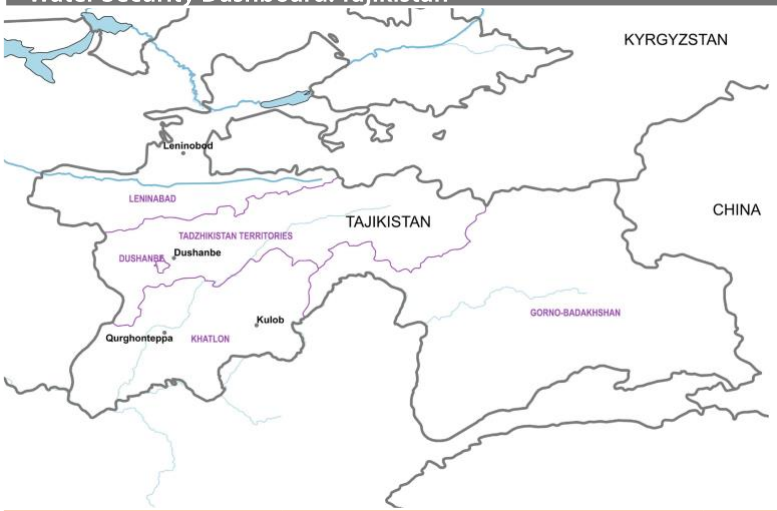
Introduction

Supplementary Figures 3-1 through 3-4 are additional dashboards created for Afghanistan, Tajikistan, Turkmenistan, and Uzbekistan. These figures were created using the data listed in Table 3-1 found in Chapter 3 of this thesis.

Supplementary Figure 3-1: Water security dashboard for Afghanistan

Supplementary Figure 3-2: Water security dashboard for Tajikistan

Water Security Dashboard: Tajikistan



Drivers

				1990–MRV	Future
	Population:	8,921,343		↗	↗
	Urban Population:	26.98	% of total	↘	↗
	Net Migration:	-99,999		↗	
$	**HDI:**	0.65*		↗	
$	**Gini Coefficient:**	34		↗	
$	**Gender Gap in Wages:**	-		2017	
$	**Ag Employment:**	51.28	% of Employment	↘	
$	**GDP per Capita:**	1,020.14*	2010 USD/inhab	↗	
	Economic Makeup				
$	Total GDP:	9.10*	10^9 2010 USD	↗	↗
$	Ag Value Added:	20.4	% of GDP	↘	
$	Industry Value Added:	27.24	% of GDP	↘	
$	Services Value Added:	42.26	% of GDP	↗	
	Technology Development:	126.31*	No. of water-related patents	2000-2016	
	Fragile States Index:	77.7		↘	
	Environment				
	Average Yearly Temp:	2.83	° Celsius	↗	↗
	Intraannual Temp CV:	3.37		↘	
	Total Yearly Precip:	488.6*	mm	↗	↘
	Intraannual Precip CV:	0.86		↗	

The Water Resource System

	Conventional Water Endowment			
	Total Renewable Freshwater:	21.91	10^9 m³ /year	
	Renewable Groundwater:	6	10^9 m³ /year	
	Renewable Surface water:	18.91	10^9 m³ /year	
	Transboundary Dependency Ratio:	17.34	%	
	Total Renewable Freshwater per Capita:	2,456*	m³/inhab/year	↘
	Unconventional Water Endowments			
	Desalinated Water Produced:	0	10^9 m³ /year	
	Direct Use of Treated Wastewater:	0	10^9 m³ /year	
	Net Virtual Water Imports:	-0.92*	10^9 m³ /year	1996-2005
	Usage			
	Agriculture:	9.58	10^9 m³ /year	↘
	Industry:	0.37	10^9 m³ /year	↘
	Municipal:	0.59	10^9 m³ /year	↗
	Environment:	6.23	10^9 m³ /year	
	Renewable Groundwater[a]:	0.53	10^9 m³ /year	↘
	Renewable Surface water[a]:	9.89	10^9 m³ /year	↗
	Infrastructure			
	Cultivated Land Equipped for Irrigation:	84.91*	%	↗
	Teated Wastewater:	58.85*	%	2018
	Total Storage Capacity:	29,500	m³	↗
	Institutions			
	Government Institutions:	8		
	International Freshwater Treaties:	12		

System Performance

	Number of Recorded Droughts:	2		1990-2017
	Number of Recorded Floods:	29		1990-2017
	Water Stress:	67.28	%	↘
$	Water Productivity	0.58*	2010 USD /m³	↗
	Water Quality - Pollution Index:	0.31		2014
	Continuity of Service:	21.95*	hrs/day	
	Degree of IWRM Implementation:	-		2018

Outcomes

	Access to Improved H20:	83.52*	%	↗
	Access to Improved Sanitation:	99.43*	%	↗
	Deaths from Flood:	1,612		1990-2017
$	Agriculture Gross Value Added:	1.72	10^9 2010 USD	↗
$	Cost of Flood:	0.97	10^9 2017 USD	1990-2017
$	Cost of Drought:	0.08	10^9 2017 USD	1990-2017
	Biodiversity Threat Index:	0.65		2014
	Flow Violations Index:	0.35		2014

Most recent value (MRV) shown, unless otherwise noted. For example, technology development, flood and drought data are all cumulative values for the range of years listed.
Trends indicated when available for 1990 – MRV, unless otherwise noted. Arrow size represents average annual growth. For example, ↗ Large Positive Growth (>3%) ↗ Medium Positive Growth (1-3%) ↗ Low Positive Growth (<1%)
Indicators within the top 75th percentile are highlighted, with the majority being ranked from highest to lowest. An * indicates a ranking from lowest to highest.
[a] Groundwater and Surface water usage sum to a different total water usage value than the summation of sectoral water usage. Please see text for further explanation.

Supplementary Figure 3-3: Water security dashboard for Turkmenistan

Water Security Dashboard: Turkmenistan



Drivers

				1990–MRV	Future
	Population:	5,758,075		↗	↗
	Urban Population:	51.15	% of total	↗	↗
	Net Migration:	-25,001		↘	
$	**HDI:**	0.71*		↗	
$	**Gini Coefficient:**	40.8			
$	**Gender Gap in Wages:**	-		2017	
$	**Ag Employment:**	22.94	% of Employment	↘	
$	**GDP per Capita:**	7,317.55*	010 USD/inhab	↗	
	Economic Makeup				
$	Total GDP:	42.13*	10^9 2010 USD	↗	↗
$	Ag Value Added:	9.30	% of GDP	↘	
$	Industry Value Added:	56.97	% of GDP	↗	
$	Services Value Added:	28.14	% of GDP	↗	
	Fragile States Index:	71.4		↘	
	Technology Development:	151.51*	No. of water-related patents	2000-2016	
	Environment				
	Average Yearly Temp:	16.31	° Celsius	↗	↗
	Intraannual Temp CV:	0.66		↘	
	Total Yearly Precip:	141.6*	mm	↗	↘
	Intraannual Precip CV:	0.88		↗	

The Water Resource System

	Conventional Water Endowment			
	Total Renewable Freshwater:	24.77	10^9 m^3 /year	
	Reneable Groundwater:	0.41	10^9 m^3 /year	
	Renewable Surface water:	24.36	10^9 m^3 /year	
	Transboundary Dependency Ratio:	97	%	
	Total Renewable Freshwater per Capita:	4,302*	m^3/inhab/year	↘
	Unconventional Water Endowments			
	Desalinated Water Produced:	0	10^9 m^3 /year	
	Direct Use of Treated Wastewater:	-	10^9 m^3 /year	
	Net Virtual Water Imports:	-3.05*	10^9 m^3 /year	1996-2005
	Usage			
	Agriculture:	32.09	10^9 m^3 /year	↗
	Industry:	1.02	10^9 m^3 /year	↗
	Municipal:	0.92	10^9 m^3 /year	↗
	Environment:	7.65	10^9 m^3 /year	
	Renewable Groundwater[a]:	0.31	10^9 m^3 /year	
	Renewable Surface water[a]:	27.56	10^9 m^3 /year	
	Infrastructure			
	Cultivated Land Equipped for Irrigation:	94.81*	%	↘
	Treated Wastewater:	74.79*	%	2018
	Total Storage Capacity:	6,220	m^3	↗
	Institutions			
	Government Institutions:	5		
	International Freshwater Treaties:	7		

System Performance

	Number of Recorded Droughts:	0		1990-2017
	Number of Recorded Floods:	1		1990-2017
	Water Stress:	198.77	%	↗
$	Water Productivity:	0.60*	2010 USD /m^3	↗
	Water Quality - Pollution Index:	0.55		2014
	Continuity of Service:	-	hrs/day	
	Degree of IWRM Implementation:	-		2018

Outcomes

	Access to Improved H20:	100*	%	↗
	Access to Improved Sanitation:	99.97*	%	↗
	Deaths from Flood:	0		1990-2017
$	Agriculture Gross Value Added:	2.56	10^9 2010 USD	
$	Cost of Flood:	0.17	10^9 2017 USD	1990-2017
$	Cost of Drought:	-	10^9 2017 USD	1990-2017
	Biodiversity Threat Index:	0.66		2014
	Flow Violations Index:	0.10		2014

Most recent value (MRV) shown, unless otherwise noted. For example, technology development, flood and drought data are all cumulative values for the range of years listed.
Trends indicated when available for 1990 – MRV, unless otherwise noted. Arrow size represents average annual growth. For example, ↗ Large Positive Growth (>3%) ↗ Medium Positive Growth (1-3%) ↗ Low Positive Growth (<1%)
Indicators within the top 75th percentile are highlighted, with the majority being ranked from highest to lowest. An * indicates a ranking from lowest to highest.
[a] Groundwater and Surface water usage sum to a different total water usage value than the summation of sectoral water usage. Please see text for further explanation.

Supplementary Figure 3-4: Water security dashboard for Uzbekistan

Water Security Dashboard: Uzbekistan



Drivers

				1990–MRV	Future
	Population:	32,387,200		↗	↗
	Urban Population:	50.55	% of total	↗	↗
	Net Migration:	-44,314		↗	
$	**HDI:**	0.71*		↗	
$	**Gini Coefficient:**	35.3		↘	
$	**Gender Gap in Wages:**	-		2017	
$	**Ag Employment:**	33.52	% of Employment	↘	
$	**GDP per Capita:**	2,031.05*	2010 USD/inhab	↗	
	Economic Makeup				
$	Total GDP:	65.78*	10^9 2010 USD	↗	↗
$	Ag Value Added:	16.98	% of GDP	↘	
$	Industry Value Added:	29.47	% of GDP	↘	
$	Services Value Added:	39.85	% of GDP	↗	
	Fragile States Index:	75.7		↘	
	Technology Development:	177.86*	No. of water-related patents	2000-2016	
	Environment				
	Average Yearly Temp:	13.27	° Celsius	↗	↗
	Intraannual Temp CV:	0.87		↘	
	Total Yearly Precip:	197.2*	mm	↘	-
	Intraannual Precip CV:	0.76		↗	

The Water Resource System

	Conventional Water Endowment			
	Total Renewable Freshwater:	48.87	10^9 m^3 /year	
	Renewable Groundwater:	8.8	10^9 m^3 /year	
	Renewable Surface water:	42.07	10^9 m^3 /year	
	Transboundary Dependency Ratio:	80.07	%	
	Total Renewable Freshwater per Capita:	1,509*	m^3/inhab/year	↘
	Unconventional Water Endowments			
	Desalinated Water Produced:	-	10^9 m^3 /year	
	Direct Use of Treated Wastewater:	-	10^9 m^3 /year	
	Net Virtual Water Imports:	-10.23*	10^9 m^3 /year	1996-2005
	Usage			
	Agriculture:	42.16	10^9 m^3 /year	↘
	Industry:	1.25	10^9 m^3 /year	↘
	Municipal:	3.43	10^9 m^3 /year	↗
	Environment:	13.46	10^9 m^3 /year	
	Renewable Groundwater[a]:	0.49	10^9 m^3 /year	↘
	Renewable Surface water[a]:	58.41	10^9 m^3 /year	↗
	Infrastructure			
	Cultivated Land Equipped for Irrigation:	90.29*	%	↗
	Treated Wastewater:	0*	%	2018
	Total Storage Capacity:	22,160	m^3	-
	Institutions			
	Government Institutions:	4		
	International Freshwater Treaties:	20		

System Performance

	Number of Recorded Droughts:	1		1990-2017
	Number of Recorded Floods:	1		1990-2017
	Water Stress:	112.96	%	↘
$	Water Productivity:	0.97*	2010 USD /m^3	↗
	Water Quality - Pollution Index:	0.48		2014
	Continuity of Service:	21.30*	hrs/day	
	Degree of IWRM Implementation:	45*		2018

Outcomes

	Access to Improved H20:	97.83*	%	↗
	Access to Improved Sanitation:	100*	%	↗
	Deaths from Flood:	0		1990-2017
$	Agriculture Gross Value Added:	10.44	10^9 2010 USD	↗
$	Cost of Flood:	-	10^9 2017 USD	1990-2017
$	Cost of Drought:	0.07	10^9 2017 USD	1990-2017
	Biodiversity Threat Index:	0.71		2014
	Flow Violations Index:	0.48		2014

Most recent value (MRV) shown, unless otherwise noted. For example, technology development, flood and drought data are all cumulative values for the range of years listed.
Trends indicated when available for 1990 – MRV, unless otherwise noted. Arrow size represents average annual growth. For example, ↗ Large Positive Growth (>3%) ↗ Medium Positive Growth (1-3%) ↗ Low Positive Growth (<1%)
Indicators within the top 75th percentile are highlighted, with the majority being ranked from highest to lowest. An * indicates a ranking from lowest to highest.
[a] Groundwater and Surface water usage sum to a different total water usage value than the summation of sectoral water usage. Please see text for further explanation.

4 ASSESSING WATER SECURITY ACROSS SCALES: A CASE STUDY OF THE UNITED STATES

Abstract: Water security is a multi-dimensional concept that varies across spatial scales. However, evaluations tend to focus on a single scale, which can be problematic. For example, many national water security assessments have been questioned due to their inability to account for sub-national heterogeneity. We have identified four considerations encountered when selecting a scale in water security analyses: (1) the natural scale of phenomena, (2) the scale of data availability, (3) the decision-making scale, and (4) questions of precision versus accuracy. To explore these considerations and conduct a multiscale analysis, we have created a water security index, which is comprised of ten sub-indicators focused on system performance and outcomes. These sub-indicators are assembled across three scales: the United States of America and its constituent states and counties. A tiered multiscale analysis was difficult for several reasons, not least because of the challenges of obtaining requisite data. Nonetheless, the multiscale analysis has proved to be worthwhile by exposing clusters of water insecurity within the United States both at the state and county levels that would otherwise be obscured. Combining the sub-national indicators with a more comprehensive national assessment can support decision-making in terms of prioritization of policies and investments to target hotspots of water insecurity.

4.1 Introduction

4.1.1 Water security and scale

Water security was originally used in the early 1990s as a way to discuss concerns of water scarcity and its effects on national security (Starr, 1991). It has since been expanded to become an all-encompassing concept of water-related concerns. This conceptual breadth is illustrated by its many different definitions and the scope of several definitions (Cook and Bakker, 2012). For example, one well-known definition simply, and very generally, describes water security as "a tolerable level of water-related risk to society" (Grey et al., 2013). This definition could be interpreted as the risk a farmer faces when confronted with drought, the risk a city may face from climate induced sea-level rise, or the risk a nation may face when dealing with systemic issues of water services provision. Each of these situations may be addressed by decision maker(s) across various spatial and temporal scales.

Given this conceptual ambiguity, the first and most fundamental question of any security analysis is "security for whom?" (Baldwin, 1997). The definition above is not alone in leaving this fundamental question open-ended, with several other water security definitions doing the same (UN, 2000; Grey and Sadoff, 2007; UN Water, 2013). This is useful in the sense that the concept can be applied to different actors across scales, but also leads to the concept repeatedly being framed and evaluated in numerous ways, often with no heed paid to potential cross-scale linkages or the masking of spatial heterogeneity.

The majority of evaluations of water security in the literature are applied to a single scale of analysis. These include the household (Kujinga et al., 2014); rural (Norman et al., 2013); urban (van Ginkel et al., 2018); country (Lautze and

Manthrithilake, 2012); regional (Cashman, 2014); river basin (Petersen-Perlman et al., 2012); or global scale (Vörösmarty et al., 2010). The country was found to be a routinely used scale in two different concept reviews of water security (Cook and Bakker, 2012; Gerlak et al., 2018), and there have been several country-level and multi-country reports generated (World Bank, 2017, 2018a). However, finer resolution studies have shown how water security can vary within a country (Vörösmarty et al., 2010; Gain et al., 2016). For example, in one report, Australia is listed as one of the most water secure regions in Southeast Asia (ADB, 2016). However, the map created in Vörösmarty et al. (2010) shows areas on the East coast of Australia that have both a high incidence of human and biodiversity threats to water security.

Given the different and sometimes conflicting messages that are yielded by assessments at different spatial scales, there has been a call in the literature (Cook and Bakker, 2012; Wheater and Gober, 2013) and across the policy discourse (GWSP, 2013) for the formation of multiscale water security analyses. For example, Cook and Bakker (2012) go so far as to say that "a true picture of country water security requires assessment at multiple scales – from the local to the national – for both human and ecosystem needs." Despite this need, there are hardly any multiscale studies in existence. The seminal assessment by Sadoff et al. (2015) for the Global Water Partnership and the OECD looked at water security across different scales, but did not conduct a tiered analysis of a single location. Rather this was an evaluation of multiple unrelated basins, cities, and aquifers (Sadoff et al., 2015). Young et al. (2019b) conducted a country-level diagnostic assessment of Pakistan's water security. This study includes data and discussion primarily at the country and province level, but also touches on basins, the Indus delta, and cities such as Karachi (Young et al., 2019b). However, Young et al. (2019b) do not provide a systematic methodology to compare the overall water security between areas.

Finally, the Asian Development Bank's (ADB) (2013, 2016) studies do incorporate sub-indicators on household and urban water security. Nonetheless, these indices are also not comparable, as they use different sub-indicators.

Even though multiscale assessments are not yet prevalent within the water security literature, there have been attempts in other social science fields, such as vulnerability studies (McLaughlin and Cooper, 2010; Huynh and Stringer, 2018) and adaptive capacity (Vincent, 2007; Marzi et al., 2018). In each of these domains, the authors used a composite indicator at multiple scales. However, the majority of studies used different indicators at each scale of analysis, with one study going so far as to say that "it is not meaningful to transfer one index across scales" (Vincent, 2007). Given these examples of multiscale studies within the social sciences and the lack in the water security literature, is a tiered analysis possible? To begin our exploration of this question, we examine some of the challenges associated with a multiscale water security assessment.

4.1.2 Spatial scaling difficulties in water security studies

The concept of water security is not constrained by spatial scale, so it needs to be defined for each analysis. The scale of analysis can range from the individual to global. We have discussed how larger country or regional water security analyses can obscure spatial heterogeneity, potentially devaluing their validity. Yet, there are tradeoffs with the use of finer scales of analysis. Difficulties in selecting a scale of analysis are not solely an issue of water security studies, as spatial scaling issues have been discussed in the broader natural and social sciences (Gibson et al., 2000). We summarize the difficulties that arise from the selection of a spatial scale into four primary considerations that are

further elaborated upon below: (1) the natural scale of the phenomenon, (2) the scale of data availability, (3) the discussion-making scale, and (4) precision versus accuracy.

(**1**) Water security encompasses a range of phenomena in coupled human and natural systems. The conceptualization of these phenomena is subjective and can include nested processes (Montello, 2001), but examining the literature, we observe recurrent units of assessment, which suggest that at least some of these phenomena have a 'natural scale.' Examples include river basins as the natural scale at which to analyse and manage water resources (Garrick and Hall, 2014), and the individual or household as being natural scales at which to analyse the human dimension of water security (Jepson et al., 2017b). Although, each of these are ambiguously defined and contested, such as social processes being more precisely bound by political jurisdictions (Gibson et al., 2000). In addition, water security is affected by large scale processes such as climate change (Wheater and Gober, 2013). There are also changing land uses, economic transitions, and population dynamics that can occur across scales (Wheater and Gober, 2013). Monitoring of infrastructure used to manage water systems typically occurs at a national or local level (Garrick and Hall, 2014), and institutional monitoring at the local, river basin, or national levels (Grey et al., 2013). Outcomes in terms of people, the economy, and the environment occur and are monitored across scales. As such, they can be measured differently or manipulated for a desired purpose. For example, if a dam may not have a desired economic outcome for a locale, one could change the scale of analysis and show that in terms of the river basin at large, it could be economically feasible (Reisner, 1987). This manipulation of scale touches on how phenomenon can be a part of a hierarchy, such as a "constitutive hierarchy" relating to a population that makes up a city that then makes up a country (Gibson et al., 2000). This nesting of phenomena increases the complexity

of water security and contributes to the already existing tension between the scales of the underlying phenomena of water security.

(2) Obtaining data to describe and, where appropriate, quantify phenomena of interest is a perennial challenge in water security studies. This is one of the main reasons why multiscale studies are rare (Watson, 1978). Ideally, we would like to examine local heterogeneity, but data is seldom available. Thus, studies have tended to be dictated by the scale of data availability (Montello, 2001). First, data may not be available. For example, the data on the affordability or reliability of water services may not be reported or may not be publicly accessible. Then there is data that is not available for the desired scale. One is then left with the choice of switching scales, limiting the analysis to match the available data, or manipulating the data for the desired scale. In terms of manipulation, data can either be downscaled or upscaled, but both come with flaws. For example, climate patterns can be downscaled to the community level, but each stepwise disaggregation carries increasing uncertainty (Wheater and Gober, 2013). Additionally, certain observed local phenomena may not be replicable across scales (Meentemeyer, 1989; Meyer et al., 1995). For example, a recent review of household water security found that current metrics have low replicability across cultures or regions (Jepson et al., 2017b).

(3) Water security studies are often used to inform decision-making. Therefore, the evidence that is provided by a water security assessment should ideally map onto the scale of decision-making. Decisions include investments in both soft and hard infrastructures, which typically occur at the local or national levels (Garrick and Hall, 2014). Decision-making could involve changes to institutional governance and capacity that could occur at the local, river basin, national, or international levels (Grey et al., 2013). Water security decisions can also occur at an individual or household level. A

household may have to weigh the options of where to obtain their drinking water or whether to incorporate drought-tolerant agriculture.

(4) The final consideration over-arches the phenomenon, data, and decision-making considerations: the tradeoff between precision versus accuracy. Given the tendency for larger levels of analysis to obscure finer variability, the assumption may be that the finer the resolution, the better. However, using a finer resolution or higher precision may, in fact, be detrimental (Goodchild, 1995). This is primarily due to the lack of accuracy that may come along with increased precision as one moves away from the scale of the phenomenon (Montello, 2001). For example, if looking at the individual or household, the large-scale process of climate change would have to be significantly downscaled to fit this level of aggregation. Hydrological data would also have to be considerably downscaled. Ultimately, it may be more beneficial to study a coarser resolution or limit a case study to a single dimension, to preserve accuracy. However, this may also conflict with the scale of decision-making and be limited by the scale of data availability.

Each of these considerations is encountered when selecting a scale of analysis for any water security study. The considerations raised in (2) and (4) are especially evident within a multiscale analysis. For example, indicators no longer need to be available for a single scale, but multiple scales. Indicators may not be available for a given scale, limiting the scope of the study. The issue with precision versus accuracy is also significant since there is bound to be a tradeoff between them across each scale. Finally, a specific issue with multiscale analyses is the comparability of data. If the primary goal is to conduct a hierarchical analysis that is comparable across scales, indicators should focus on the same underlying data and be broad enough that they can be replicable across scales. Yet, drivers of change may vary based on scale, as well as the effects of certain large scale

dynamics, due to their non-linear propagation across scales (van Der Zaag and Gupta, 2008). So, all indicators cannot be assumed to be replicable across scales.

Given these issues, how does one systematically conduct a multiscale analysis that is comparable across scales? In this study, we create a systematic process to study water security across scales and is therefore novel in its intent. To do so, we propose the use of a composite indicator, as it allows for the comparison of multiple dimensions of water security and since it has been used in previous multiscale assessments on vulnerability (McLaughlin and Cooper, 2010; Huynh and Stringer, 2018) and adaptive capacity (Vincent, 2007; Marzi et al., 2018). Our primary objective is a tiered comparison across scales, and thus we are limited to data that can be extracted at multiple scales. Therefore, the water security index is based on ten sub-indicators comprised of both performance and outcome related data. Due to data availability, we use the United States of America (USA) as our case study. These indicators are amassed for the USA and its constituent states and counties. The final composite index is only generated at the county and state scales and is not replicable across other countries due to data availability. Thus, it does not allow for cross-country comparisons. However, by systematically evaluating water insecurity across two sub-national scales, it does allow for a tiered analysis of water security across administrative boundaries. Even though the exact indicators may be subject to data availability, the overall methodology can be adapted to a given nation. Therefore, this method will be useful for policymakers as a way to focus resources on areas of water insecurity.

The following section focuses on the methodology for the creation of the water security index. The results are then presented, with the composite index being mapped at the state and county scales. We then discuss the results and what we have learned from this multiscale assessment. This is followed by concluding remarks.

4.2 Methodology

The first step in the methodology is to describe the water security framing that serves as the basis for the composite indicator. We then discuss our choice of case study. The framing and decision of scale lead to the identification of ten separate indicators focused on system performance and outcomes. These indicators are amassed for the USA and its constituent states and counties. We then discuss how these indicators were normalized, aggregated, and weighted to create the overall composite index.

4.2.1 Framing for the composite index

The underlying framing is one of the most critical factors in the creation of a composite indicator (OECD, 2008; Huang et al., 2015). During a review of urban sustainability indices, there were several frameworks used: "Pressure-State-Response" (PSR), "theme-oriented," and "material and energy flow" (Huang et al., 2015). After review, the authors recommended a PSR or themed-based framing (Huang et al., 2015). Thus, we chose to focus on a multi-dimensional or theme-based framing of water security that was created by Doeffinger et al. (2020). This framing builds upon previous work by Briscoe (2009). The framing consists of "seven categories of information" that are vital to the understanding and evaluation of water security: "(1) drivers, (2) historical and cultural context, (3) the water resource system, (4) system performance, (5) outcomes, (6) actions, and (7) trends" (Doeffinger et al., 2020). Of these seven categories, the index is comprised of only two: system performance and outcomes. These two categories were selected as they indicate the status of water security. Whereas, the other categories either indicate how water security may change in the future, provide context, detail the current status of the resource system, or examine potential intervention decisions (Doeffinger et al., 2020). Also, several notable composite indicators focus either on process-based or

outcome-based indicators (Jacobs et al., 2004). In this case, system performance indicators speak to whether water is being managed constructively, and outcomes relate whether water-related risks have been mitigated or if water security has been achieved.

System performance covers both the resource as well as the infrastructure and institutions that are already in place (Doeffinger et al., 2020). In terms of the water resource, indicators could include sustainability of use, overall quality, productivity, and efficiency. Each of these indicators has the potential to affect other water-related indicators. For example, poor water quality can affect the amount of water available in a system and relates to outcomes in terms of people, the economy, and the environment. Infrastructure and institutional performance are also important and could include the deterioration of infrastructure as well as future needs. It also entails understanding the current institutional capacity and effectiveness. Here, outcomes keep with the triple bottom line definition of sustainability and focus on people, the economy, and the environment (Doeffinger et al., 2020). Outcomes in terms of people primarily revolve around their experience with water services as well as impacts from water-related shocks. The economy is also susceptible to water-related shocks, and there can also be economic losses due to issues with poor services. Finally, the environment can be affected in terms of single species deterioration or overall ecosystem loss.

4.2.2 Case study selection

The USA is used as a case study to illustrate the spatial variability of water security. This is done for two primary reasons, first, due to the availability and access to data across reporting scales. Second, the USA is a vast country with known spatial heterogeneity for several water security indicators. When looking at the country as a whole, it does not appear to exhibit any acute signs of water insecurity, such as a lack of

access to improved drinking water sources (WHO/UNICEF, 2019), high vales of water stress (FAO Aquastat, 2019), or a national issue with pollution (Sadoff et al., 2015). However, the country, as a whole, is subject to frequent flood events that are both costly in terms of dollars and loss of life (Guha-Sapir, 2019). There is also evidence of specific water security challenges: rising seas in Miami (Wdowinski et al., 2016), water stress in the Southwest (Wada and Bierkens, 2014), and groundwater reduction across the Great Plains (Steward and Allen, 2016). These sub-national issues are obscured when conducting a country analysis.

There are many scales available for analysis in the USA, with system performance and outcomes typically reported based on administrative boundaries. The main administrative boundaries used in the USA are as follows (ordered from coarsest to finest resolution): country, states, counties (including parishes and independent cities in Virginia), census tracts, and households. The institutional and infrastructure performance data are primarily aggregated and reported at the state and county levels. Even though hydrological data is situated to the river basin (Garrick and Hall, 2014), in the USA, data on water withdrawals are reported at the county level (Dieter et al., 2018a), and data on quality is reported at the county and state level (EPA, 2013, 2020a). Outcomes can be reported across all of the administrative boundaries listed above. Ultimately, we chose to assemble indicators at the country, state, and county levels as they are representative across the majority of indicator types and allow for a tiered analysis.

4.2.3 Indicator selection

The data selection was driven by the need to have similar indicators across both the county and state scales for comparisons. The study was limited by the county scale, with more data being available at the state level. All data for the country, state, and county

scales are from the same source, except for impaired stream/river length. All data, except for the number of aquatic species of conservation concern, are publicly available, and references can be found in Table 4-1. The data fall between 2004 – 2018, with the most recent year of data availability being used for each indicator. Finally, the number of drought deaths is not included within this index as there were none reported within the USA during the time period. Each indicator is described in detail below, along with each of their respective limitations.

Table 4-1: Indicators and their sources

Dimension	Indicator	Unit	Timeframe	Source
Systems Performance				
Sustainability of Usage	Water Stress	%	2014	WRI Aqueduct, 2019
Water Quality	Impaired Stream/River Length*	%	2004 - 2010	EPA, 2013
Productivity	Agricultural Water Productivity	2019 USD/m^3	2015	Dieter et al., 2018a; BEA, 2019; USDA, 2019b
Infrastructure	Wastewater Investment Need	2019 USD	2012	EPA, 2012a
Institutions	CWS Not in Compliance	%	2018	EPA, 2020a
Outcomes				
People				
Service	Lacking Complete Plumbing	%	2017	ACS, 2020
Floods	Flood Deaths	-	2008 - 2018	NOAA, 2020
Economy				
Floods	Flood Damages	2019 USD	2008 - 2018	NOAA, 2020
Droughts	Drought Damages	2019 USD	2008 - 2018	USDA RMA, 2019
Environment				
Biodiversity	Aquatic Species of Conservation Concern	-	2019	NatureServe, 2019a

* State data is from EPA, 2020b

Water stress was used as an indicator of the sustainability of water usage and was gathered from the World Resources Institute's (WRI) Aqueduct (2019) database. It is calculated as the total gross water withdrawals divided by the total water available minus the net water withdrawals (Hofste et al., 2019). It is reported at the sub-basin level. So, it is aggregated to the country and state levels and separately disaggregated to the county level for this analysis through weighted averaging. There are several drawbacks to this data: it does not account for environmental flows, there are negative water stress values (which were changed to zeros), and there are several areas deemed "arid and low water use regions" that are given a value of 100% stress (Hofste et al., 2019). There is also the issue with data aggregation. Since the data is calculated at the sub-basin scale, it has already been downscaled from the original united of measure, the river basin. Thus, the accuracy of this metric will become more uncertain with each change of the

aggregation level. Therefore, the county, state, and USA data should be viewed as approximations. Given these limitations, it is one of the only water stress indicators available that allows for the spatial aggregation needed. Several alternatives were considered (Averyt et al., 2011; Shi et al., 2013), but due to data availability and ease of access, they were not used.

Water quality is approximated by looking at the **percentage of impaired stream/river length**. The country and state indicators were calculated by dividing the assessed stream/river length deemed as 'impaired' by the total assessed stream/river length. Data was collected from the EPA Water Quality Assessment (EPA, 2020b). The most recent value is used for each state over a time period of 2004 – 2010 (except for Maryland, which uses 2012). This time period was chosen as this state data was downscaled to calculate the county value along with additional data sources (EPA, 2013, 2014). This indicator has several weaknesses starting with the use of two different sources of data, as seen in Table 4-1. Another key issue is that it only takes into account the length of streams or rivers assessed within the state, which varies by state. For example, Texas only assessed 12.3% of their 191,228 miles of streams/rivers in 2010, whereas New Hampshire assessed 100% or 16,896 miles of its streams/rivers (EPA, 2020b). Then there is the term 'impaired.' The source does not explicitly define the term and states that a stream/river is labelled 'impaired' "if any one of its assessed uses is not met" (EPA, 2020b). Both of these issues make it hard to compare values across states. However, this metric looks at the impaired stream/river length across several different potential usage categories, such as drinking water, recreation, and wildlife (EPA, 2020b). This makes it a comprehensive measure of quality as it does not merely focus on the quality of drinking water.

We solely focused on **agricultural water productivity** as an overall proxy for productivity due to data limitations. Productivity can be described as "the ratio of output to total input" and can be measured in terms of economic output for a given amount of water ($/m^3) (Doeffinger and Hall, 2020). The value was calculated using Equations (1-2), which are adapted from the UN SDG 6.4.1 on water-use efficiency (FAO, 2019b).

$$A_{wp} = \frac{GDP_f \times (1 - C_r)}{V_a} \quad (1)$$

where:

Awp = Irrigated Agricultural Water Productivity

GDP_f = Gross domestic product from farms

C_r = Proportion of farms GDP produced by rainfed agriculture

V_a = Volume of water used by the agricultural sector (m^3)

$$C_r = \frac{1}{1 + \left(\frac{A_i}{(1 - A_i) * .375}\right)} \quad (2)$$

where:

A_i = Proportion of irrigated land to total cropland

.375 = Generic default ratio between rain and irrigated yields

Water withdrawal data is sourced from the United States Geological Survey (Dieter et al., 2018a) and reported on at the county level. The most recent water withdrawal data is from 2015, so productivity was calculated for this year. Agricultural water withdrawal data comprises the following uses: total irrigation, livestock, and aquaculture (Dieter et al., 2018b). Total irrigation is a combination of crop irrigation and irrigation for golf courses. The following 14 states do not separate the two values (crops vs. golf courses): Arkansas, Hawaii, Louisiana, Mississippi, Missouri, Montana, Nebraska, New Jersey, North Dakota, Oklahoma, South Dakota, Texas, Wisconsin, and Wyoming. So, productivity values for these states and their counties may be underestimated. Data for

the country, state, and county farms GDP come from the US Bureau of Economic Analysis (BEA) (2019). Farms GDP is reported at the country and state level, but county values had to be calculated. The proportion of irrigated land in 2015 is estimated through interpolation or extrapolation of USDA data from 2007 through 2017 (USDA, 2019b). This value was calculated by taking the total irrigated area divided by the total cropland. This is not a perfect metric, but data was limited by the county scale. There are some gaps in the county data, as not all areas were provided "to avoid disclosure of confidential information" (BEA, 2019; USDA, 2019b). As a result, the agricultural productivity indicator is only available for 2,834 counties.

The **wastewater infrastructure investment need** is calculated over a 20-year future time period and is used as an indicator of infrastructure performance. This value is collected by facilities at the county level and aggregated to generate state and country values, with higher values indicating lower infrastructure performance. The data comes from the 2012 Clean Watersheds Need Survey (EPA, 2012a) and is converted from 2012 USD to 2019 USD. The needs survey includes both short term and long term infrastructure needs indicated by each facility for two main categories: (1) "wastewater treatment and collection" and (2) "wet-weather management" (EPA, 2012b). A small caveat, South Carolina, did not participate in the 2012 survey, so data for this state and its counties are gathered from the 2008 survey. Data is available for 2,483 counties. The counties reporting no value could have done so for three reasons: (1) have no need, i.e. a value of zero; (2) have not reported a need; (3) submitted a need request form not meeting the EPA's criteria. This indicator is used in the ASCE Infrastructure Report Card (ASCE, 2017). The ASCE reports on the amount of drinking water infrastructure needs (ASCE, 2017). This indicator was not included in this analysis, as it is not available at the county level.

To capture the performance of institutions, we use the **percentage of Community Water Systems (CWS) not in compliance**. This measurement was created by summing up the total number of CWS facilities listed as a 'violator' or a 'serious violator' and then dividing by the total number of CWS facilities. This was done for the country, state, and county levels. This data comes from the EPA's Drinking Water Dashboard (EPA, 2020a). A violator is classified as any facility "in violation of the Safe Drinking Water Act (SDWA)", and each violation is given a score of one, five, or ten points based on the severity of the violation (EPA, 2020a). Violations can occur for health reasons, issues with monitoring or reporting, failing to notify the public, or for other reasons (EPA, 2020a). A serious violator is one that has "an aggregate score of at least eleven points" (EPA, 2020a). This indicator only focuses on CWS facilities and does not include Transient Non-Community or Non-Transient Non-Community water systems. This indicator does not account for all water-related institutional performance, but it gives an idea of how CWS facilities are complying with national policy.

The service provision level is estimated by looking at the **percentage of occupied households lacking complete plumbing**. To create this indicator, the number of occupied houses lacking complete plumbing was divided by the total number of occupied houses. This data comes from the 2017 American Community Survey's (ACS) and is based on the 5-year estimate values (ACS, 2020). It is available at both the county and state levels. To be considered as having access to complete plumbing, a household has to have all three of the following facilities: "hot and cold running water, a bathtub or shower, and a sink with a faucet" (ACS, 2020). This metric has been used previously as an indicator of household water security, and the authors pointed out a key limitation being that a house could be labelled not having complete plumbing even if they have two out of the three facilities (Deitz and Meehan, 2019).

The number of **flood related deaths** are used to show the outcome of flood related disasters in relation to people. This value is a summation of both direct and indirect related deaths. Data comes from the National Oceanic Atmospheric Administration's (NOAA) Storm Events Database, which has tracked all significant weather related events across the USA since 1950 (NOAA, 2020). The data included for this indicator ranges from 2008 – 2018. The decade long timespan was chosen to capture significant floods across the USA. Data was gathered across the following flood event types: coastal flood, flash flood, flood, heavy rain, high surf, lakeshore flood, storm surge/tide, and tsunami (NOAA, 2020). Hurricanes and tropical depressions were not included as these event types reported damage based on wind, and the damage and loss of life due to flooding associated with a given storm were coded as a separate flood related event (NWS, 2016). In certain cases, the same flood event was listed for multiple counties. In this case, the flood deaths were included for each county affected, but were removed from the state data to avoid double counting.

To account for the outcome of floods on the economy, **flood damages** were used. This value is a summation of both property and crop damages. Property damage refers to both private property as well as public property, such as infrastructure (NWS, 2016). The same dataset (NOAA, 2020) and rationale for the flood related deaths indicator are used. The damage data was entered for the year of the event, so values were adjusted for inflation and converted to 2019 USD.

Drought damages capture the impact of drought on the economy. Originally the NOAA Storm Events Database was used in the calculation of countywide drought damages, but this source only had data for 52% of the counties and had no record of drought for several states, such as Wyoming or Ohio (NOAA, 2020). Thus, we use the United States Department of Agriculture (USDA) Risk Management Association's

(RMA) data on insured drought losses (USDA RMA, 2019) that are reported by farms at the county level. We use the same time period used for the flood related damages (2008 – 2018). This indicator only consists of crop related losses that were insured, so does not reflect the total drought damages. Farms using irrigated agriculture could not be assigned a loss as a result of drought, but could be awarded damages based on "failure of irrigation equipment", "failure of irrigation supply", or "failure to prepare their land for irrigation" (USDA, 2018). Each of these irrigation failures could occur not only based on drought, but also heat and dry winds (USDA, 2018). In addition, pastureland, rangeland, and forage land were categorized under a different form of loss, Area Risk Protection Insurance (ARPI), which includes land insured against a rainfall deficient (USDA, 2018). Therefore, the total losses included in this indicator are a total of the following: drought, heat, hot winds, ARPI, and the three irrigation failure typologies (USDA RMA, 2019). We believe this is justified by cross-checking with the US Drought Monitor (USDM) (USDM, 2020). Several counties, such as those in West Virginia, reported losses due to heat and hot winds in 2017, but no drought losses. When cross-checking with the USDM, these counties were listed as being in severe drought (D2 level) for at least two weeks during the reported damage timeframe. The crop loss data was entered for the year of the event, so values were adjusted for inflation and converted to 2019 USD. The crop losses are summed to create state and country values. The majority of states have event data listed as "all other counties" and could not be associated with a specific county (USDA RMA, 2019). Nonetheless, this data was included in the overall state values. Finally, this indicator only is available for 2,666 counties. The majority of counties that have no data are located in areas less prone to drought, such as Alaska and West Virginia.

The **number of species of conservation concern** represents the environmental outcome dimension. This indicator includes both fully and partially aquatic species. Data

was provided at the county level and summed to generate a statewide total. Data is also available at the watershed level. Fully aquatic species include the following: amphipods, crayfishes, freshwater and anadromous fishes, freshwater mussels, freshwater snails, and fairy, clam, and tadpole shrimps. Corals, other cnidarians, marine fishes, and sponges were not included in this indicator as the species count is incomplete in NatureServe's database (2019a). Partially aquatic species were also included when data was available. This includes the following species: amphibians, caddisflies, dragonflies, damselflies, some isopods, stoneflies, and aquatic reptiles such as crocodilians, some turtles, and some snakes. Only 1,966 counties have data available. As seen in Table 4-2, this makes it the most limiting indicator. There is no way to correct for this as there is no way to tell whether data is simply missing for a county or whether an area has not been assessed. This is also the only indicator that has missing data at the state level. Data was initially unavailable for Delaware, Maine, Rhode Island, and the District of Columbia. There is an additional database available through NatureServe that is curated separately (NatureServe, 2019b). This database was used to fill in the gaps for the three missing states plus the District of Columbia.

Table 4-2: County summary statistics

Indicator	No. of Counties	Min	Max	Mean	Median	SD
Water Stress (%)	3,137	0	378.37	23.13	14.52	28.09
Impaired Stream/River Length (%)	3,139	0	98.50	10.68	6.29	14.86
Agricultural Water Productivity (USD/m^3)	2,834	0	176.86	1.15	0.19	5.77
Wastewater Need (USD)	2,483	3.54E+04	9.21E+09	1.20E+08	1.18E+07	5.23E+08
CWS Not in Compliance (%)	3,129	0	100	32.87	28.13	27.86
Lacking Complete Plumbing (%)	3,142	0	37.31	0.64	0.38	1.45
Flood Deaths	3,103	0	61	0.46	0	1.83
Flood Damages (USD)	3,103	0	1.53E+10	4.31E+07	6.92E+05	5.31E+08
Drought Damages (USD)	2,666	519.98	4.30E+08	1.73E+07	6.54E+06	3.02E+07
Aquatic Species of Conservation Concern	1,966	1	36	3.95	2	4.29

Tables 4-2 and 4-3 illustrate the summary statistics at the county and state levels, respectively. There are a total of 3,142 counties within the USA. There are fifty states, plus the District of Columbia. Each indicator's issue with missing data was discussed above. From Table 4-2, we see that the county indicators all have a tendency to skew to

the right, some more prominently than others. From Table 4-3, we see the same skew pattern, except for the impaired stream/river length. For nine of the ten indicators, a higher value indicates the potential for higher water insecurity, although a lower value of agriculture water productivity would be cause for concern.

Table 4-3: State summary statistics

Indicator	No. of States	Min	Max	Mean	Median	SD
Water Stress (%)	50	3.01	88.80	23.20	18.02	18.64
Impaired Stream/River Length (%)	51	3.77	100.00	59.11	61.10	25.87
Agricultural Water Productivity (USD/m^3)	51	0	1.61	0.52	0.35	0.45
Wastewater Need (USD)	51	1.01E+08	3.49E+10	5.83E+09	3.41E+09	7.14E+09
CWS Not in Compliance (%)	51	3.82	73.93	32.94	30.91	18.12
Lacking Complete Plumbing (%)	51	0.24	3.96	0.48	0.38	0.51
Flood Deaths (#)	51	0	278	27.29	17	41.03
Flood Damages (USD)	51	0	6.10E+10	2.62E+09	2.45E+08	9.19E+09
Drought Damages (USD)	51	0	9.29E+09	9.02E+08	2.60E+08	1.59E+09
Aquatic Species of Conservation Concern (#)	51	4	692	153.12	62	187.96

4.2.4 Normalization

Since there are multiple unit types for the ten indicators, the data was normalized before aggregation. There are various ways to normalize indicators to generate a composite index, such as ranking, z-scores, scaling to have the same minimum and maximum, and categorial (Jacobs et al., 2004; OECD, 2008). The ranking normalization method was chosen as it is deemed "the simplest" (OECD, 2008). Each indicator at both the state and county level was ranked. Thus, values are ranked from lowest to highest, with the highest value receiving the highest rank value. Therefore, when aggregated, higher values will indicate areas of water insecurity. However, for agricultural water productivity, values were ranked from highest to lowest, with the lowest value getting the highest rank value since lower productivity would be more of a security concern. Given that there are missing data for each indicator at the county level, not every indicator is ranked on a scale of 1 – 3,142. In addition, some indicators have multiple counties and or states with the same value, and therefore they received an equal rank value. This is especially true for the number of aquatic species of conservation concern and the number

of flood deaths. Values that were reported as zero across all indicators were ranked as zero since this would represent zero insecurity.

This normalization method allows for the tracking of performance through time and is accommodating to outliers (OECD, 2008). However, there are drawbacks, such as the inability to discern the level of performance between states or counties for a given indicator (Jacobs et al., 2004; OECD, 2008). For example, if a large amount of data is clustered around zero, such as in the number of households lacking complete plumbing, a relatively low value of 0.9% could receive a very high ranking when looking across 3,142 counties. Also, the highest ranking state (value of 51) for poor water quality may be at 100%, but the next to highest value (ranked 49) may only be at 60%. Ultimately, there is no ideal normalization method, but ranking does meet the overall objective to highlight areas of poor performance across both counties and states.

4.2.5 Weighting and aggregation

For this analysis, indicators are given equal weights. This is a deliberate decision and means that equal importance is assigned to each indicator. As preferences can change across a range of stakeholders, this weighting essentially creates a base index that can be customized in the future to account for a given area's preferences. An alternative method that could have been adopted is based on statistical analyses such as Principal Component Analysis (PCA) or Factor Analysis (FA). However, the indicators show low correlations at the county level, with the majority being less than 0.4 (seen in Appendix B). There are stronger correlations found at the state level, but we chose to remain consistent in our methodology across scales. Overall, the highest correlation at both scales occurs between flood deaths and flood damages, which is to be expected. Nonetheless, we are interested

in the impacts of floods on both people and the economy, so they are left equally weighted.

A linear aggregation methodology (a summation of indicators) is employed. This assumes constant compensability, or that a decrease in one indicator can be accounted for by the increase in another (Shen and Hermans, 2018). This essentially says that a loss of biodiversity can be made up for by good institutional performance. This is not an ideal aggregation method. Yet, in this first attempt at generating a water security index across scales, we are primarily interested in seeing the overall compounding effect of sub-indicators. Again, this is a generic aggregation method that could easily be updated to reflect an area's desired objectives, e.g. a primary focus on the environment or sustainable water usage.

In terms of missing data and the index generation, only counties with at least nine indicators are mapped and presented in the results section. Thus, there are only 2,526 counties mapped, or 80% of all counties. As far as the state level, only Hawaii was missing a value (water stress), and it was included in the final aggregation. This is noted as only the contiguous states are shown in the results section. For a complete list of data values for states, along with their ranks and final total rank value, please see Appendix B. Finally, when looking at the overall results for the composite indicator, the summed values were placed in five separate brackets, with an equal number of counties or states in each bracket: Low Water Insecurity, Below Average Water Insecurity, Average Water Insecurity, Above Average Water Insecurity, and High Water Insecurity. This was done to allow for comparisons.

4.3 Results

4.3.1 Mapping of indicators

Two out of the ten indicators are mapped in Figures 4-1 and 4-2. Mapping of the additional eight indicators can be found in Appendix B. All maps were made using the US Census (2019) boundary shapefiles. These maps are used to show both masking of heterogeneity and areas of concern. Figure 4-1 shows the percentage of Community Water System (CWS) facilities not in compliance with the Safe Drinking Water Act (SDWA) and represents institutional performance. This indicator is mapped across three scales. In Figure 4-1a, we see that the USA as a whole does not show a high level of violations. In fact, only 31% of CWS facilities in the USA were violators in 2018. When looking at the state level, Figure 4-1b, we begin to see some variation. Here, three states show larger values (60%-80%) of noncompliance, and thirteen states show a reason for concern, with noncompliance falling between 40% to 60%. However, the vast majority of states are in the same bracket as the USA (20%-40%) or lower. It's not until we look at the counties in Figure 4-1c that we really begin to see finer variation. There are areas now that reach the highest category (80%-100%), with large concentrations of counties located in the Ohio River Valley, several South Central states, and a few North Central states. We also see counties in California, the Northeast, as well as counties around the Great Lakes with low levels of violations. Also, even though several states in the Southeastern USA show a 0-20% rate of noncompliance, Figure 4-1c, we do see several counties in this area that have a noncompliance rate of between 80%-100%. This could be due to some counties having a small number of CWS facilities, with the majority having a violation.

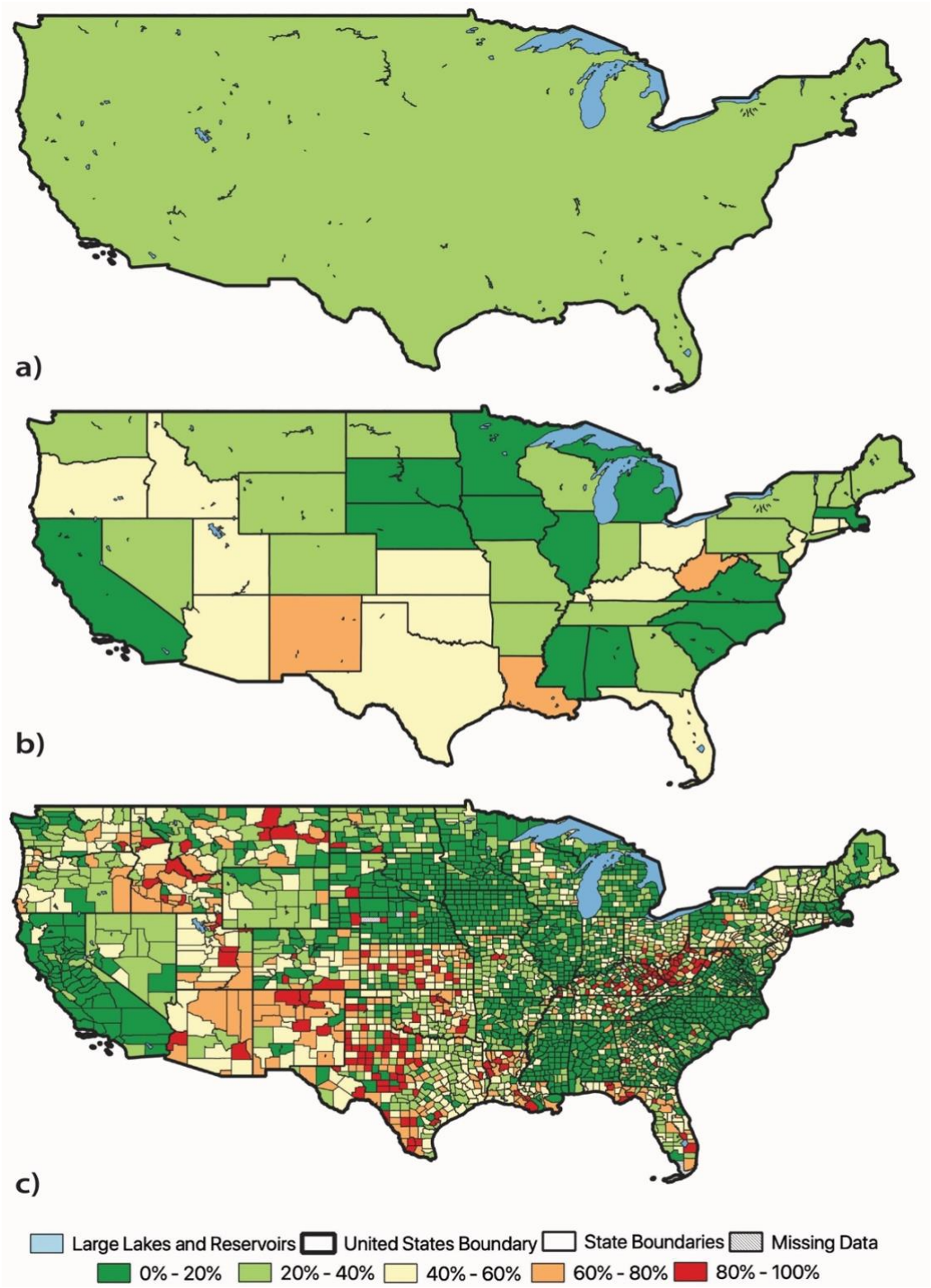


Figure 4-1: Institutional performance in terms of the percentage of CWS facilities not in compliance with the SDWA (EPA, 2020b). This figure shows results across three scales: a) country, b) states, and c) counties.

Figure 4-2 shows the amount of wastewater needs across three scales: the country, states, and counties. For this indicator, each stepwise increase in scale is an aggregation of a smaller scale. Also, this indicator is a nominal value. Thus, to make this data comparable across these scales, the data is reported in terms of needs per capita. This shows that even though data is available across scales, the comparability of nominal values may not necessarily be meaningful until placed in context.

As far as spatial heterogeneity, we see in Figure 4-2a that the USA as a whole has wastewater needs between 500 USD and 1,000 USD per capita. This is low when compared to values seen at the two other scales. For example, in Figure 4-2b, we see that nine states have a need of between 1,500 USD and 2,000 USD per capita. We can also see that the majority of states that have the highest needs often border another state with high needs as well. Finally, in Figure 4-2c, we begin to pick up on more spatial heterogeneity. However, we also see that there are a large number of counties with missing data. Several large swaths of missing data are in states such as Texas and the Dakotas that ultimately show low wastewater needs overall. These values could be uncharacteristically low due to missing data. Also, we see several states such as New York that have the majority of counties with a low need per capita, but ultimately show higher levels of need at the state level. Thus, this begins to show some of the interesting cross-scale dynamics.

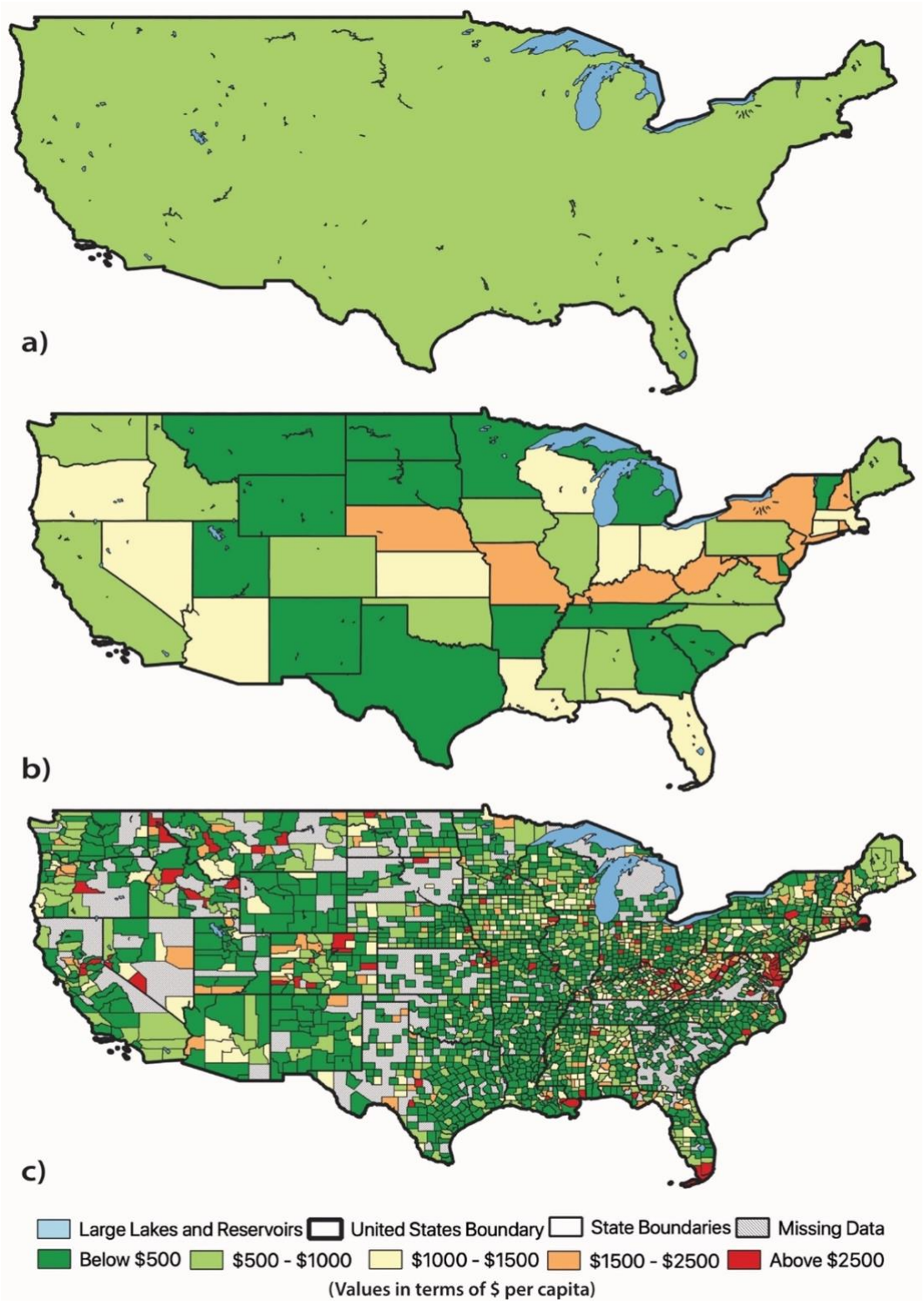


Figure 4-2: Infrastructure performance in terms of wastewater needs per capita (EPA, 2012a). This figure shows results across three scales: a) country, b) states, and c) counties. These values are in terms of USD ($) per capita to aid in cross scale comparisons. Population values are based on 5-year population estimates for 2017 (ACS, 2020).

4.3.2 Composite index

The overall composite indicator for both the state and county scales is seen in Figure 4-3. There is an equal number in each of the five brackets for both scales. Thus, the insecurity level is based on a given state or county's performance in regard to one another. In Figure 4-3a, we can start to recognize patterns and group areas based on their insecurity levels. The Northeast appears to be relatively water secure. There are areas of low insecurity in the North Central section of the USA. There is a group of high insecurity states along the southern border. This could be split into two areas: the Southwest and the Gulf Coast. There are also pockets of insecurity along the Ohio and Mississippi Rivers.

When looking at the water security index values at the county level, Figure 4-3b, we see some similarities, but also differences. The Southeast and the Southwest of the USA both seem to have areas of high insecurity at the county and state scales. One large difference is seen when comparing several states that are described as having high insecurity, but have hardly any counties within this bracket, such as Missouri. Also, there are several states listed as having low insecurity that have many counties with above average or high insecurity. This can be seen primarily in the Northeast of the USA. Finally, the higher insecurity levels in the Ohio River states actually shows specific clusters of insecurity within the broader river basin, in areas such as North Central Ohio and the Appalachian region of West Virginia. Finally, there is a large pocket of insecurity in southern Wisconsin.

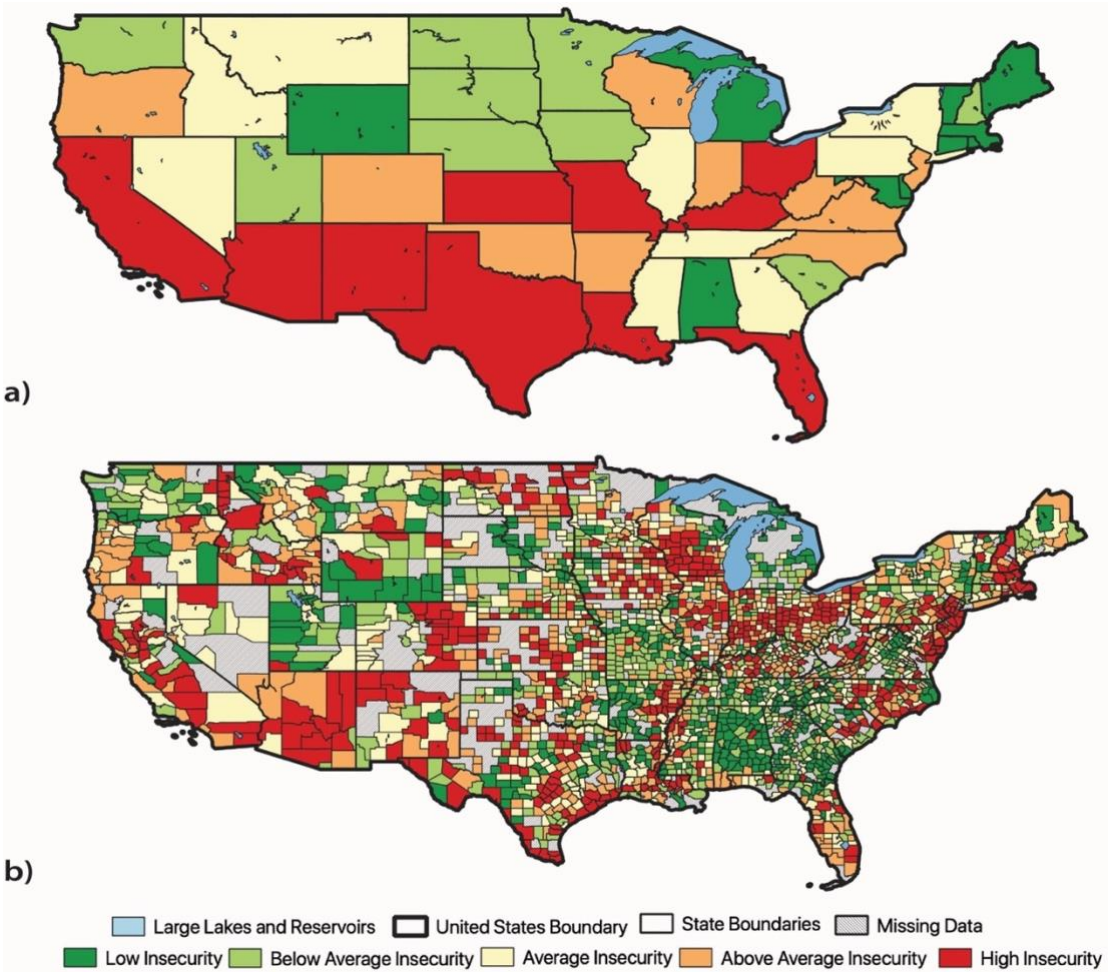


Figure 4-3: Water security composite indicator at two scales: a) the state and b) the county.

4.4 Discussion

4.4.1 Scaling issues

Through this multiscale analysis, we have encountered repeated tradeoffs regarding scale. We chose to approach the multiscale analysis by creating an index. This choice had two primary tradeoffs. First, we decided to forgo a full multi-dimensional analysis of water security by only focusing on system performance and outcomes. This limited the overall scope of the study, but helped to narrow the scale of analysis as system performance and outcomes are typically measured at a governmental scale. Second, by focusing on administrative boundaries, we sacrificed the natural scale of hydrological

indicators, such as water stress, for the accuracy of the additional indicators. We also encountered a tradeoff between data availability across scales. This primarily occurred with having to exclude useful data, in terms of system performance and outcomes, due to their unavailability at the finest resolution (the county).

This index is only as good as the data underlying it, and the index can only be compared across scales if using the same indicators and ideally the same data sources for congruency. Thus, the extent of information that can be compared is limited. Even though we have only focused on system performance and outcomes, we can see how the state and nation scales can obscure finer level details. This was not true in the case of all indicators. For example, access to complete plumbing had little variation, while water stress had extensive spatial heterogeneity (seen in Appendix B). When looking at the USA as a whole, several water stressed regions are obscured. This was as expected based on previous global studies (Wada and Bierkens, 2014). Thus, we find that a multiscale analysis can aid in the recognition of spatial heterogeneity.

4.4.2 Usefulness of the composite indicator

The creation of an index allows us to systematically assess water security across ten sub-indicators at two scales: the county and the state. Compared to looking at each indicator, the composite index allows one to get a better picture of the compounding effects of multiple water-related issues. It also allows for a classification of water security that can be compared across scales.

Even though the USA as a whole may be seen as water secure, there are actually several areas of high water insecurity throughout the country. The arid Southwest of the country and several coastal states are unsurprisingly ranked highest in terms of water insecurity. What is interesting is the pocket of water insecurity found among the Ohio

River Basin, as well as a pocket of insecurity in Southern Wisconsin. These sub-national areas of water insecurity would otherwise be obscured if looking at the entirety of the country. So, we find that a sub-national assessment would be an advantageous addition to a national water security assessment as critical areas of insecurity could be deemed water secure.

Finally, there is the issue of scalability of these findings. For example, how relevant are the low access to complete plumbing values found in the USA when looking across countries? This specific metric may not be generated by other countries, as well as the majority of the other indicators used in this study. Thus, the composite indicator used in this study is not replicable across other countries. However, the methodological approach laid out within this study could be adapted. One could change the outcome and performance indicators based on the given metrics for a country. Even though not comparable to the USA, the resulting index could be used to compare water security across administrative boundaries within a given country.

4.4.3 Limitations of the composite indicator

The quality and quantity of data is a principal limiting factor in the generation of the composite index. As mentioned above, each of the ten indicators employed in this study has its drawbacks. Several of these issues can be improved in the future as new data becomes available. For example, the USDA currently reports on irrigation water withdrawals at the state level (USDA, 2019a). If this data was reported at the county level, it could be combined with additional USDA data on net farm income and harvested irrigated land area to produce a more accurate agricultural water productivity value (USDA, 2019b). In addition, to the improvement of county related data used in this study, additional indicators could be considered once data becomes available. Key indicators

could be the affordability and reliability of water services. The American Household Survey (AHS) does ask a question regarding the stoppage of water usage by households, and this has been used as an indicator of service reliability (Pierce and Jimenez, 2015). This survey is aggregated to the national level, but disaggregated data for each state and county are not currently available (AHS, 2017). Additional water quality and environmental outcome indicators, as well as infrastructure and institutional performance indicators, would also be advantageous. Finally, more attention could be paid to the cross-scale dynamics between indicators, which this study assumed to vary linearly. This is especially true for indicators that were disaggregated or aggregated to a new scale, e.g. water stress.

There are specific issues that come along with using a composite indicator. In this case, we rank both the state and county indicators and then sum these rankings. Thus, the total summed rank total had to be placed into different categories to allow for comparison as there are 2,526 counties versus the 51 states (including DC). The method of normalization could be changed to avoid these bracket classifications of insecurity. Also, the county index includes counties that may be missing up to one indicator. This could be improved by only mapping counties with all ten indicators present, but would limit the results available. Finally, the overall accuracy of composite indicators is questioned due to the inherent uncertainty that comes with their creation (Saisana et al., 2005). This includes the following areas of uncertainty: conceptual framing, indicator selection, dealing with missing data, normalization, weighting, and aggregation (OECD, 2008). Essentially, each of these steps in the composite indicator creation introduces uncertainty.

To address these issues in the future, other normalizations could be used, such as a rescaling of the indicators or z-scores. Different weighting schemes could be included, such as using a PCA or FA to calculate a flood effect indicator based on flood deaths and

flood damages. Finally, future studies could utilize a Multi-Criteria Analysis (MCA) to apply decision rules to customize the composite indicator to their water security objectives (OECD, 2008). It is also crucial that sensitivity and uncertainty analyses be incorporated before the composite index is used for specific policy recommendations (Saisana et al., 2005). Ultimately, a composite indicator comes with inherent uncertainty and can be subjective, but it allows for customization based on specific objectives. In the future, this analysis could be applied to other countries and tailored to desired preferences (in terms of weighting) and objectives (in terms of aggregation).

4.5 Conclusions

Spatial scaling of water security studies will always present a challenge to both researchers and policymakers. The four considerations laid out in Section 4.1.2 occur during the selection of scale in any water security analysis, but can be exacerbated when conducting a multiscale analysis. Even though multiscale analysis brings more insight into phenomena of interest and can inform decision-making at multiple scales, it includes great, and sometimes insurmountable, challenges regarding data availability. There will also be an increased interest in questions of precision versus accuracy since the scales of analysis will unlikely map onto the scales of the phenomena across all scales. Therefore, it may be more productive to focus on specific dimensions of water security. This narrowing of the concept can simplify the complexity of water security to fit the multiscale study to the desired phenomenon. For example, by focusing on water security outcomes, which are typically measured based on administrative boundaries, we can capture several indicators that are naturally measured in a nested structure.

Regardless of these issues, we do find that a multiscale analysis is beneficial as we unearth spatial heterogeneity not only with individual indicators, but through the

composite index as well. This type of multiscale study would complement a more in-depth study, such as a country-level assessment. For example, a water security study of the USA could be accompanied by this multiscale water security index. This would allow for the identification of hotspots of insecurity in order to prioritize future studies and or interventions.

Moving forward, this tiered multiscale analysis could be applied to different nested scales such as the river basin and sub-basin scales. Another direction of future research could be the differences in primary drivers or characteristics of vulnerable populations across scales. For example, the administrative scales used in this study could be coupled with socio-economic data in future studies to determine factors associated with high insecurity. Finally, future investigations could include specific area related concerns such as sea-level rise for coastal areas and salinization of the water supply. Each of these future research directions could be based on the systematic approach laid out within this study.

APPENDIX B: SUPPLEMENTARY INFORMATION TO CHAPTER 4

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Appendix B1. Correlations

In order to understand the data better, as well as relationships across scales, correlations were run. When looking at the correlations between indicators across counties, seen in Supplementary Table 4-1, the majority of the correlations shown are weak (having a value less than 0.4). However, we do see a high correlation between the number of flood deaths and the total flood damages and high water stress and drought damages, which is to be expected.

Correlations at the state level, as seen in Supplementary Table 4-2, show an overall smaller number of correlations, but some with a higher value. The smaller sample size could change the amount of correlations present as well as their strength. Again, we find the highest correlation between the number of flood deaths and the total amount of flood damages. There is a high (value of 0.42) correlation between aquatic species at risk and flood deaths. Examples of states with a high number of flood deaths and a higher number of aquatic species at risk are the following: Arkansas, California, Kentucky, North Carolina, Tennessee, and Texas. There is also a high correlation between drought damages and both the number of flood deaths and total flood damages. This could primarily be driven by Texas, which experienced the highest drought losses, greatest flood damages, and the most flood deaths during the time period. Missouri was also susceptible to flooding and recorded high drought losses.

Supplementary Table 4-1: County correlation values

	Stress	Impaired Rivers	Ag Productivity	Wastewater Needs	CWS No Compliance	Lack of Plumbing	Flood Deaths	Flood Damages	Drought Damages	Aquatic at Risk
Stress	1									
Impaired Rivers	-0.09*	1								
Ag Productivity	-0.00	0.05*	1							
Wastewater Needs	0.13*	0.12*	0.12*	1						
CWS No Compliance	0.04*	0.05*	-0.01	0.04	1					
Lack of Plumbing	-0.02	-0.07*	-0.01	-0.06*	0.15*	1				
Flood Deaths	0.04*	0.03	0.02	0.24*	0.03	0.01	1			
Flood Damages	0.01	0.04*	0.00	0.09*	0.01	-0.01	0.46*	1		
Drought Damages	0.31*	-0.09*	-0.06*	-0.06*	0.09*	0.00	-0.05*	-0.02	1	
Aquatic at Risk	0.05*	-0.03	0.04	0.07*	-0.01	-0.03	0.07*	-0.02	-0.05*	1

*p < 0.05

Supplementary Table 4-2: State correlation values

	Stress	Impaired Rivers	Ag Productivity	Wastewater Needs	CWS No Compliance	Lack of Plumbing	Flood Deaths	Flood Damages	Drought Damages	Aquatic at Risk
Stress	1									
Impaired Rivers	0.04	1								
Ag Productivity	-0.02	0.27	1							
Wastewater Needs	0.20	0.10	0.26	1						
CWS No Compliance	0.05	0.05	-0.24	-0.01	1					
Lack of Plumbing	-0.04	0.04	-0.25	-0.16	0.33*	1				
Flood Deaths	0.22	-0.12	-0.07	0.36*	0.08	-0.04	1			
Flood Damages	0.15	-0.01	0.10	0.26	0.13	-0.04	0.81*	1		
Drought Damages	0.18	0.00	-0.03	0.12	-0.08	-0.10	0.70*	0.67*	1	
Aquatic at Risk	0.10	-0.05	0.19	0.25	-0.11	-0.13	0.42*	0.20	0.15	1

*p < 0.05

Appendix B2. State Values and Rankings

The values for each indicator, along with the rank value and the state's overall rank total can be seen in Supplementary Table 4-3. Data found in this table comes from sources listed in Table 4-1 in Chapter 4. Actual values for the number of aquatic species were not publishable, since this is private data.

Supplementary Table 4-3: State ranking values and total composite index score

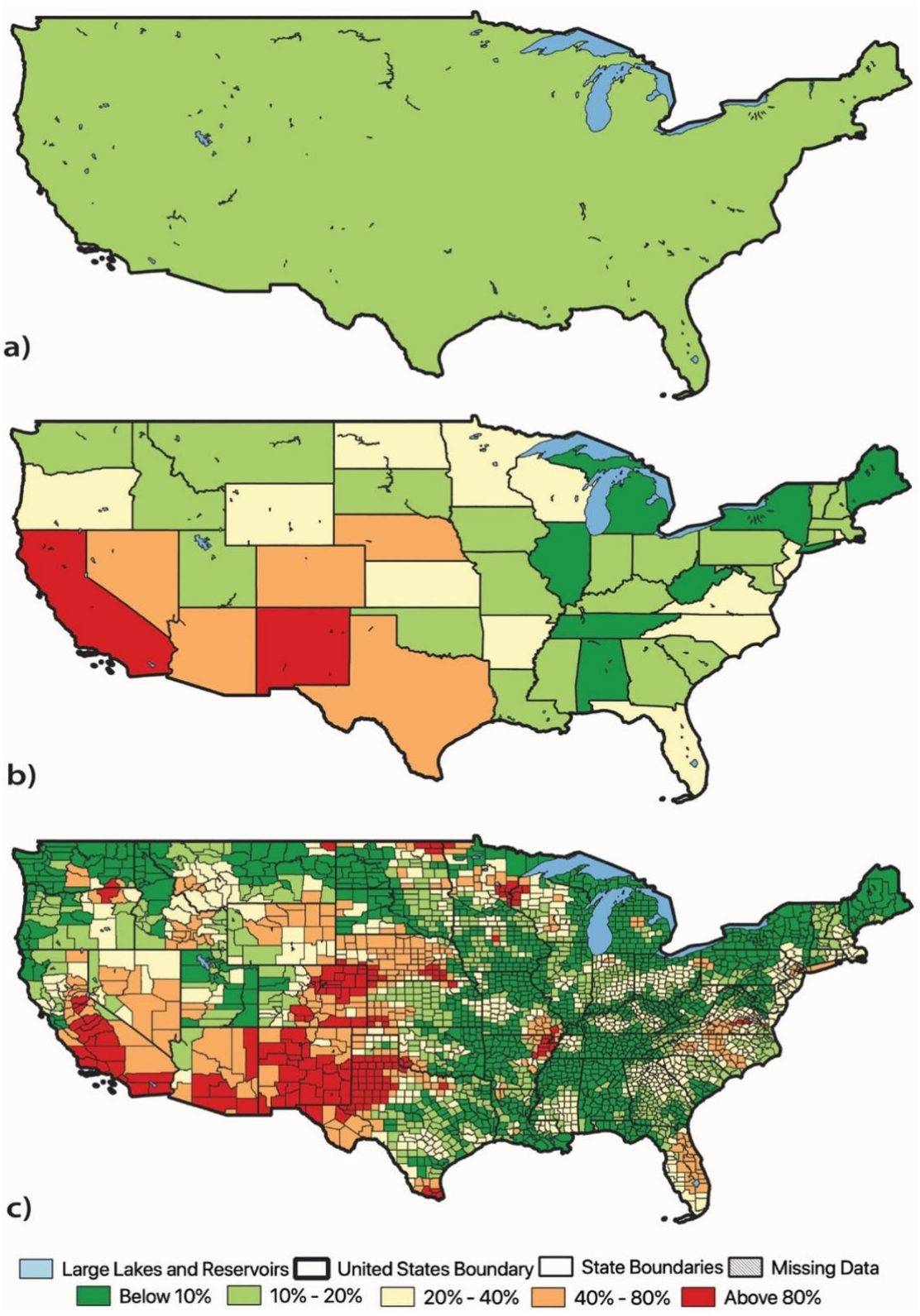
State	Stress		Impaired Stream/Rivers		Ag Product		Wastewater Needs		CWS Violators	
	Value	Rank	Value	Rank	Value	Rank	Value	Rank	Value	Rank
Alabama	6.47%	4	28.05%	8	$ 0.64	15	$ 3,433,155,979.65	27	10.93%	5
Alaska	6.80%	5	73.68%	35	$ 0.00	50	$ 220,546,450.56	4	68.54%	50
Arizona	63.63%	48	45.21%	16	$ 0.24	34	$ 7,521,911,032.86	40	52.82%	43
Arkansas	21.90%	32	44.46%	15	$ 0.10	43	$ 793,108,166.82	10	23.14%	17
California	81.99%	49	89.53%	45	$ 0.92	10	$ 29,123,777,321.97	50	11.89%	8
Colorado	53.10%	46	18.67%	5	$ 0.09	46	$ 5,210,667,347.88	34	36.18%	31
Connecticut	14.75%	21	42.53%	13	$ 1.04	8	$ 5,140,312,076.91	33	47.35%	38
Delaware	28.58%	38	99.65%	49	$ 1.61	1	$ 228,519,263.10	5	18.10%	15
District of Columbia	5.54%	3	100.00%	50	$ -	0	$ 3,105,453,758.79	25	50.00%	39
Florida	29.20%	39	80.36%	41	$ 1.13	7	$ 20,449,326,598.05	49	50.96%	41
Georgia	18.16%	26	58.11%	21	$ 1.41	4	$ 3,018,546,409.80	24	23.99%	18
Hawaii			90.48%	47	$ 0.41	25	$ 2,405,320,353.03	19	4.27%	2
Idaho	18.87%	28	54.88%	18	$ 0.10	44	$ 1,530,506,615.79	13	55.01%	46
Illinois	9.66%	8	56.50%	19	$ 0.71	12	$ 7,256,537,877.21	39	13.94%	10
Indiana	16.58%	23	69.06%	33	$ 1.30	6	$ 7,949,451,813.00	42	27.41%	22
Iowa	11.77%	15	75.86%	38	$ 0.60	18	$ 2,705,779,730.67	22	12.71%	9
Kansas	29.52%	40	88.39%	44	$ 0.21	37	$ 4,181,305,924.14	29	55.01%	45
Kentucky	11.18%	12	65.94%	29	$ 0.47	23	$ 6,931,945,039.41	36	54.19%	44
Louisiana	11.16%	11	75.69%	37	$ 0.24	33	$ 4,952,760,327.51	32	60.23%	48
Maine	3.01%	1	3.77%	1	$ 0.61	17	$ 1,076,954,489.70	12	25.61%	20
Maryland	11.41%	13	75.03%	36	$ 1.52	3	$ 11,018,663,320.32	45	21.29%	16
Massachusetts	18.65%	27	64.63%	28	$ 0.35	26	$ 9,271,333,511.43	43	7.44%	3
Michigan	3.09%	2	70.28%	34	$ 0.93	9	$ 2,305,354,191.48	18	16.78%	12
Minnesota	25.87%	36	79.40%	39	$ 0.86	11	$ 2,652,044,490.81	20	11.63%	7
Mississippi	13.12%	17	56.65%	20	$ 0.33	27	$ 2,258,368,596.33	17	10.25%	4
Missouri	19.18%	30	28.90%	9	$ 0.25	31	$ 10,667,741,182.62	44	32.17%	28
Montana	17.05%	24	85.14%	43	$ 0.04	48	$ 402,688,046.64	8	33.56%	29
Nebraska	57.17%	47	61.10%	26	$ 0.56	20	$ 2,850,547,129.47	23	11.00%	6
Nevada	44.04%	45	53.93%	17	$ 0.09	45	$ 3,414,522,240.93	26	28.72%	24
New Hampshire	14.63%	20	100.00%	50	$ 0.31	28	$ 2,195,837,484.48	16	26.67%	21
New Jersey	36.69%	42	90.06%	46	$ 1.60	2	$ 19,404,457,516.38	48	52.70%	42
New Mexico	88.80%	50	60.64%	24	$ 0.20	38	$ 354,954,202.71	7	65.38%	49
New York	6.99%	6	24.46%	7	$ 0.49	22	$ 34,897,269,968.94	51	29.86%	25
North Carolina	29.66%	41	31.38%	10	$ 0.18	41	$ 5,878,924,888.08	35	3.82%	1
North Dakota	22.70%	34	5.28%	2	$ 0.16	42	$ 242,871,330.00	6	25.08%	19
Ohio	14.84%	22	96.74%	48	$ 0.22	36	$ 16,191,736,314.63	47	40.05%	34
Oklahoma	18.93%	29	81.58%	42	$ 0.24	35	$ 2,675,792,033.94	21	50.17%	40
Oregon	20.30%	31	67.47%	31	$ 0.19	39	$ 4,315,680,087.69	30	41.12%	36
Pennsylvania	12.21%	16	19.00%	6	$ 0.29	30	$ 7,714,768,271.46	41	35.25%	30
Rhode Island	24.55%	35	59.73%	22	$ 1.40	5	$ 2,133,003,501.36	15	46.07%	37
South Carolina	17.89%	25	66.30%	30	$ 0.69	13	$ 628,175,395.80	9	15.22%	11
South Dakota	14.61%	18	60.50%	23	$ 0.53	21	$ 184,492,709.28	3	16.88%	13
Tennessee	7.80%	7	42.16%	12	$ 0.58	19	$ 1,919,400,992.13	14	39.57%	33
Texas	43.44%	44	43.83%	14	$ 0.41	24	$ 13,130,402,854.71	46	40.56%	35
Utah	14.62%	19	34.07%	11	$ 0.18	40	$ 934,593,344.46	11	57.23%	47
Vermont	10.54%	10	7.22%	3	$ 0.25	32	$ 170,768,047.68	2	36.96%	32
Virginia	27.64%	37	68.26%	32	$ 0.29	29	$ 7,246,095,448.98	38	17.12%	14
Washington	11.59%	14	79.65%	40	$ 0.67	14	$ 4,520,271,599.16	31	28.10%	23
West Virginia	9.94%	9	61.67%	27	$ 0.02	49	$ 3,616,348,440.48	28	73.93%	51
Wisconsin	22.66%	33	60.79%	25	$ 0.64	16	$ 7,025,602,513.74	37	32.09%	27
Wyoming	37.28%	43	18.03%	4	$ 0.05	47	$ 100,921,463.07	1	30.91%	26

Supplementary Table 4-3: Continued

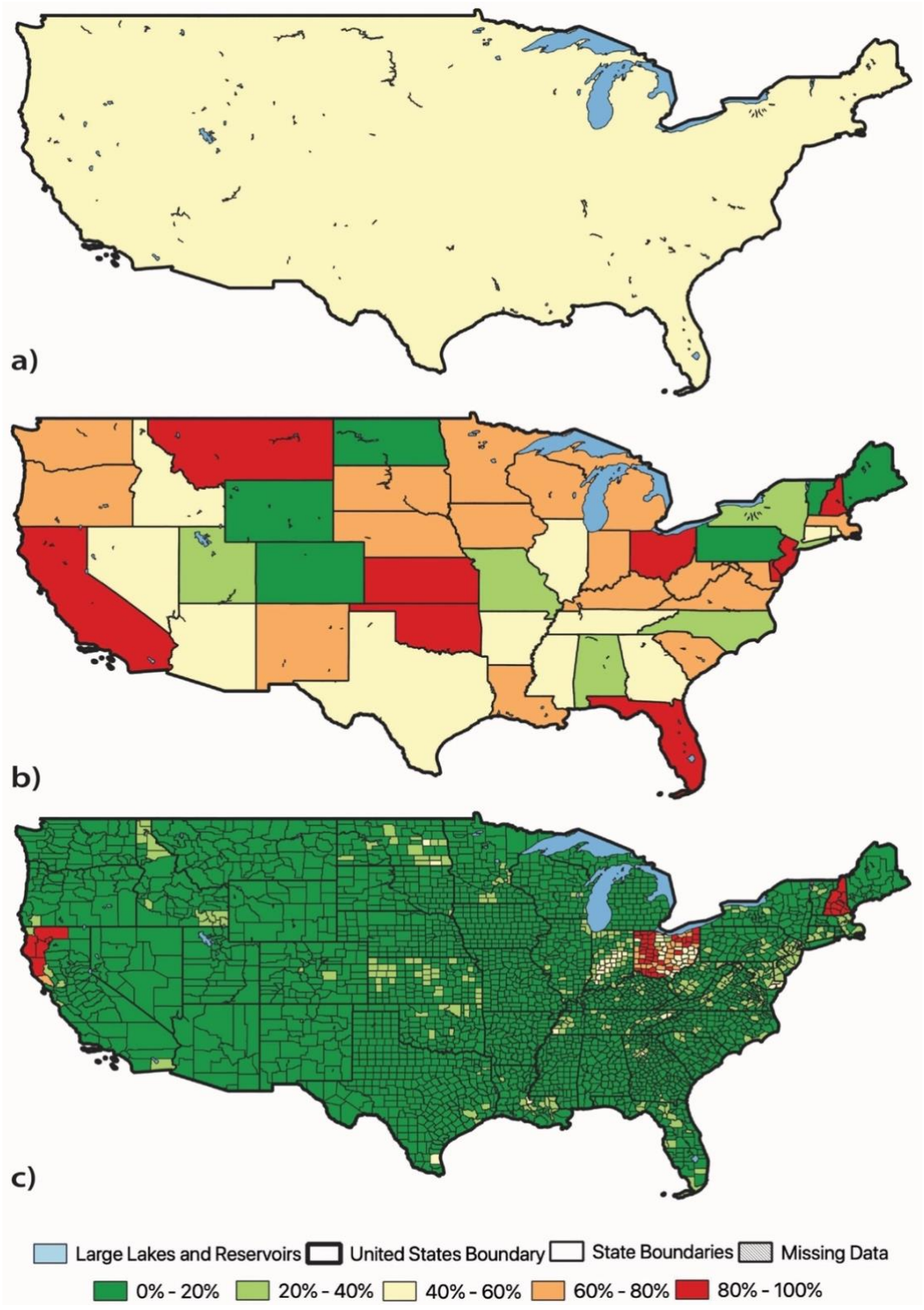
State	Lack of Plumb		Flood Deaths		Flood Damages		Drought Damates		Aquatic		Total (Sum of Rankings)
	Value	Rank	Value	Rank	Value	Rank	Value	Rank	Value	Rank	
Alabama	0.35%	20	17	13	$ 119,275,289.56	17	$ 260,494,295.50	25	-	43	177
Alaska	3.96%	51	9	9	$ 173,615,554.90	19	$ 184,995.18	1	-	4	228
Arizona	0.65%	48	41	24	$ 111,221,496.50	15	$ 282,832,806.62	26	-	31	325
Arkansas	0.50%	41	74	31	$ 921,140,161.75	34	$ 252,274,885.45	22	-	38	283
California	0.43%	35	68	29	$ 1,406,372,678.81	38	$ 1,533,113,373.49	40	-	42	346
Colorado	0.32%	14	10	10	$ 832,214,497.20	33	$ 1,037,594,442.65	38	-	9	266
Connecticut	0.30%	7	5	5	$ 25,416,579.00	1	$ 3,680,069.16	4	-	8	138
Delaware	0.26%	2	2	2	$ 60,732,820.00	8	$ 52,974,275.69	13	-	3	136
District of Columbia	0.24%	1	0	0	$ -	0	$ -	0	-	2	120
Florida	0.28%	4	41	24	$ 2,825,782,613.47	45	$ 221,780,412.29	20	-	44	314
Georgia	0.34%	17	15	12	$ 392,741,182.28	30	$ 759,771,164.54	34	-	46	232
Hawaii	0.63%	47	29	21	$ 45,312,200.00	5	$ 9,439,681.91	9	-	18	193
Idaho	0.55%	45	2	2	$ 181,363,256.00	20	$ 172,146,636.41	18	-	28	262
Illinois	0.28%	5	42	25	$ 1,582,770,365.74	39	$ 3,784,914,455.27	48	-	23	228
Indiana	0.32%	12	34	23	$ 1,787,019,205.65	42	$ 1,590,578,878.72	41	-	40	284
Iowa	0.30%	8	8	8	$ 3,616,150,860.80	46	$ 3,480,413,377.28	47	-	15	226
Kansas	0.40%	28	15	12	$ 82,245,252.40	9	$ 4,695,003,062.35	49	-	19	312
Kentucky	0.48%	39	49	26	$ 199,456,933.88	21	$ 816,655,577.23	35	-	39	304
Louisiana	0.42%	32	28	20	$ 12,280,688,327.60	48	$ 172,170,540.71	19	-	30	310
Maine	0.72%	49	3	3	$ 51,289,820.00	6	$ 8,241,948.10	8	-	7	124
Maryland	0.31%	9	10	10	$ 127,747,061.90	18	$ 137,146,284.57	16	-	10	176
Massachusetts	0.36%	22	3	3	$ 289,207,442.80	28	$ 6,611,891.17	6	-	6	192
Michigan	0.34%	18	9	9	$ 2,555,403,100.00	44	$ 393,633,673.87	30	-	14	190
Minnesota	0.33%	16	8	8	$ 286,582,856.50	27	$ 1,187,562,212.15	39	-	24	227
Mississippi	0.47%	38	13	11	$ 1,388,559,462.00	37	$ 328,878,201.32	28	-	35	234
Missouri	0.42%	31	72	30	$ 1,102,732,380.00	35	$ 2,044,920,584.23	44	-	34	316
Montana	0.51%	43	3	3	$ 30,610,343.00	2	$ 629,977,817.55	32	-	22	254
Nebraska	0.31%	10	5	5	$ 393,169,603.50	31	$ 2,226,199,635.84	46	-	13	227
Nevada	0.35%	19	9	9	$ 88,270,475.00	10	$ 77,210,254.81	15	-	32	242
New Hampshire	0.51%	44	1	1	$ 89,445,650.50	11	$ 530,451.58	3	-	3	197
New Jersey	0.29%	6	23	16	$ 24,865,999,185.04	49	$ 22,252,276.96	10	-	17	278
New Mexico	1.00%	50	25	18	$ 106,925,916.60	14	$ 256,275,493.27	24	-	25	299
New York	0.40%	29	57	28	$ 1,745,362,783.00	41	$ 75,361,836.22	14	-	11	234
North Carolina	0.32%	13	56	27	$ 2,105,242,743.69	43	$ 888,740,295.21	36	-	40	287
North Dakota	0.35%	21	5	5	$ 245,037,741.00	25	$ 1,719,315,644.48	42	-	3	199
Ohio	0.37%	24	23	16	$ 265,460,045.50	26	$ 756,861,336.16	33	-	33	319
Oklahoma	0.38%	25	49	26	$ 33,502,258.00	3	$ 1,763,586,675.21	43	-	29	293
Oregon	0.43%	34	21	15	$ 98,247,509.00	13	$ 251,806,491.97	21	-	36	286
Pennsylvania	0.39%	27	30	22	$ 549,096,818.88	32	$ 167,511,857.79	17	-	21	242
Rhode Island	0.32%	11	6	6	$ 118,776,809.00	16	$ 319,522.65	2	-	1	150
South Carolina	0.36%	23	24	17	$ 220,301,315.77	23	$ 254,867,267.31	23	-	20	194
South Dakota	0.59%	46	5	5	$ 52,214,092.00	7	$ 2,109,109,920.84	45	-	12	193
Tennessee	0.41%	30	42	25	$ 5,251,499,519.50	47	$ 335,629,259.23	29	-	45	261
Texas	0.45%	36	278	32	$ 60,996,727,068.65	50	$ 9,293,900,513.97	50	-	41	372
Utah	0.28%	3	26	19	$ 91,402,027.00	12	$ 24,104,942.81	11	-	26	199
Vermont	0.50%	40	4	4	$ 1,599,714,933.50	40	$ 3,880,467.33	5	-	2	170
Virginia	0.33%	15	24	17	$ 241,156,270.90	24	$ 321,567,288.54	27	-	37	270
Washington	0.43%	33	-	0	$ 212,490,932.96	22	$ 595,696,061.14	31	-	16	224
West Virginia	0.51%	42	42	25	$ 315,069,462.00	29	$ 7,153,677.03	7	-	27	294
Wisconsin	0.46%	37	20	14	$ 1,253,322,841.44	36	$ 955,599,980.34	37	-	27	289
Wyoming	0.38%	26	7	7	$ 39,573,432.00	4	$ 45,255,110.81	12	-	5	175

Appendix B.3 Maps of Additional Indicators

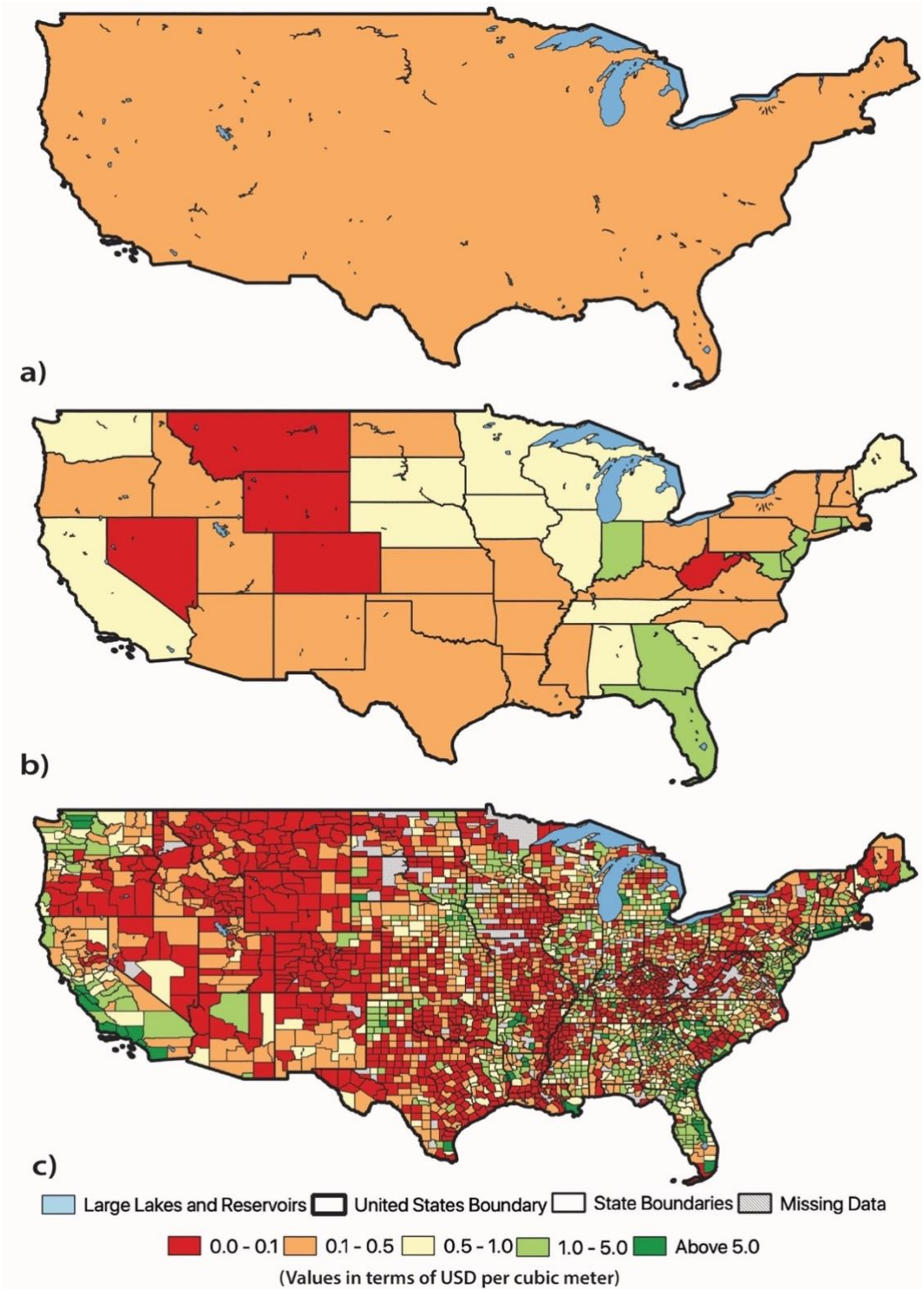
Supplementary Figures 4-1 through 4-8 show maps of the eight additional indicators that were not shown in the accompanying journal article. The underlying data for each map can be found in Table 4-1 in Chapter 4.



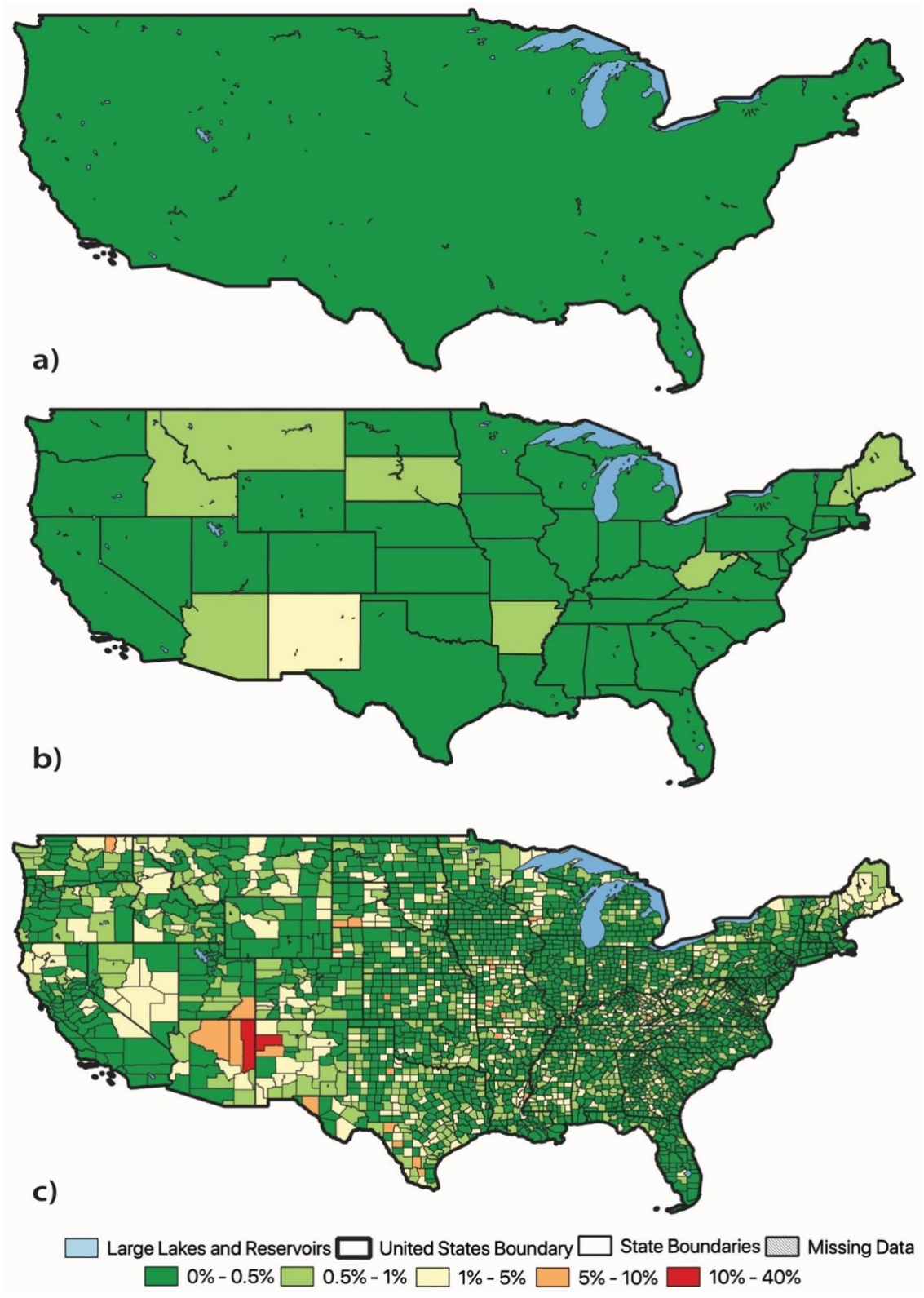
Supplementary Figure 4-1: Sustainability of use in terms of water stress (WRI Aqueduct, 2019). This figure shows results across three scales: a) country, b) states, and c) counties. The five different categories of water stress are set out in WRI Aqueduct (2019).



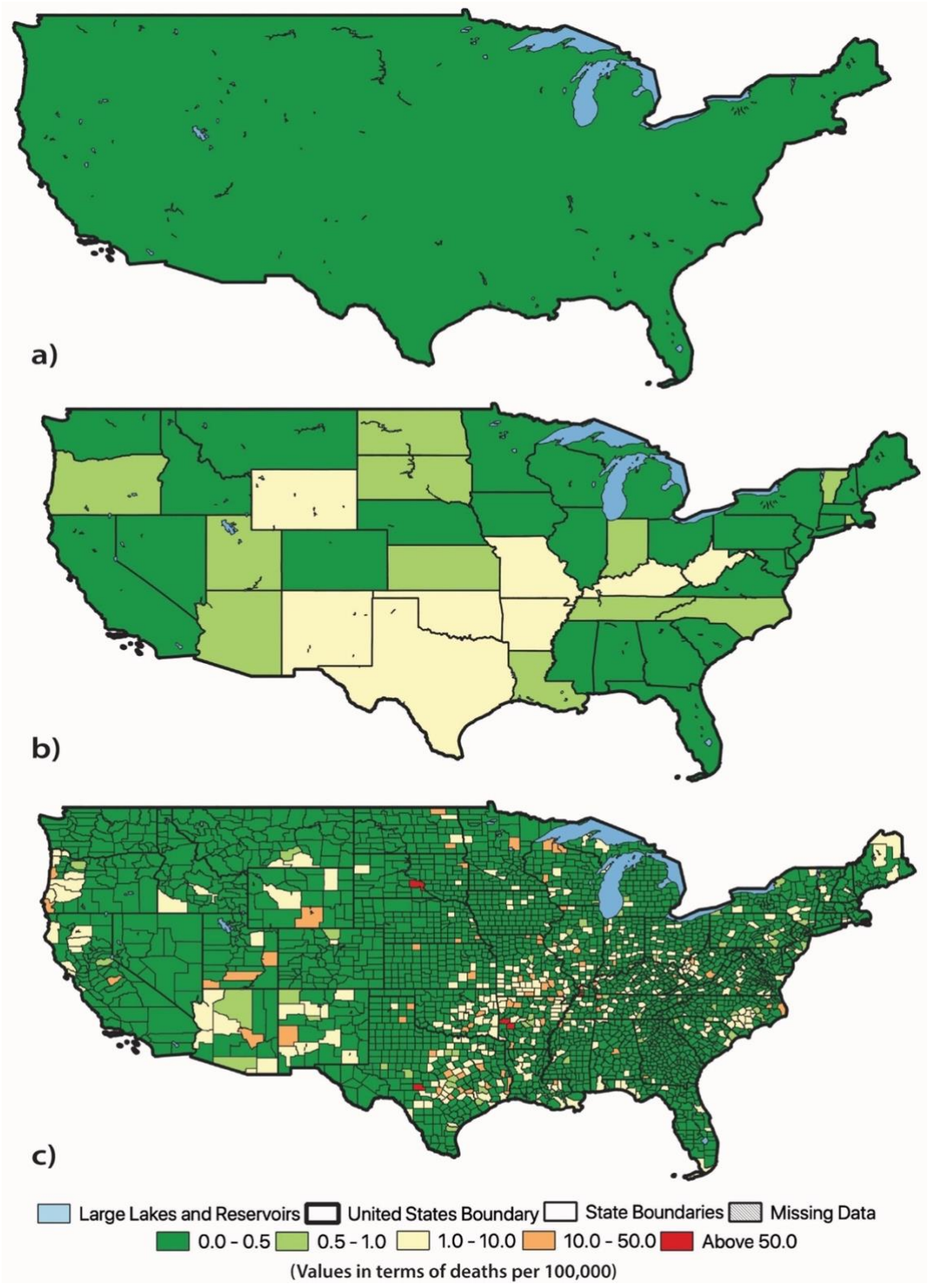
Supplementary Figure 4-2: Water quality in terms of the percentage of impaired stream/rivers. This figure shows results across three scales: a) country (EPA, 2020a), b) states (EPA, 2020a), and c) counties (EPA, 2013).



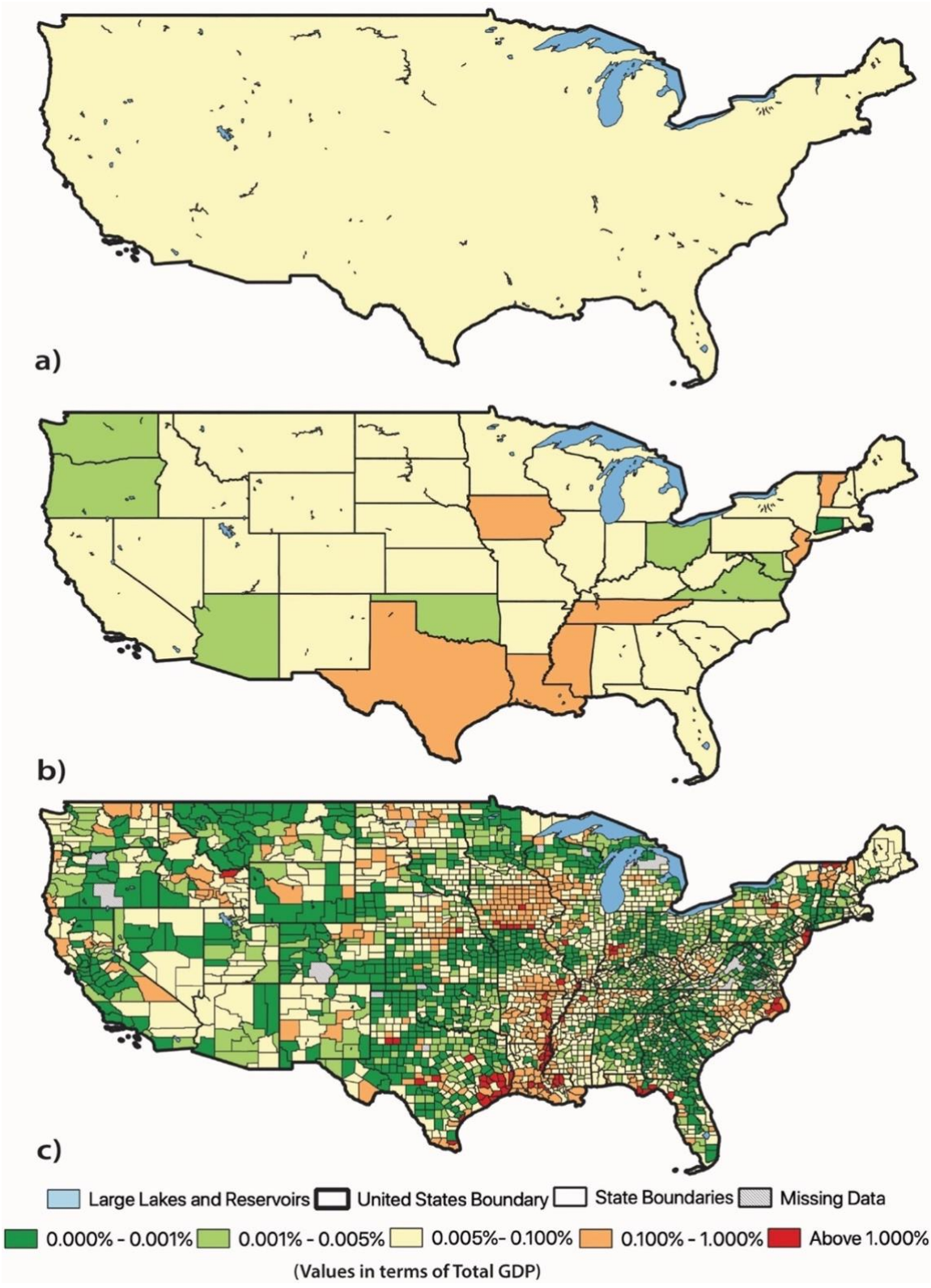
Supplementary Figure 4-3: Productivity in terms of agricultural productivity (Dieter et al., 2015a; BEA, 2019; USDA, 2019b). This figure shows results across three scales: a) country, b) states, and c) counties.



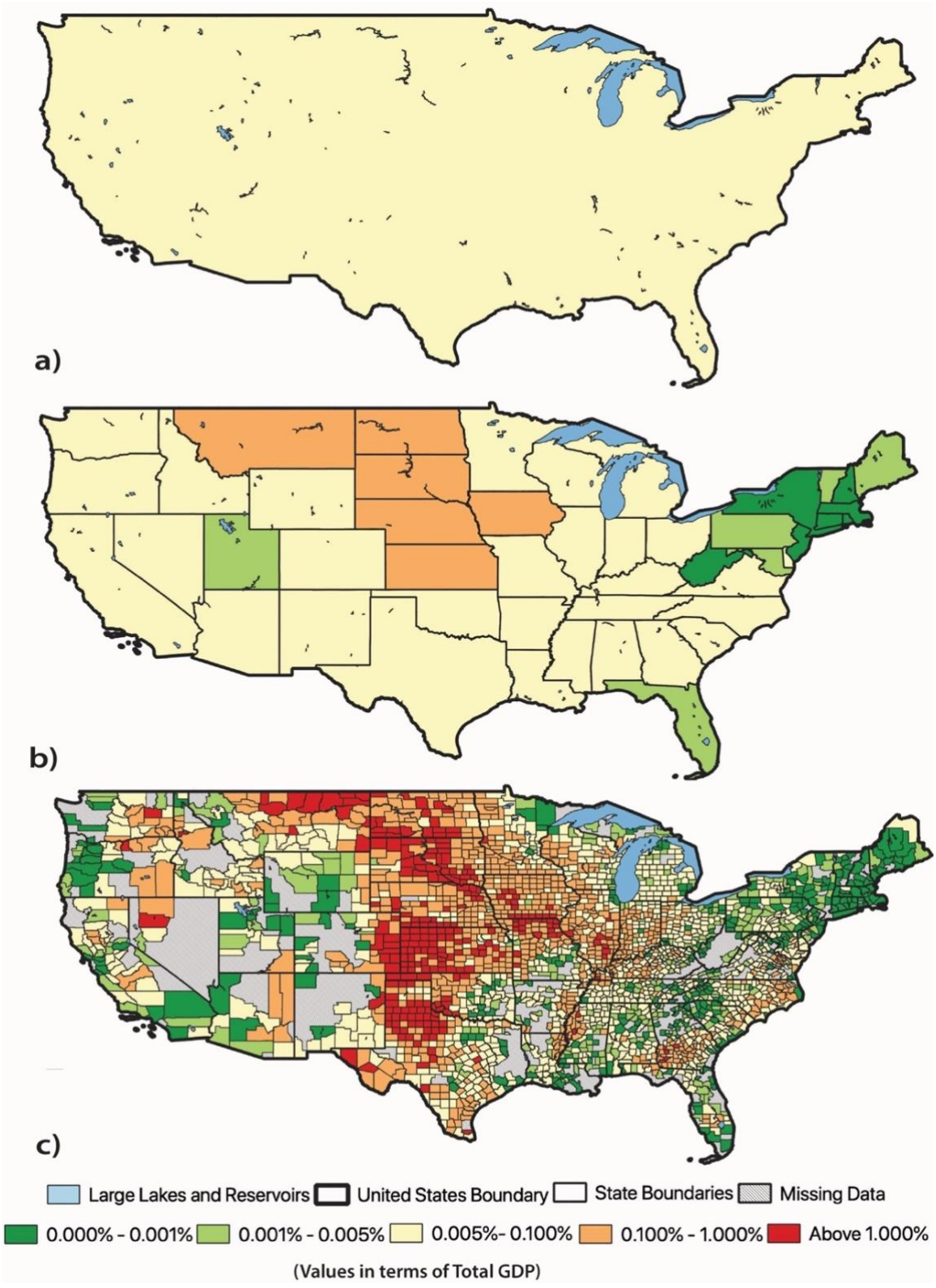
Supplementary Figure 4-4: Outcomes for people in terms of percentage of occupied households without access to complete plumbing facilities (ACS, 2020). This figure shows results across three scales: a) country, b) states, and c) counties.



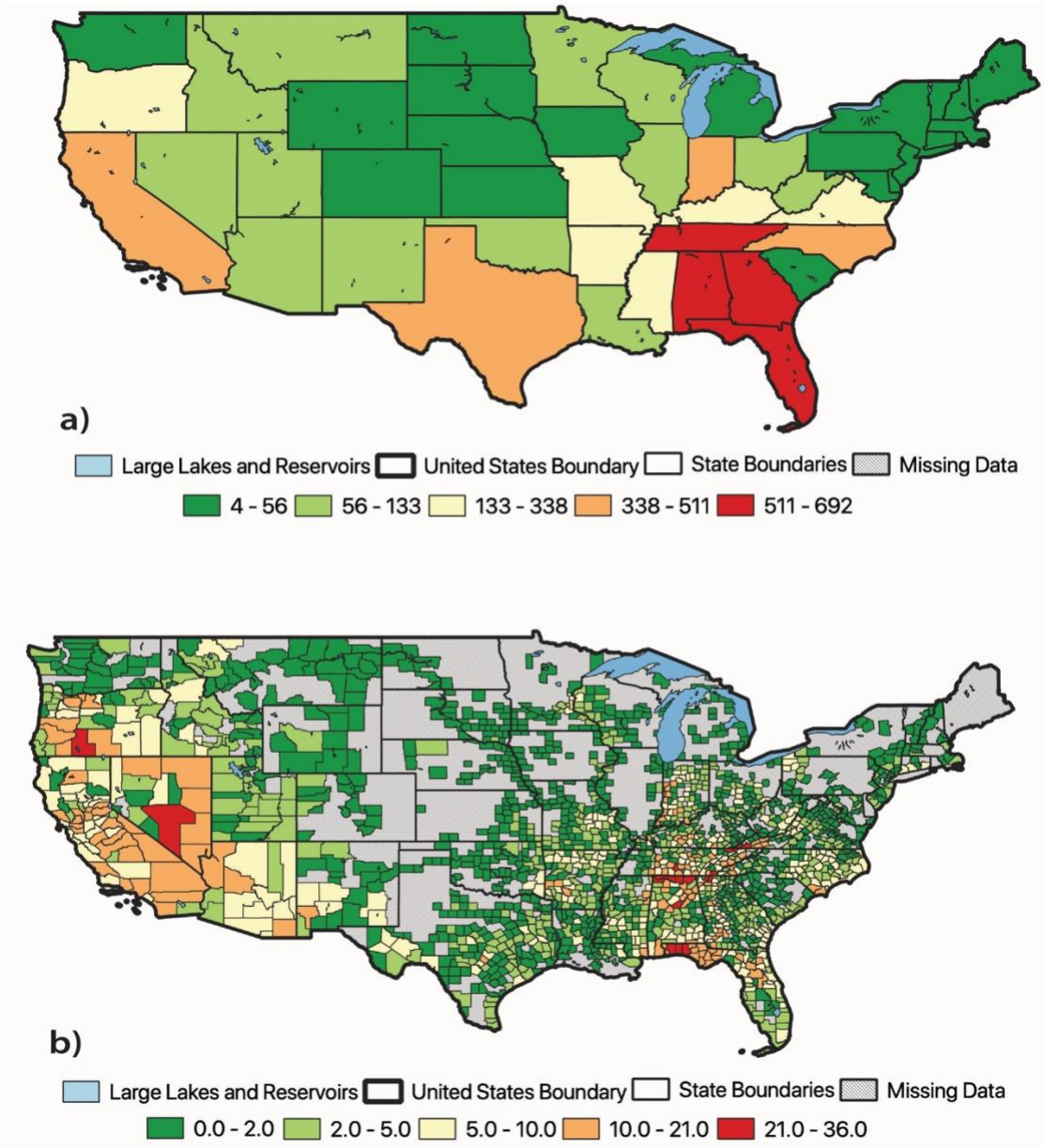
Supplementary Figure 4-5: Outcomes for people in terms of flood deaths per 100,000 (NOAA, 2020). This figure shows results across three scales: a) country, b) states, and c) counties. Population values are based on 5-year population estimates for 2017 (ACS, 2020).



Supplementary Figure 4-6: Outcomes for the economy in terms of flood damages as a percentage of the total GDP (NOAA, 2020). This figure shows results across three scales: a) country, b) states, and c) counties. Total GDP values are summed over the 2008-2018 timeframe and are in 2019 USD (BEA, 2019).



Supplementary Figure 4-7: Outcomes for the economy in terms of drought damages as a percentage of the total GDP (USDA RMA, 2019). This figure shows results across three scales: a) country, b) states, and c) counties. Total GDP values are summed over the 2008-2018 timeframe and are in 2019 USD (BEA, 2019).



Supplementary Figure 4-8: Outcomes for the environment in terms of the number of aquatic species of conservation concern (NatureServe, 2019a; NatureServe, 2019b). This figure shows results across two scales: a) states and b) counties.

5 WATER STRESS AND PRODUCTIVITY: AN EMPIRICAL ANALYSIS OF TRENDS AND DRIVERS

Abstract: Water scarcity is a global risk that could arguably be mitigated by using water more efficiently, that is, increasing water's productivity. However, the effects of water productivity on water stress have not been empirically tested or validated across countries. Evidence from other natural resource sectors suggests that improving productivity may, in fact, lead to 'rebound' effects that exacerbate resource exploitation. An econometric analysis is used to evaluate the relationship between water stress and productivity at the country level. A 1.0% increase in productivity is associated with a 0.81% decrease in water stress through time within a country, on average, and accounts for 75% of the variance of water stress. This suggests that targeting improvements in productivity have the ability to lower water stress. Analysis of trends in stress and productivity demonstrates that several developed countries are starting to exhibit decreasing trends in stress. Conversely, stress is low in developing countries, but rising. Productivity is generally increasing across all countries. Fixed effects panel regressions demonstrate that population, cultivated land, and political stability are also related to a variance in stress within a country. Differences in gross domestic product and precipitation explain variations in stress when looking across countries. The results of this analysis show that as a country develops, water stress is initially likely to increase. Increasing water productivity, which typically occurs later in a country's development pathway, is linked to decreasing stress, so water stress has the potential to be mitigated if a 'productivity transition' were to take place sooner.

5.1 Introduction

Water scarcity is a lack of water or the inability to meet human, economic, and environmental needs for water (Damkjaer and Taylor, 2017). It is estimated that more than 4 billion people face blue water scarcity at least 1 month a year, with scarcity occurring if withdrawals exceed availability (Mekonnen and Hoekstra, 2016). This statistic is a metric of water stress, as it measures the amount of water used versus the available amount. By capturing the stress placed on the resource, it is possible to highlight areas of water scarcity. In the coming decades, scarcity is expected to increase in locations such as continental Europe, the Middle East and North Africa (MENA), regions of the American Southwest, and central Asia (Wada and Bierkens, 2014).

Policymakers have several options when attempting to assuage water scarcity. There is the option of increasing the supply by incorporating desalinization, new reservoirs, or facilities to treat water for reuse. In addition, policies may be adopted to reduce demand for water. This could include shifting away from water intensive agriculture in favor of virtual water imports (Kummu et al., 2017) or implementing other policies such as regulating water withdrawals, pricing mechanisms, and enhancing the efficiency of water use (Dilling et al., 2019). It has been found that an increase in efficiency can lead to a rise in productivity (Playán and Mateos, 2006). There is some confusion within the literature as to the difference between efficiency and productivity. We attempt to disentangle this below, but essentially, efficiency is a measure of utilized input relative to total input, while productivity is the ratio of output to total input.

One aim of policy instruments that target efficiency and productivity could be to reduce overall water usage. Many authors imply that one might expect a negative relationship between water stress and efficiency or productivity (Mekonnen and Hoekstra, 2016; Scheierling and Treguer, 2016; Khair et al., 2019). For example, Khair

et al. (2019) suggest "that competition for scarce resources will lead to greater efficiency." However, there have been few studies that empirically test this relationship. A 2017 article asserted that "improvements in water productivity would reduce the requirement for additional freshwater by an estimated 16% against a business as usual baseline" (Unver et al., 2017). However, the same article goes on to question this by saying, "improvements in water productivity do not necessarily mean more water for others … farmers might use the water they save due to increased efficiency to expand production" (Unver et al., 2017). Zheng et al. (2018) showed that by increasing water productivity (yield/m^3), water usage went down. There have also been studies that look at specific subsectors of water usage and how their efficiency or productivity affects scarcity. For example, Porkka et al. (2016) studied changes in green-blue water scarcity and found that "by 2009 the same food supply could be produced with half of the water it took a century earlier." This gives evidence that productivity (in terms of agricultural yield) has increased. In Wada et al. (2016), the authors compare three global water models and focus specifically on domestic and industrial water usage projections. The results show an increase in domestic and industrial water usage by 2050, but the actual estimates are sensitive to underlying assumptions regarding socioeconomic drivers such as economic growth (Wada et al., 2016). They also find that the industrial estimates vary across models partially due to the differences in projections of efficiency improvements (Wada et al., 2016). So it is understood in these global models that variations in efficiency have the ability to alter future industrial water usage.

As documented in the energy literature, increasing efficiency or productivity may result in a 'rebound effect', meaning that overall resource use does not reduce as much as anticipated (Sorrell, 2009; Jenkins et al., 2011). The exact strength of this rebound effect is debated and likely varies by case (Greening et al., 2000). There have been several

studies on the rebound effect in the water literature with a specific focus on the relationship of withdrawals to efficiency, but none of a global nature. Pfeiffer and Lin (2014) found an increase in groundwater withdrawal after efficiency measures were put in place in Kansas. Freire-González (2019) found a minor rebound effect in his analysis of Spain. Given both the potential for a rebound effect and the possible benefits that could be achieved by increasing water efficiency and productivity, it is essential to obtain more empirical evidence of the extent to which increasing productivity leads to lower water stress.

Many different methods have been proposed for measuring stress and productivity. They have been grouped as the UN Sustainable Development Goals (SDG) Target 6.4: "water use and scarcity" (UN Water, 2019). For this analysis, we use the equations associated with SDG Target 6.4. Before we empirically test the relationship between productivity and stress, we first take a more in-depth look at water stress and productivity. Water stress, in terms of SDG indicator 6.4.2, is readily reported on (FAO Aquastat, 2019; World Bank Databank, 2019). It has been mapped, with country-level mapping showing higher water stress in western countries along with MENA and Asia (FAO, 2018a). The most recent UN summary report on SDG 6.4.2 found that water stress "increased for most countries in the world", but "that it had decreased in 44 countries half of which are in Europe" (FAO, 2018a). This report did not map trends or analyse if trends were significant. Little work has been done on SDG indicator 6.4.1, as it develops a new calculation for water-use efficiency. The most recent UN report only listed the most recent value for each country (FAO, 2018b). A recent article by Giupponi et al. (2018) estimated water-use efficiency using the same equations, but only for South and South-East Asia from 1980 to 2100. Thus, this new metric, which we believe is a better measure

of water productivity, as discussed below, has yet to be created in a time series for all countries. Therefore, a global trend analysis of this metric has yet to be developed.

In addition to water productivity, several other variables have the potential to affect water stress. These include socioeconomic drivers such as population growth and a country's wealth (Fant et al., 2016), as well as physical drivers such as climate (Le Blanc and Perez, 2008; Wada and Bierkens, 2014). These variables, among others, are included in our exploratory analysis to control for their effect and to understand their impact on water stress. Several studies have been done in this regard. When looking across potential drivers of increased water stress, Fant et al. (2016) find that socioeconomic drivers are more important than the climate in the future of water scarcity. Veldkamp et al. (2015) find that hydro-climatic variability contributes to the variation in global water scarcity in the short term, whereas socioeconomic drivers become more important after 6 to 10 years.

Ultimately, we aim to answer three main research questions: (1) Are there significant trends in water productivity and water stress? (2) What is the relationship between water productivity and water stress? (3) What are the main drivers of water stress? Significant trends in water productivity and water stress have yet to be mapped. In this paper, we use an econometric analysis to verify whether or not a relationship between water stress and water productivity is present. It is important to note that even though we may find a relationship between stress and productivity, there may be multiple mechanisms that lead to a relationship. Playán and Mateos (2006) indicate that productivity can be increased by incorporating “high-value crops”, “increased yield”, or “reduced water application.” So even though productivity is rising, it does not necessarily mean that withdrawals are decreasing. We then continue our econometric analysis to look at how multiple variables affect stress. This is, therefore, also novel since this combination of productivity and drivers of stress has yet to be studied. Ultimately, this

research aims to understand the water productivity and water stress metrics better, how they interact, and what drives stress. The results of this research can affect policymakers since they can take this evidence into account when evaluating the implementation of policies to improve productivity based on its relationship with water stress.

Before going further, it is important to have an understanding of the concepts used in this analysis due to their ambiguity. This includes water stress, water efficiency, water productivity, and what we consider a driver. Next, we discuss how water stress and productivity were calculated and describe the methods used to analyse trends and relationships. The results are then presented and discussed, followed by concluding remarks.

5.2 A Review of Metrics

5.2.1 Water stress

Water stress measures the amount of water withdrawn relative to the amount of water available. It essentially captures the pressure on a water resource and is one way to measure water scarcity. There are at least 150 indicators of water scarcity (Damkjaer and Taylor, 2017). Several review articles specifically highlight the evolution of these indicators (Chenoweth, 2008; Brown and Matlock, 2011; Damkjaer and Taylor, 2017). These review articles list the Falkenmark indicator that measures the amount of renewable freshwater per capita, as the first water scarcity indicator (Chenoweth, 2008; Brown and Matlock, 2011; Damkjaer and Taylor, 2017). Many metrics have been created, with the literature expanding in two different directions; one toward the human development side (Ohlsson, 2000; Sullivan, 2002) and the other toward a more physical measurement (Raskin, 1997; Chaves and Alipaz, 2007). On the physical side, the "use-to-resource ratio" was a precursor for the water stress metric that is widely used today

(Raskin, 1997). This indicator looks at the withdrawals compared to the total amount of renewable supply, and a country is highly stressed if they are using more than 40% of their renewable water (Raskin, 1997). This indicator has been adapted in several different metrics, such as the watershed sustainability index (Chaves and Alipaz, 2007).

Given the number of water scarcity metrics available, there is little consensus as to which is best. Particular articles have chosen to focus on what is lacking from current metrics or what an ideal measurement should include. Wada and Bierkens (2014) listed items missing from current indicators: nonrenewable water usage, lack of environmental flows, and foresight into future water needs. Vanham et al. (2018) set out seven criteria for a holistic water stress metric to measure water stress: (1) gross versus net water use; (2) environmental flows; (3) temporal scale saying the finer, the better; (4) spatial scale meaning the finer, the better; (5) surface and groundwater use; (6) alternative water sources; and (7) water storage or reuse.

It is useful to compare the SDG indicator 6.4.2 to these criteria. This SDG indicator is titled "water stress", and its purpose is to "ensure sustainable withdrawal and supply of freshwater to address water scarcity" (FAO, 2019c). This indicator meets several of the above criteria: it incorporates water usage across sectors, environmental flow needs, and includes both renewable surface and groundwater usage. However, the SDG indicator fails to capture nonrenewable water use, alternative water use, and water storage values. There is also an issue with the quantity and quality of water resource data available to measure and monitor the indicator at the national scale. Nevertheless, this indicator is widely reported in country-level statistics (FAO Aquastat, 2019; World Bank Databank, 2019) and will, therefore, be used in our analysis.

5.2.2 Water productivity and water efficiency

Water productivity and water efficiency are both system performance metrics that are often used interchangeably. In an article focused on a review of water productivity, 55 of the 59 articles assessed also mentioned efficiency (Clement, 2013). Efficiency can be thought of as getting the most out of each unit of input. It is typically a unitless quantity or represented by a percentage. Productivity can be thought of as getting the greatest value for your work, so typically has units of output per unit input. These basic system definitions have not translated fully to water resources, so in the water literature, a variety of sometimes inconsistent definitions and measurements are found. For example, Lankford (2013) deems irrigation efficiency as the ratio of "beneficial water consumption to total water withdrawals (m^3/m^3 or %)." He calls productivity, a form of "dimensional efficiency" that measures "economic output per input (USD/m^3) (Lankford, 2013). Thus, Lankford (2013) distinguishes between dimensionless efficiency, which is typically referred to as 'efficiency' and a dimensional efficiency called 'productivity'. He also classifies them both as performance metrics (Lankford, 2013). Even with these definitions, water efficiency and water productivity are still measured in many different ways.

In the biological sciences, water-use efficiency is typically defined as gross primary production over evapotranspiration (Xue et al., 2015; Sun et al., 2016; Sun et al., 2018). Essentially, this is how well a plant and or leaf utilizes the water available to it. Pereira et al. (2012) discuss how efficiency is typically considered the beneficial water used versus the water applied in percentage terms. This water-use efficiency is dimensionless. These metrics refer to efficiency in terms of the amount of water used for a task compared to the total amount of water supplied for the task. van Halsema and Vincent (2012) cite a similar explanation as Lankford (2013) but show that this is more

of an engineering term for efficiency. Finally, there are cases where water-use efficiency is defined in terms of dollars per water used ($/m^3) (Long and Pijanowski, 2017), that is, in terms that are closer to the conventional definition of productivity.

Water productivity is referred to as crop yields per water use or dollars generated per water used (Molden et al., 2010). The first type of productivity is typically referred to as physical or agricultural water productivity (Molden et al., 2010). Agricultural water productivity is regarded as an indicator of farm water management, but its usefulness is debated (Wichelns, 2014). The second type of productivity is most often referred to as economic water productivity and refers to the amount of value in monetary terms that is gained from the water used (Molden et al., 2010). Economic water productivity can either use total gross domestic product (GDP), gross value added (GVA), or be broken down by sectors, that is, agriculture, industry, or services. As a quick note, GVA measures the amount of output (USD) of a good minus the input(s) used to produce it (World Bank Databank, 2019). GDP is the total GVA plus taxes and minus subsidies (World Bank Databank, 2019). Currently, the total economic water productivity, in terms of GDP, is the only productivity or efficiency metric reported on the country scale. It can be found in the World Bank's Databank, and the data are available back to 1960. However, it becomes increasingly intermittent the further back one looks. Select studies have mentioned that water productivity is a better metric to report on than efficiency, since it implies an incentive for users such as farmers, with the incentive being higher profit or yields, and also that it is easier to target and measure across scales (Unver et al., 2017). Additional authors agree, citing the suitability of productivity rather than efficiency since efficiency is hard to account for at larger scales (Molden, 1997; van Halsema and Vincent, 2012).

The creation of SDG indicator 6.4.1 has further complicated matters by defining water-use efficiency as the amount of GVA gained from water withdrawals by sector (FAO, 2019b). The units are in (USD/m^3). This, therefore, is closer to previous definitions of economic productivity. The UN website for the indicator explains,

> *"The indicator differs from water productivity as it does not consider the productivity of the water used in a given activity as an input to production, or even better the marginal productivity of the extra dose. Instead, this indicator will show how much the growth of the economy is linked to the exploitation of natural water resources, indicating the decoupling of economic growth from water use. In other terms, if the value added (VA) produced by the economy doubles, how much will the water use increase" (FAO, 2019b)?*

This indicator makes methodological strides in calculating the monetary value gained from water because it is broken down by economic sectors and factors in the proportion of water used by each respective sector. Thus, it has the potential to offset high productivity values from countries that have a large service sector GVA but only use a small proportion of their water budget on services. This helps to give a more accurate depiction of total economic water productivity. However, based on the discussion above, we argue that it is an indicator of productivity rather than efficiency. Pereira et al. (2012) explicitly state that "water use efficiency should only be used to measure the water performance of plants and crops, irrigated or non-irrigated, to product assimilates, biomass and/or harvestable yield." Ultimately, SDG 6.4.1 is a measure of output (USD) over input (m^3), which is the definition of productivity. Hence, the remainder of this article will refer to SDG 6.4.1 as a measure of water productivity.

5.2.3 Drivers

A driver is an item that can affect the state of a system or its performance. For example, as population increases (driver), water stress (system performance) may increase due to more demand for water, even if per capita consumption remains the same.

Drivers give us an idea of what is happening within the overall system and indicate where it might be headed in the future. Social-ecological system theory highlights four 'settings' that have the potential to influence a social-ecological system, and we adopt these four settings as our categories of drivers: social, economic, political, and environmental (Ostrom, 2009). We selected a primary indicator for each category based on the second-tier variables in Table 1 of Ostrom's (2009) framing: S2, S1, S3, and ECO1. GDP was used as a proxy of economic development corresponding to the (S2) variable and population as an indicator for demographic change corresponding to (S1) (Ostrom, 2009). Temperature and precipitation indicate changing climate patterns (ECO1) (Ostrom, 2009). In Ostrom's (2009) framing, (S3) is categorized as political stability. The Fragile States Index is a comprehensive indicator and a top choice to measure stability since it measures state vulnerability across 12 metrics (The Fund for Peace, 2019). However, data reporting on this indicator only began in 2006, and this would detrimentally affect the size of our time series. The political stability indicator from the World Bank World Governance Indicators was ultimately chosen as a proxy. The World Governance Indicators measures governance across six separate categories, and political stability was selected since it is closest in meaning to the (S3) variable set out in Ostrom's (2009) framing, as well as being the main indicator out of the six that specializes in government stability (World Bank, 2019). Finally, we add one additional driver regarding the amount of agriculture within a country, the percent of cultivated land, since it consumes a large part of a country's water budget. As of 2012, 99 out of 159 countries (62%) had agricultural water usage that accounted for over 50% of their total usage (Doeffinger and Hall, 2019). The amount of cultivated land is used as a proxy for the actual amount of land irrigated, as the later has substantial data gaps. In this instance, cultivated land

includes both arable and permanent crops, which include annual and perennial crops (FAO Aquastat, 2019).

Previous studies have already analyzed several of these relationships. It has been found that population growth increases water stress (Chenoweth, 2008; Mekonnen and Hoekstra, 2016). Fant et al. (2016) find that population and GDP both have the ability to increase stress. Studies show that as precipitation goes down, stress will increase in sub-Saharan African (Le Blanc and Perez, 2008), and higher temperatures are found to increase water stress (Wada and Bierkens, 2014). One dimension that has not been studied as readily is the effect of governance and political stability on water stress. However, there is ample literature that cites the importance of good governance and strong institutions for water security (Gupta et al., 2013; Pahl-Wostl et al., 2013b; Klümper et al., 2017). In terms of agriculture and water stress, Mancosu et al. (2015) find that several already stressed basins are expected to have increased water stress due to increasing crop irrigation demands.

5.3 Methods

The research design employed in this study was an exploratory empirical analysis done through panel regressions and does not attempt to discern causation. Panel regressions can also be referred to as longitudinal regressions and allow for the added insight of changes through time, whereas ordinary least squares (OLS) regression does not. A panel analysis allows us to account for changes both within a country (how stress changes over time for each country) and across countries (how stress differs by country) through time. To the best of our knowledge, this is the first econometric study of water stress and water productivity. For the analysis, we have a strongly balanced panel with

data gaps, which are discussed below. It is also a short panel since N (number of countries) is greater than T (time steps).

5.3.1 Data

Data were collected from secondary sources for all countries (Table 5-1). The first five variables in Table 5-1 were used to calculate water stress and water productivity (see section 5.3.2) and were, therefore, not included in any of the regression models. The last six variables in Table 5-1 were considered drivers and used in specific regression models. All data listed in Table 5-1 have been compiled and are publicly available (Doeffinger and Hall, 2019).

Table 5-1: Main data and their sources

Variable	Unit	Years Available	Source
Data for Calculations			
Water Withdrawals* (total and by sector)	m^3	1973-2012 (5-year time step), 2013	Lui et al., 2016; FAO Aquastat, 2019; USGS, 2019
Total Renewable Freshwater	m^3	1958 – 2017 (5-year time step)	FAO Aquastat, 2019
Environmental Flow Require	m^3	1958 – 2017 (5-year time step)	FAO Aquastat, 2019
Proportion of Irrigated Land*	ratio	1958 – 2017 (5-year time step)	FAO Aquastat, 2019
Gross Value Added by Sector (Ag, Industry, and Services)	constant 2010 US$	1960 – 2017	World Bank Databank, 2019
Drivers			
Population	inhabitants	1960 – 2017	World Bank Databank, 2019
GDP	constant 2010 US$	1960 – 2017	World Bank Databank, 2019
Cultivated Land	%	1958 – 2017 (5-year time step)	FAO Aquastat, 2019
Avg Yearly Precipitation	mm	1950 – 2015	CRU TS v 4.02 from Harris et al., 2014
Avg Yearly Temperature	°Celsius	1950 – 2015	CRU TS v 4.02 from Harris et al., 2014
Political Stability	Adjusted Scale (0-100)	1996 – 2018	World Bank, 2019

* Have large data gaps that were accounted for through interpolation, extrapolation, and inverse distance weighting.

The first limiting factor in this study was the water withdrawal data. FAO Aquastat (2019) currently reports this data in 5-year windows, broken down into the agricultural, domestic, and municipal sectors. These 5-year windows start with 1958–1962 and run through to 2013–2017. The data entered for each country can be listed for any of the years within the 5-year window, so this creates gaps and inconsistencies within the withdrawal data. A study in 2016 generated a new water withdrawal data set reporting data across countries on a 5-year time step from 1973 to 2012 and then 2013 (Liu et al., 2016). The data set created by Liu et al. (2016) was created through interpolation and inverse distance weighting to fill in gaps from the FAO Aquastat data and has been used

in this study for the calculations of water stress and water productivity. It was cross-referenced with the current FAO database to update any new data entries. Based on these updates, adjustments in interpolations and extrapolations were made.

The second limiting factor for this analysis was the political stability indicator used as a proxy indicator for the political driver category. Since this metric was not created until 1996, it limited our study to five time steps (1997, 2002, 2007, 2012, and 2013). In the beginning, these data were only collected every 2 years. So data for 1997 were linearly interpolated from the 1996 and 1998 data points. The data were normalized to a 0–100 scale.

A third limiting factor was the list of countries that varied across sources and many countries that contained missing data. Countries were removed from the sample for the following reasons: no water withdrawal data available, missing data for two or more drivers, and South Sudan was removed due to its formation in 2011. The resulting panel data set used in this study contains values for a maximum of 179 countries, with data gaps being present. These gaps can be better understood by looking at the summary statistics in Tables 5-2 through 5-4. Table 5-2 lists the descriptive statistics for the six drivers. Population and GDP are both right skewed, so the log transform was used to normalize them.

Table 5-2: Descriptive statistics for drivers

	Mean	Median	SD	Min	Max	# Countries	# Obs
Population (inhabitants)	3.68E+07	8.18E+06	1.35E+08	4.38E+04	1.36E+09	179	893
GDP (Constant 2010 USD)	3.43E+11	2.61E+10	1.29E+12	1.25E+08	1.58E+13	175	867
Cultivated Land (%)	17.83	13.86	14.93	0.04	64.60	179	888
Precipitation (mm)	96.62	83.19	68.11	2.8	331.94	178	890
Temperature (°Celsius)	19.29	22.80	8.15	-4.9	29.00	178	890
Political Stability (0-100)	62.52	64.33	19.90	0	100	179	892

5.3.2 Calculating metrics

Water stress and water productivity were calculated values based on the first five variables of Table 5-1. Water stress is currently reported in FAO Aquastat (2019) but was calculated for this study based on the water withdrawal data from Liu et al. (2016). This creates a more complete water stress data set. In addition, a time series of water productivity based on SDG 6.4.1 was generated for the majority of countries for the first time.

5.3.2.1 Water stress

Water stress was calculated using Equation 1 as provided by UN SDG 6.4.2 (FAO, 2019c).

$$WS = \frac{TWW}{TRWR - Env} * 100 \qquad (1)$$

where:

WS = Water Stress (%)

TWW = Total Freshwater Withdrawal (not including desalinization or reuse) (m^3)

TRWR = Total Renewable Freshwater Resources (m^3)

Env = Environmental Water Requirements (m^3)

The total water withdrawal does not include water from desalinization or water that has been reused. Nonrenewable abstraction is included in water withdrawals such as groundwater usage, but not in the overall water availability. This results in countries having over 100% water stress. The total renewable freshwater has not changed in the FAO Aquastat database between 1958 and 2017. So the water stress metric does not account for interannual variability in renewable freshwater. The descriptive statistics water stress can be seen in Table 5-3. Water stress is skewed to the right, so it is log

transformed for the analysis. Water stress also exhibits large between and within country variance—with the largest being between countries.

Table 5-3: Descriptive statistics for water stress

	Water Stress (%)
Mean	75.97
Median	8.48
SD	371.35
Min	0.01
Max	5157.78
Between Variance	349.09
Within Variance	123.99
Number of Countries	179
Number of Observations	886

5.3.2.2 Water Productivity

Water productivity was first calculated based on the formula set out by the UN for SDG 6.4.1 (FAO, 2019b) and seen in Equations 2–6. Water productivity 'wp' is substituted for water use efficiency 'we' in Equations 2–6 and thus differs in terminology from the UN calculation (FAO, 2019b).

$$WP = A_{wp} \times P_A + M_{wp} \times P_M + S_{wp} \times P_s \quad (2)$$

where:

WP = Water productivity

A_{wp} = Irrigated agriculture water productivity (USD/m^3)

P_A = Proportion of water used by the agricultural sector over the total use

M_{wp} = Mining and quarrying; Manufacturing; Electricity, gas steam and air conditioning supply; Constructions (MIMEC) water productivity (USD/m^3)

P_M = Proportion of water used by the MIMEC sector over the total use

S_{wp} = Services water productivity (USD/m^3)

P_s = Proportion of water used by the service sector over the total use

$$A_{wp} = \frac{GVA_a \times (1 - C_r)}{V_a} \quad (3)$$

where:

GVA_a = Gross value added by agriculture (excluding river and marine fisheries and forestry) (USD)

C_r = Proportion of agricultural GVA produced by rainfed agriculture

V_a = Volume of water used by the agricultural sector (m^3)

$$C_r = \frac{1}{1+\left(\frac{A_i}{(1-A_i)*.375}\right)} \quad (4)$$

where:

A_i = Proportion of irrigated land on the total cultivated land, in decimals

.375 = Generic default ratio between rain and irrigated yields

$$M_{wp} = \frac{GVA_m}{V_m} \quad (5)$$

where:

GVA_m = Gross value added by MIMEC (including energy) (USD)

V_m = Volume of water used by MIMEC (including energy) (m^3)

$$S_{wp} = \frac{GVA_s}{V_s} \quad (6)$$

where:

GVA_s = Gross value added by services (USD)

V_s = Volume of water used by the service sector (m^3)

While the UN (FAO, 2019b) relates specifically to agriculture (GVA_a), global data typically report forestry and fisheries in the same sector as agriculture, but the UN calculation calls for these subsectors to be excluded from the calculation. Alternative methods were considered to disaggregate agriculture from fisheries and forestry, such as a global input-output model (Lenzen et al., 2012). Past studies have listed the World Bank as the primary data source for all GVA data (FAO, 2018b; Giupponi et al., 2018). However, GVA data for the industrial and service sectors from the global input-output

model did not match World Bank estimates. So we chose to obtain our GVA data from the World Bank to remain consistent in our calculations, even though fisheries and forestry are included in the overall agriculture GVA.

There was an additional issue with calculating irrigated agricultural water productivity (A_{wp}) since irrigation data at the country level are intermittent. Again, additional sources were considered, including satellite data. The World Bank data on irrigated agriculture land were evaluated since it was used in other studies (FAO, 2018b; Giupponi et al., 2018). However, we chose to use data from FAO since it better aligned with the definition laid out by FAO (2018b). These data were limited, so interpolation was used, and extrapolation was also used on countries with three or more data points. It is also important to note that the final agricultural water productivity value includes water from desalinization and water reuse, as these are included in sector withdrawal values from FAO Aquastat (2019).

Ultimately, three versions of water productivity were calculated, and their summary statistics can be seen in Table 5-4. The first water productivity metric calculated is based on Equations 2–6 and is simply referred to as Productivity in Table 5-4. The second metric calculated is referred to as Productivity_no_CR, and it excluded Equation 4 and removed Cr from Equation 3, thus no longer taking into account the amount of irrigated agriculture. Stated another way, Productivity_no_CR includes the GVA from both rainfed and irrigated agriculture. We then calculated a productivity metric based on the World Bank definition of water productivity, which is simply GDP divided by total water withdrawals. This is listed as WB_Productivity in Table 5-4.

Table 5-4: Descriptive statistics for water productivity metrics

	Productivity ($/m^3)	Productivity_no_CR ($/m^3)	WB_Productivity ($/m^3)
Mean	29.7	37.02	52.54
Median	11.09	14.08	17.21
SD	56.66	84.54	115.73
Min	0.14	0.14	0.19
Max	644.14	1163.46	1307.62
Between Variance	78.29	96.32	108.84
Within Variance	7.75	22.12	38.43
Number of Countries	149	166	175
Number of Observations	475	729	857

These additional metrics were calculated due to limited irrigation data resulting in a low number of observations for the analysis. Moving forward, we chose to use the Productivity_no_CR value as a proxy for water productivity. This metric gives us more accuracy than the World Bank productivity measure. Productivity_no_CR accounts for the fraction of water used by each sector, thus lowering the potential for total water productivity to be skewed by a high service sector GVA. The productivity_no_CR metric also gave us more observations to work with than the full productivity metric from generated from Equations 2–6. Table 5-4 shows that the data for all metrics are skewed right. Therefore, the log transformation was used. In addition, Table 5-4 shows that productivity varies both between countries (between variance) and within each country (within variance)—the largest variance occurring between countries.

5.3.3 Trend analysis

OLS regression was used for trend detection rather than nonparametric tests such as Mann Kendall. This is based on the characterization of our sample, since there are only five time steps and several countries oscillate between increasing and decreasing stress. Nonparametric tests tend to underperform in the presence of cyclical trends or small sample sizes (Hess et al., 2001; Helsel and Hirsch, 2002). Additionally, OLS was chosen over generalized least squares regression with AR errors, since there is no expected autocorrelation within the water stress or water productivity metrics given that they are a

short time series and lack seasonality. A t-test for the difference was not used due to it being a small time series. Using OLS, we sought to determine the presence of a significant trend in both water stress and water productivity metrics. Equation 7 shows the model used to estimate a trend in water stress. A similar model was used for water productivity. The results were then mapped.

$$Y_i = \beta_0 + \beta_1 X_1 + \varepsilon_i \quad (7)$$

where:

Y_i is the dependent variable, i.e. water stress

β_0 is the y-intercept

β_1 is the slope or coefficient

X_1 is the independent variable (time)

ε_i is the error term

5.3.4 Panel regressions

We first used the panel data set to explore if water productivity had any influence on water stress. The benefit of the panel data set is that it compounds the effects of each cross section through time. Panels show how changes in the independent variable(s) affect the dependent variable not just in one instance but also over several instances. The panel regression models used were based on country fixed effects and time fixed effects. The fixed effects account for the change in the dependent variable based on individual country features, whereas the time fixed effects account for any factors that occurred during the time period that could have similarly affected all countries (Khan et al., 2017). We tested for the need to include time fixed effects within the models, and it was needed in some cases and not in others. To remain consistent, we chose to include time fixed effects in all models. In addition to fixed effects models, there are also random effects

models. Random effects are typically used if estimating effects on a population from a random sample of data (Khan et al., 2017).

Various diagnostic tests were run to determine the validity of each model. We used the Breusch-Pagan Lagrange multiplier to test whether there are any effects present within the country(s) or whether a simple OLS regression would be more appropriate. Each model showed the presence of fixed effects, so fixed effects and random effects regressions were used. However, OLS regressions were also run for all models based on Equation 7. These multiple regression types allow us to show the strength of the fixed or random effects. The test for serial correlation, a unit root, and cross-sectional dependence could not be run due to gaps in the data. The test for a unit root and cross-sectional dependence were deemed unnecessary since we are using a short panel ($N > T$). All models showed the presence of heteroscedasticity. The clustered robust standard error approach was used for all models to correct the heteroscedasticity and the potential of serial correlation. It is important to note that we found no presence of multicollinearity within these models. All had a mean variance inflator factor below 3.0.

The first regression model focused solely on the relationship between water productivity and water stress. The model specification can be seen in Equation 8, which is similar to a model used by Khan et al. (2017). We first ran the regression for all countries. The panel regression differs from the standard OLS model in Equation 7, by adding in the fixed effects (a_i) and time fixed effects (ρ_t). We then looked at the outcome based on different income levels: high, upper middle, low middle, and low. The country income levels are from the World Bank (2018b), and changes over the period are included. OLS, fixed effect, and random effect regressions were run in all cases. A Hausman test was performed after each regression to indicate which model was more

appropriate: fixed effects or random effects, and the fixed effects model was deemed appropriate in this case.

$$Y_{it} = \beta X_{it} + a_i + \rho_t + \varepsilon_{it} \quad (8)$$

where:

Y_{it} represents the dependent variable (water stress) for the *i*th country during the year *t*

β is the coefficient for the independent variable (water productivity)

X_{it} represents the independent variable (water productivity) the *i*th country in year *t*

a_i is the country fixed effect

ρ_t is the time fixed effect

ε_{it} is the error term

We then ran several regression models exploring possible relationships between water stress and its potential drivers. The first model included all potential drivers of water stress, including water productivity. The second model we created included all potential drivers, excluding water productivity, in order to determine the overall effect of the additional drivers. We then proceeded to create additional models based on a backward stepwise elimination method. Essentially, drivers that were not statistically significant were removed from the analysis. We ran OLS, fixed effects, and random effects regressions in all cases. Based on the Hausman test, the fixed effects regressions were more appropriate in all cases; thus, we only report the results of the OLS and fixed effect regressions.

5.4 Results and Discussion

5.4.1 Trends

Figure 5-1 shows the trends in water stress from 1997 to 2013. Trends shown are those significant to a p-value <0.05. Several developed countries show a decline in water

stress while developing countries show an increase. Most notably, countries in Eastern Europe and Australia exhibit this trend. Countries in Latin America, Africa, the Middle East, and Southeast Asia are generally showing an increase in water stress. The largest increases can be found in Saudi Arabia and Kuwait, where the highest declines are seen in Belgium, Uzbekistan, Kyrgyzstan, and Thailand. A few of the trends might not be as meaningful such as the increase in water stress in Argentina, Columbia, and Venezuela since these countries have relatively low values of water stress.

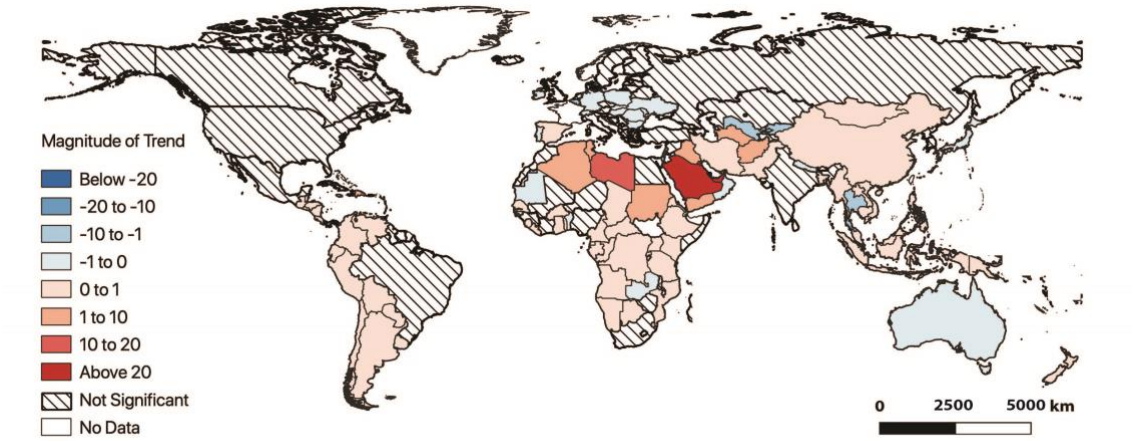


Figure 5-1: Map of significant trends in water stress from 1997 – 2013

We find a total of 29 countries with a significant negative trend in water stress, with close to half coming from Western and Eastern European countries. 19 of the countries with a decreasing trend are categorized as high or upper-middle-income countries. This finding is in contrast to the 44 countries the UN reported on with half coming from Western countries (FAO, 2018a). It is, therefore, crucial to continue to measure this trend, to accurately determine if developed countries are indeed decreasing water usage and when as this could inform policymaking for developing countries.

Figure 5-2 shows the trends in water productivity from 1997 to 2013. The figure includes total water productivity as well as agricultural, industrial, and services productivity trends. Total water productivity trends were first mapped for a p-value

<0.05, with only 28 countries showing a significant trend. To highlight the possible existence of trends in water productivity, the presented results show a p-value <0.1 in all cases. In this first study to map global water productivity trends, we find that all categories of water productivity are generally increasing, as seen in Figure 5-2. The largest increases in total water productivity can be found in Eastern Europe, Australia, and the United States.

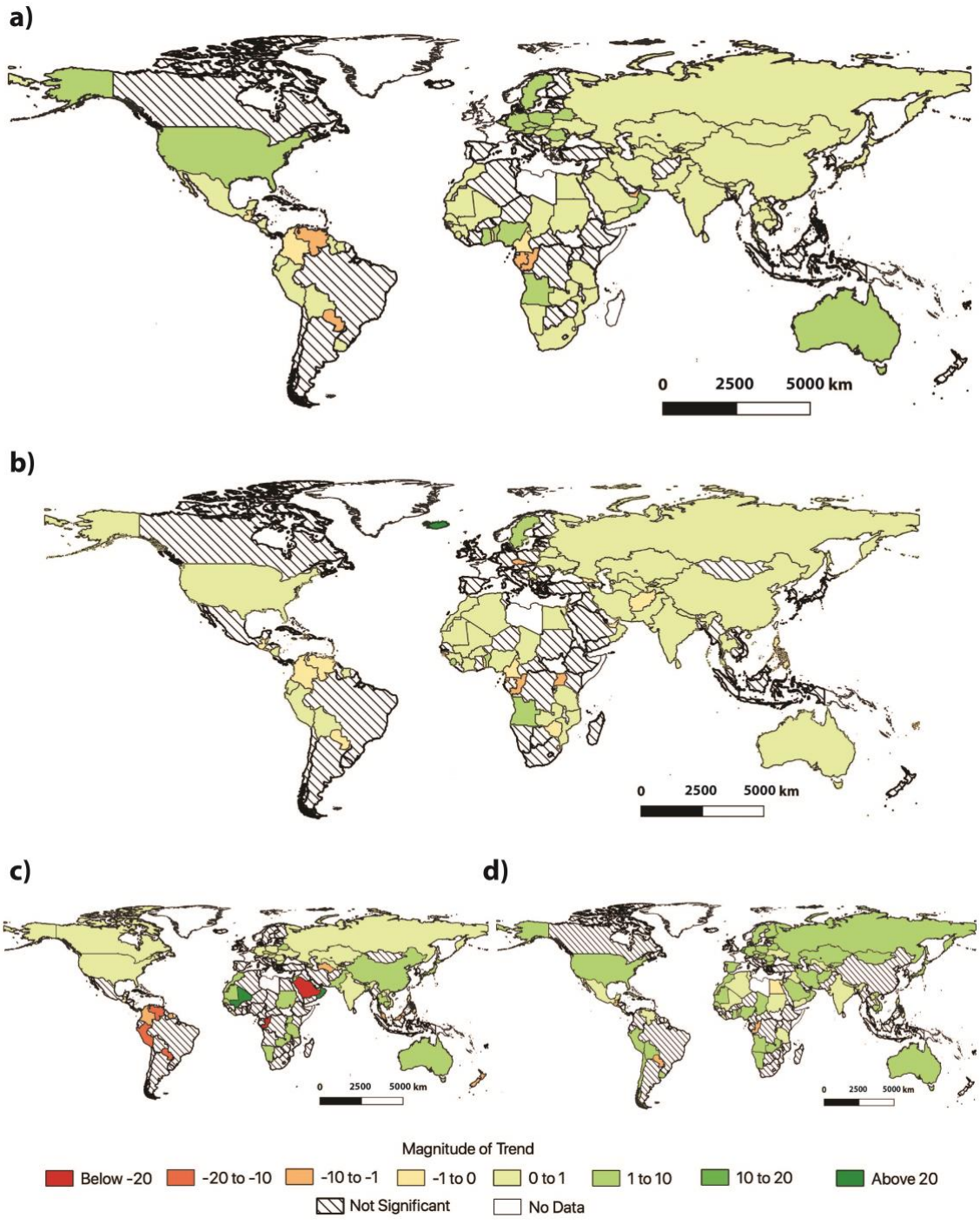


Figure 5-2: Map of Significant Trends in Water Productivity from 1997 – 2013: a) Total Water Productivity, b) Agricultural Water Productivity, c) Industrial Water Productivity, and d) Services Water Productivity.

However, several countries are experiencing a decline in total productivity: Belize, Cameroon, Colombia, El Salvador, Eswatini, Guatemala, Gabon, Guinea-Bissau, Paraguay, The Republic of the Congo, Timor-Leste, UAE, and Venezuela. Countries such as Columbia, Guinea-Bissau, and Venezuela have had massive increases in their

industrial water withdrawals and show a decline in industrial productivity, as seen in Figure 5-2c. Cameroon and the UAE have had large increases in their agricultural withdrawals and show a decline in their agricultural water productivity, as seen in Figure 5-2b. The rest of the countries have either significant withdrawal increases or a mix of withdrawal increase coupled with declining GVA, which could be causing the decline in total productivity.

The water service productivity metric shows 88 countries having a statistically significant trend, with 78 countries showing an increasing trend. Industrial productivity has trends increasing for 47 out of 64 statistically significant countries, and agricultural productivity has 45 out of 74 countries with a rising trend. As far as trends in agriculture, Porkka et al. (2016) found that water requirements needed to generate a referenced food yield decreased in East Asia, North America, Western Europe, and Southeast Asia. We show similar findings in Figure 5-2b. However, Porkka et al. (2016) found increasing water requirements for food in Northern Africa, Southern Africa, and the Middle East. We do find a few instances of decreasing agricultural productivity in Africa, but we find that the majority of countries in Africa and the Middle East either show no trend or show an increase in agricultural productivity. There are two main reasons for the differences in these findings. First, Porkka et al. (2016) used a longer time period of analysis 1901–2009 and would thus have a better opportunity of discovering long-term trends. Second, the measures of productivity are different. This study focused on productivity in terms of ($/m^3), whereas Porkka et al. (2016) focused on yield. Our measure is tied to value added and is thus subject to commodity prices. So even though yield may decrease, a crop could have a high and or rising commodity price, which would result in a rise in productivity in terms of ($/m^3).

It may appear that the services water productivity is driving the overall total water productivity trend, but it is important to remember the calculation for total water productivity factors in the proportion of water used by each sector. Thus, since services water use is typically low, the overall effect of the services water productivity is mitigated within the total productivity calculation. Ultimately, for the majority of countries that exhibit a statistically significant trend, all productivity metrics are rising. However, some countries are experiencing an increase in productivity even though they see an increase in withdrawals. An example of this is China, which has seen a rise of total water productivity from \$3.4/m^3 to \$13/m^3. However, China's water withdrawals have increased from 525 to 598 billion cubic meters. This example illustrates the importance of investigating the reason behind a change in productivity. We see here that an increase in productivity does not necessarily amount to a decrease in overall withdrawals.

5.4.2 Water stress and water productivity

Results for the panel regressions of water stress and water productivity can be found in Table 5-5. The global model was run for all available countries (166). Based on the Hausman test, the fixed effects model is more appropriate here (Prob > chi^2= 0.00). Reading through the global fixed effects result, if water productivity increases by 1%, we would expect stress to decrease by 0.81%. This example of a 1% difference is one instance from the log-log relationship identified in the regressions. For example, a 10% increase in productivity would result in an 8.1% decrease in stress. A 10% increase in productivity would be going from \$10/m^3 to \$11/m^3. The coefficient remains similar across all models, as does the negative relationship. This robust relationship is in contrast to evidence against the usefulness of productivity found in more localized case studies (Wichelns, 2014). Lankford (2013) also suggested that there could be adverse side effects

to increased productivity, such as a rebound effect. Given that the relationship remained negative both across the OLS and fixed effects regressions as well as globally and the four different economic levels, the results robustly support the negative relationship for the sample and time steps used here. For a comparison of how these results change based on the other two productivity metrics found in Table 5-4, please see Appendix C.

Table 5-5: Regression results for water stress versus water productivity[a]

	Global		High Income		Upper Middle		Lower Middle		Low	
	OLS	Fixed	OLS	Fixed	OLS	Fixed	OLS	Fixed	OLS	Fixed
Coefficient	-0.23***	-0.81***	-0.51**	-0.96***	-0.68***	-0.85***	-0.98***	-0.92***	-0.96***	-0.69***
Robust Errors[b]	0.05	0.05	0.2	0.08	0.16	0.11	0.10	0.04	0.07	0.1
R2	0.03	0.75	0.04	0.81	0.12	0.82	0.32	0.94	0.46	0.71
No. Countries		166		47		60		79		64
Avg. No. of Years		4.4		3.1		2.7		2.7		3.3

[a]Each column represents a different model specification, i.e. high income countries versus low income countries. The top row shows whether OLS or fixed effects regression were used. The dependent variable is the natural log of water stress. The independent variable is the natural log of Productivity_no_Cr.

[b]Shows robust errors for OLS regressions and clustered robust errors for fixed effects regressions.

***p<0.01

**p<0.05

We found a much higher variation of water stress to water productivity within a country through time compared to between countries. This relationship can be seen by looking at the R^2 values for the fixed effects regression versus the OLS regressions. All models showed this relationship. The OLS shows variance between countries or how water stress differs by country, while the fixed effect regressions show the variance within a country or how stress changes over time for each country. For example, the global model explains that 75% of the variance in water stress within countries is attributed to productivity. However, only 3% of the variation in water stress between countries can be attributed to productivity. The largest variance within countries can be found in lower-middle income countries at 94%. These findings show that productivity does not explain why Zambia may have less water stress than the United Kingdom. However, if we were looking at how water stress has changed within Zambia, we could expect that as their productivity increases, there, in turn, would be a decrease in water stress. This validates the negative relationship and allows policymakers to understand that by targeting productivity, they could have the potential to lessen water stress (assuming that this effect dominates over the impact of stress on productivity).

5.4.3 Water stress and drivers

This analysis shows how drivers are related to water stress and is based on a backward stepwise removal process across five separate models. These model results can be found in Table 5-6. Model (1) incorporates all drivers, including water productivity. Model (1) accounts for 62% of the variance in water stress between countries, but 96% of the variation within countries. The results show a positive statistically significant relationship between water stress and GDP and the percent of cultivated land, and a negative association with population and productivity for the OLS version. It also shows

a positive relationship with temperature and a negative relationship with precipitation, as was expected (Le Blanc and Perez, 2008; Wada and Bierkens, 2014). As for the fixed effects results, water stress exhibits statistically significant relationships with productivity, GDP, and temperature.

We remove water productivity in Model (2) in order to determine the effects of the remaining drivers. Model (2) accounts for 41% of the variance in water stress between countries. However, the variance within countries now drops to 27%, solidifying the impact water productivity has on the stress within a country. As far as the OLS results for Model (2), the nature and significance remain the same as Model (1). For the fixed effects results of Model (2), GDP is now no longer significant. This indicates a form of overlap between productivity and GDP, which could be explained by the inclusion of a country's wealth in its productivity calculation.

Models (3)–(5) were generated by removing drivers that showed low statistical significance based primarily on the fixed effects regression results. In Model (3), GDP is removed due to its lack of statistical significance in the fixed effects regression results in Model (2). Model (3) accounts for 31% of the variation in stress between countries and 27% of the variance in water stress within countries. Model (3) fixed effects results show a statistically significant relationship between water stress and population, cultivated land, political stability, temperature, and precipitation. However, precipitation is not as significant as the other three drivers, so it is removed in Model (4). Once precipitation is removed from the analysis, the variance between countries drops to only 5%, highlighting its importance. Finally, temperature is removed in Model (5), since it is not significant in the OLS regression. When excluding temperature in Model (5), the OLS and fixed effects R^2 values change by only 1%.

Table 5-6 Regression results for water stress versus potential drivers[a]

	Model 1		Model 2		Model 3		Model 4		Model 5	
Variables	OLS	Fixed	OLS	Fixed	OLS	Fixed	OLS	Fixed	OLS	Fixed
lnProductivity	-0.92*** [0.04]	-0.97*** [0.02]								
lnGDP	1.23*** [0.05]	0.98*** [0.04]	0.63*** [0.05]	0.05 [0.11]						
lnPopulation	-1.23*** [0.06]	0.06 [0.07]	-0.56*** [0.06]	0.91*** [0.17]	0.12*** [0.03]	0.89*** [0.15]	0.21*** [0.04]	0.88*** [0.15]	0.21*** [0.03]	0.92*** [0.16]
Cultivated Land	0.04*** [0.00]	-0.00 [0.00]	0.03*** [0.00]	0.01** [0.01]	0.02*** [0.00]	0.01** [0.01]	0.01** [0.00]	0.01** [0.01]	0.01*** [0.00]	0.01* [0.01]
Political Stability	-0.00 [0.00]	0.00 [0.00]	-0.01 [0.00]	0.01** [0.00]	0.02*** [0.00]	0.00** [0.00]	0.01**[0.00]	0.00** [0.00]	0.01***[0.00]	0.01*** [0.00]
Temperature	0.09*** [0.01]	-0.02*** [0.01]	0.07*** [0.01]	-0.08** [0.03]	0.05*** [0.01]	-0.08*** [0.03]	-0.00 [0.01]	-0.08*** [0.03]		
Precipitation	-0.02*** [0.00]	-0.00 [0.00]	-0.02*** [0.00]	0.00* [0.00]	-0.02*** [0.00]	0.00* [0.00]				
R2 Overall[b]	0.62	0.96	0.41	0.27	0.31	0.27	0.05	0.27	0.04	0.26

[a]Each column represents a different model specification. The analysis was conducted using backwards stepwise elimination. Productivity was removed first to determine the overall effects of the additional variables. Following this, insignificant variables were removed based on the fixed effects regressions results. The top row shows whether OLS or fixed effects regression were used. The dependent variable is the natural log of water stress. Values in [] show robust errors for OLS regressions and clustered robust errors for fixed effects regressions.

[b]R2 value for OLS regressions is the 'overall R2' value. R2 for fixed effects regressions is the 'within R2' value.

***p<0.01

**p<0.05

*p<0.1

There are several interesting results from these findings. There is a negative relationship between population and water stress in the OLS regressions for both Models (1) and (2). Once GDP is removed from the analysis, the relationship turns positive. A possible reason for this could be due to the large water stress values found in MENA, such as Bahrain, Israel, Kuwait, Oman, Qatar, United Arab Emirates, and also Singapore. Each of these countries has a relatively high GDP, coupled with a lower population. The reason why these countries could sway the relationship in the OLS regression and not the fixed effects is due to the OLS looking at all values as a single cross section of data. So essentially, each of these countries is represented five times within the OLS regression model. It is important to note that the positive relationship between stress and population that we had expected is seen across all models for the fixed effects regressions.

We find a positive and statistically significant relationship between temperature and water stress in the OLS version of Models (1)–(3). This corroborates a finding that an "increase in irrigation water consumption is primarily driven by rising regional temperature" (Wada and Bierkens, 2014). However, the fixed effect regressions across all models show a negative relationship. When Models (1)–(4) were run across subregions, the only two regions to exhibit this similar relationship were found in Eastern Europe and Latin America. Specific Eastern European countries, such as Belarus, Bulgaria, the Czech Republic, Hungary, Moldova, Poland, Romania, Russia, Slovakia, and Ukraine, were found to have some decline in water stress between 1997 and 2013, coupled with a decrease in average temperature (albeit a small one). This seems to have influenced the relationship between temperature and water stress in the fixed effect regression models. This could potentially be improved by adding more data points in order to generate a longer time series.

We found several statistically significant relationships between the drivers and water stress in terms of both the variation in stress between countries, but also within a country. The main drivers in this analysis that are related to variation in water stress by country are a combination of productivity, GDP, population, percent of cultivated land, temperature, and precipitation. This is based on the OLS findings in Model (1) found in Table 5-6. However, we found that water productivity only accounts for 3% of the variation in water stress based on the OLS findings in the global model found in Table 5-5. Based on Models (4) and (5) found in Table 5-6, we also find that the combination of population, cultivated land, temperature, and political stability result in only a 4 to 5% variation in water stress. Thus, based on our model specifications, we can reasonably say that the variation in water stress across countries is associated with GDP and precipitation. We also see that some developing countries are exhibiting an increase in water stress, whereas 19 high or upper-middle-income countries are starting to show signs of decreasing stress (Figure 5-1). Adding this to our finding of the positive association of GDP with stress across countries might suggest the presence of a Kuznets curve. However, studies that have previously looked at water usage and income have yet to definitively prove its existence (Duarte et al., 2013).

Across time, within a country, precipitation does not play as large of a role, while GDP also becomes insignificant when water productivity is removed from the model. This leaves population as a principal driver of the variation in water stress within a country. We negate temperature here since the variation in water stress does not change with its removal in Model (5) found in Table 5-6. There is also a statistically significant relationship between water stress and cultivated land as well as political stability in Models (3)–(5) found in Table 5-6. This shows an increase in cultivated land, and an increase in political stability are related to an increase in stress. The positive relationship

between stress and cultivated land was expected (Mancosu et al., 2015). However, the positive relationship with political stability is in contrast to our initial hypothesis. This could be explained since countries with higher GDP may be associated with higher political stability, even though we tested for collinearity between these two drivers.

5.4.4 Limitations

Conducting analysis on the scale reported in this paper has been challenging because of several data limitations. FAO Aquastat (2019) provides time series data on country-level water resource availability, water withdrawals, environmental flow requirements, irrigation, and several other water resource categories. However, data are only reported on 5-year time steps and becomes increasingly intermittent the further back one goes in time. Currently, around half of the countries in FAO Aquastat (2019) have data on whether water withdrawals come from surface or groundwater. However, no data are reported on sectoral water usage in regard to whether or not water is withdrawn from surface or groundwater sources. This would be a useful analysis as it could show whether groundwater reserves or surface water is bearing the brunt of water stress, and how it varies by sector. Water quality is another important factor that would be useful to factor in but was excluded due to limited data. Poor water quality limits the amount of water available for use. Thus, water stress values may actually be higher than reported. Quality could also affect stress and productivity based on the intended use; that is, water for irrigation is held to a different standard than drinking water (USDA, 2011). Hot spots of water stress based on water quality issues could occur due to increasing salinization, such as in coastal Bangladesh (Vineis et al., 2011; Chen and Mueller, 2018).

Because the analysis has been done using national data, sub-national spatial heterogeneity has not been analyzed, though it can be significant, particularly in large

countries. For example, there are several hotspots of water stress in the United States, such as the American Southwest, where groundwater is relied on more heavily (Wada and Bierkens, 2014). However, the overall water stress value for the United States may be relatively low due to areas such as the Northeast that have low water stress (Wada and Bierkens, 2014). The same holds true for water productivity, which is likely to have spatial ambiguities such as reliance on irrigated agriculture.

The results of some of the regressions to identify the effect of drivers raised questions about plausible mechanisms, such as the negative relationship between water stress and population in the OLS Models (1) and (2) found in Table 5-6. A negative relationship between temperature and stress was identified across the fixed effects models in Table 5-6. These show the limitations of the given models and their sensitivity to abnormal conditions, such as a decrease in temperature and an increase in stress found in some Eastern European countries. Certain drought conditions may also have a nonlinear effect with water stress, as at a certain point, agriculture may no longer be viable, and irrigation water needs could decline or be curtailed, which occasionally happens in the United States (Stubbs, 2016). Thus, these models could be greatly improved by adding more time steps, gathering new and updated information on all metrics, and incorporating multiple scales of analysis. In addition, global water models such as those reviewed in Wada et al. (2016) separate their analyses into the subsectors of water usage: domestic, industrial, and agricultural. This offers a more nuanced approach to understanding the specific drivers and mechanisms for each of these subsectors instead of total water usage and or total water stress. Moving forward, it would be useful to conduct analyses looking at what drives water stress in these three water usage sectors and how productivity has the ability to assuage each sector's stress.

Finally, there are some concerns around the usefulness of the productivity indicator and its ability to help alleviate water scarcity conditions (Lankford, 2013; Wichelns, 2014). Clement (2013) also warns of the unintended consequences of increasing productivity, mentioning that switching to more productive crops could price poorer farmers out of the market. This same argument was made by Boelens and Vos (2012), who warn of applying normative productivity and efficiency ideals on countries because it might harm the poor. It is also important to note that the primary rationale behind increasing water productivity could be for profit rather than a reduction in water usage. This is also subject to spatial heterogeneity.

5.5 Conclusions

We found that water stress is increasing in developing countries such as Latin American and Africa as well as countries in the Middle East. However, we only found evidence of 29 countries out of 179 with a significant decreasing trend, which is in contrast to 44 countries found to show a decrease in a recent report (FAO, 2018a). Water productivity was found to be generally increasing worldwide, with a few notable exceptions in South American and Africa. On the whole, we expect that as a country becomes more developed (i.e. its GDP rises), it will become more productive in its use of water. We are now able to understand whether or not a country's rising water productivity is solely related to the growing economy, or if it is due to a growing economy and a decline in water usage. This key piece of information is essential since the panel regression analysis showed an overall negative relationship between water stress and water productivity. This relationship is based on global data that is imperfect, but the negative relationship across both OLS and fixed effect regression models for five different cases (global and four economic tiers) strengthens the case that a negative

relationship is present. These results give substantive evidence to implement policies targeted to increase productivity to lower water stress and overall water scarcity.

We also find that water productivity plays a far greater role in water stress within a country than differentiating between levels of stress across countries. This research intuits that the leading cause of water stress between countries is based more on a country's climate, in terms of precipitation, and development stage. However, productivity plays a much higher role in the change in water stress within a country, giving strength to the argument that productivity should be a policy target to reduce stress. In addition to productivity, we find that population, cultivated land, and political stability are related to water stress levels within a country.

Overall, this study gives evidence to the intuition that improving productivity can decrease water stress. As more reliable data and metrics become available, additional studies should be conducted to explore the relationship and causality of not only water productivity and water stress across the three primary sectors but also water efficiency. There is also a need to understand how and what types of efficiency techniques to incorporate to increase productivity and lower stress and how the effects of these techniques can promote sustainable use of water resources. An example of this could be to study the specific drivers of each sub-productivity metric, that is, agriculture, industry, and services, to target specific mechanisms to enhance productivity. As water scarcity becomes more frequent due to climate change and increased pressure from anthropogenic forces, it becomes even more imperative to understand how to implement these performance metrics to obtain the greatest reduction in water scarcity.

APPENDIX C: SUPPLEMENTARY INFORMATION TO CHAPTER 5

Contents of this file

Tables Supplementary 5-1 to 5-2

Introduction

Supplementary Tables 5-1 and 5-2 show the results of OLS and fixed effects regressions of water stress versus two alternative water productivity metrics respectively. The productivity metric in Supplementary Table 5-1 was calculated using Equations [2-6] from Chapter 5 and using data from FAO Aquastat, 2019; Lui et al., 2016; and the World Bank Databank, 2019. The productivity metric in Supplementary Table 5-2 was calculated based on the World Bank definition of water productivity (GDP divided by total water withdrawals). A complete dataset including these calculated values of water productivity are publicly available [Doeffinger and Hall, 2019].

Supplementary Table 5-1: Regression results for water stress versus water productivity[a]

	Global		High Income		Upper Middle		Lower Middle		Low	
	OLS	Fixed	OLS	Fixed	OLS	Fixed	OLS	Fixed	OLS	Fixed
Coefficient	-0.07	-0.74***	-0.25	-0.96***	-0.27	-0.89***	-0.81***	-0.88***	-0.92***	-0.62***
Robust Errors[b]	0.06	0.08	0.26	0.18	0.17	0.12	0.10	0.05	0.09	0.18
R2	0.00	0.64	0.01	0.73	0.02	0.81	0.25	0.90	0.44	0.58
No. Countries		149		41		50		63		53
Avg. No. of Years		3.2		2.2		2.2		2.2		2.5

[a]Each column represents a different model specification, i.e. high income countries versus low income countries. The top row shows whether OLS or fixed effects regression were used. The dependent variable is the natural log of water stress. The independent variable is the natural log of Productivity calculated by using Equations (2-6).

[b]Shows robust errors for OLS regressions and clustered robust errors for fixed effects regressions.
***p<0.01

Supplementary Table 5-2: Regression results for water stress versus water productivity[a]

	Global		High Income		Upper Middle		Lower Middle		Low	
	OLS	Fixed	OLS	Fixed	OLS	Fixed	OLS	Fixed	OLS	Fixed
Coefficient	-0.12***	-0.78***	-0.18	-0.91**	-0.47***	-0.85***	-0.81***	-0.90***	-0.92***	-0.71***
Robust Errors[b]	0.05	0.05	0.17	0.06	0.14	0.09	0.11	0.04	0.07	0.10
R2	0.01	0.74	0.01	0.75	0.07	0.84	0.26	0.94	0.44	0.76
No. Countries	-	175	-	48	-	68	-	86	-	70
Avg. No. of Years	-	4.9	-	4	-	2.7	-	2.8	-	3.4

[a]Each column represents a different model specification, i.e. high income countries versus low income countries. The top row shows whether OLS or fixed effects regression were used. The dependent variable is the natural log of water stress. The independent variable is the natural log of WB_Productivity.

[b]Shows robust errors for OLS regressions and clustered robust errors for fixed effects regressions.
***p<0.01
**p<0.05

6 Concluding Remarks

6.1 Thesis Summary

The primary goal of this thesis has been to operationalize the concept of water security. This aim was separated into seven objectives: (1) develop a comprehensive framing of water security, (2) develop a replicable methodology to operationalize water security, (3) develop a way to quickly visualise and compare the multiple dimensions of water security, (4) develop a multiscale assessment of water security, (5) map water security across scales to determine if spatial heterogeneity is present, (6) calculate a time series for water productivity, and (7) empirically test the relationship between water stress and water productivity. These objectives were achieved through three separate studies that have been submitted to peer-reviewed journals.

The first three objectives were the focus of Chapter 3. To start, a water security framework was created, based principally on previous work by Briscoe (2009), along with work by Ostrom (2007). This systems-based framing of water security strives to provide a broad understanding of the current water security situation in a given country. A diagnostic methodology is complementary to this framing, as the first step in the method is to synthesize large swathes of information to determine the current system state (i.e. level of water security). Since an appropriate level of water security is context dependent, there was a focus on highlighting key challenges (i.e. risks) and opportunities. This was done using a dashboard tool that hones the methodology's first step by highlighting key challenges in terms of system performance, outcomes across actors, drivers of change, and the water resource system. Thus, the dashboard facilitates a quick

and streamlined approach to Step 1 of the diagnostic methodology and thereby assists the process of reaching a working or initial diagnosis. This dashboard tool acts as a starting point for future, more detailed analyses. Due to the harmonized dataset, it also allows for cross-country comparisons.

Chapter 4 sought to address the fourth and fifth objectives. Even though spatial heterogeneity can be lost in larger water scale security studies, very few tiered multiscale assessments have been conducted to investigate spatial heterogeneity across scales. This could be a result of the four considerations that go into the selection of spatial scale being exacerbated during a multiscale assessment. These considerations were revisited repeatedly throughout the creation of a water security index, with data being amassed for the United States of America (USA), as well as for two sub-national administrative boundaries. The water security index was comprised of indicators focused on system performance and outcomes and was limited due to data availability across scales. Despite the difficulties encountered in its creation, this index demonstrates the spatial heterogeneity of water insecurity across states and counties within the USA.

The last two objectives were approached in Chapter 5. In order to meet these objectives, the framing of water security was narrowed to specifically evaluate the untested relationship between water stress and water productivity, along with additional drivers of water stress. Chapter 5 continues the use of the framing of water security detailed in Chapter 3 by focusing on drivers and key indicators of system performance. The relationship between the calculated values of stress and productivity had yet to be studied at this scale, primarily due to the creation of a new methodology for productivity set out by the United Nations (FAO, 2019b). This methodology was used to create a time series of water productivity for 166 countries. This study found a negative relationship

between productivity and stress. It also found that drivers of stress vary through time when compared across countries versus within countries.

The findings of this thesis, as well as the methods and tools developed, have the potential to impact both academic audiences and policymakers. This is achieved through the development of innovative ways to evaluate water security in the form of diagnostics, a multiscale assessment, and statistical analyses. The dashboard tool and the systematic creation of a sub-national water security index highlight key water security challenges and hotspots that can be used by policymakers to inform potential interventions. This thesis also sheds light on relationships between water security indicators, and it can ultimately help focus future water security analyses.

6.2 Main Research Contributions

The primary research contributions of this thesis are in the form of methodological advancements to assess water security. However, each of these methodologies is underscored by the multi-dimensional framing of water security set out in Chapter 3. Rather than focusing on specific indicators, this framing is based on seven key categories of information needed to assess water security. These seven categories of information are featured throughout the thesis. The following principal research contributions of this thesis are thus reliant on the water security framing:

- A diagnostic methodology was generated to operationalize a comprehensive framing of water security to capture the current water security situation in a given country. This was done through a dashboard format that highlights key water security challenges to support the communication and visualisation of the first step in a broader diagnostic methodology. This dashboard is unique as it

incorporates trends and is based on a harmonized set of national indicators that allow for cross-country comparisons.

- Four key considerations regarding the selection of spatial scale in water security analyses are discussed. This discussion is useful for understanding the challenges that go into selecting a spatial scale of analysis for any water security study, but also highlights potential issues with multiscale assessments of the concept.
- To compare water security across scales, a systematic methodology was developed. This was done through the creation of a composite indicator at two sub-national scales. The index uses similar underlying sub-indicators, allowing it to be compared across scales.
- The definitions and methods for the calculation of water productivity versus water efficiency were discussed. This led to one of the first time series of water productivity being generated for 166 countries.
- A novel empirical analysis was conducted between the two SDG 6.4 indicators: water productivity and water stress. This empirical analysis allowed for the consideration of relationships between productivity and stress, as well as additional drivers of stress through time both across and within countries.

6.3 Practical Applications

In addition to the research contributions, this thesis is aimed at operationalizing water security in a way that has practical applications for a range of stakeholders, including policymakers and water resource managers. The practical applications of this thesis are as follows:

- The dashboard tool generated in Chapter 3 has practical applications and could be employed by a range of users, such as large multi-lateral development

organizations. The dashboard format offers a streamlined dissemination of information across five key categories that are crucial to the understanding of water security. If directly linked to the underlying information sources, this tool could allow for the rapid assessment of a given country's key challenges and strengths of a given country, while also allowing for cross-country comparisons.

- Even though the nation-state is a commonly used scale of assessment, there is known sub-national heterogeneity (Vörösmarty et al., 2010; Cook and Bakker, 2012; Gain et al., 2016), and the methodology developed in Chapter 4 is a systematic way to capture this heterogeneity. Given its focus on system performance and outcomes, it is primed for practical applications. When combined with a national assessment, it could help to highlight hotspots of insecurity and focus interventions.
- The findings in Chapter 5 also have practical implications. It is found that water stress has only had a statistically significant decreasing trend for 29 out of 179 countries. This implies that the majority of countries are not reducing their water usage (due to underlying data, supply remains constant in the water stress calculation). Thus, more efforts should be made to curb unsustainable usage. The negative relationship found between productivity and stress, specifically when looking within a given country, provides initial evidence for the assumption that increasing productivity will be a valid way to lessen scarcity, and therein improve water security. This is the first study to measure the relationship between stress and productivity, and given these findings, it proves an interesting area of research both within academia as well as by practitioners.

6.4 Cross-Cutting Findings and Recommendations

This thesis primarily worked with indicators based on empirical data from secondary sources to explore the status and trends of water security across scales. Several key insights emerged throughout this thesis regarding indicators and scaling that should be considered by others interested in pursuing this path of study. First, when analyzing water security using empirical data, one of the most limiting factors is data availability. In addition, indicators may not adequately communicate all the information necessary to develop a full picture of an area's water security. For example, information relating to historical and cultural context and the political economy of an area may not lend themselves to an indicator format or be fully understood through the dashboard structure. However, even with these limitations, indicators based on empirical data allow for a robust understanding of water security across scales and allow for comparisons between areas, e.g. countries. The methods laid out in Chapters 3 – 5 could be replicated in other studies in the future or continually updated as new indicators emerge or as their accuracy improves. This is especially true for the dashboard generated in Chapter 3.

Second, some underlying contextual understanding of a given area is instrumental in interpreting water security indicators. This is particularly true in the case of the dashboard used in Chapter 3, but also the composite index found in Chapter 4. This contextual knowledge allows for a more nuanced understanding of the data and the story that may emerge from it, and it may also prove useful in appraising the accuracy of the data.

Finally, when reflecting on indicators, it also became apparent that agricultural water productivity may provide more value than the total productivity indicator used in SDG 6.4.1. This is because the service and industrial water productivity, when taken on their own, are less accurate measures of productivity, as the water used in each respective

sector only contributes to a fraction of each sector's income. When looking at total productivity, this is accounted for by taking the percentage of water used across each sector (FAO, 2019b). However, if data is limited, it would be recommended to put more resources into accurately quantifying agricultural productivity, as was done in Chapter 4.

In terms of spatial scaling, it is an important aspect of water security that is referred to throughout this thesis. As mentioned above, any water security study will be limited by data availability. This has the potential to influence how water security is framed at different scales. For example, as is seen in Table 2-3, environmental outcomes were not evaluated as frequently at smaller spatial scales. Thus, it may be worthwhile to start with a broad framing of water security, but be aware that it will likely be narrowed and reshaped by data availability at a given scale. This limitation is especially present when attempting a multiscale analysis. For example, when comparing a composite index across scales, narrowing a broad framing of water security to solely focus on performance and outcomes is a reasonable recommendation, as the drivers and contextual factors affecting water security may not hold across scales. Several well-known composite indices also employ performance and outcome based sub-indicators (Jacobs et al., 2004). Further, based on this thesis, it is recommended that future national assessments of water security that endeavor to offer a comprehensive assessment be accompanied by a sub-national assessment. This could be done across administrative boundaries, such as states or provinces. The results in Chapter 4 show the extensiveness of sub-national heterogeneity for the majority of the ten indicators assessed and show that, even though challenging, a multiscale analysis of water security is a feasible endeavor.

In addition, there is no set spatial scale of analysis for water security as it is applicable across scales. However, it may prove more likely to determine whether an individual has actually 'achieved' water security (i.e. staying within a given risk

tolerance) rather than a nation, not only due to the spatial heterogeneity present at larger scales, but also due to the variation in possible risk tolerances that would undoubtedly emerge at larger scales. Nevertheless, many investment decisions are made at scales larger than the individual, and improving water security-related outcomes offers a worthwhile goal for an area (e.g. country) to strive to achieve. Thus, it is urged that the assessment of the concept be continued across scales, with a renewed focus on multiscale studies as well as a merging between bottom-up and top-down analyses.

6.5 Future Research

There are several different directions of future research. Future research in terms of the diagnostic methodology and dashboard could continue in three primary ways. First, the underlying data in the dashboard could be improved. This could be done by the inclusion of superior indicators as they become available, such as those for water quality and variation in water supply between years. In the future, the historical and cultural context category could be added to the dashboard in the form of a timeline, as was used by Sadoff et al. (2015). This was not included in the current iteration of the dashboard since, at present, there is no standardized way to construct such a timeline for water security studies. Essentially, the type of information that could be included in such a timeline will vary based on country, but a guideline regarding the appropriate timeframe, frequency, or primary topics of inclusion could be created. Also, more insight from a political economy perspective would do much to further the understanding of the underlying dynamics that lead to policies being chosen, as Allan (1999) suggested. Second, Chapter 3 only illustrated the first step in the overall six-step diagnostic methodology. More work will need to be done to test the validity of the entire methodology. Third, the diagnostic methodology, along with the dashboard, could be

tested across scales. This could include other administrative boundaries, such as a city. However, the underlying data included in the assessment would be expected to change based on scale, not only due to data availability, but also due to changing objectives and values.

The continuation of the multiscale assessment outlined in Chapter 4 could continue in several ways. The index could be tailored based on desired objectives by changing the normalization, weighting, or aggregation methods. The index could be applied to different countries. As of now, it is not common to have standardized sub-national metrics across all countries. Thus, for this methodology to be applied to a different nation, the underlying indicators will likely change. Currently, the index is compared across each scale, assuming linear changes across scales. This is often not the case. Future work could thus elaborate on the cross-scale dynamics of indicators, such as water stress. This would greatly improve the accuracy of information gathered through upscaling and downscaling of data. Given Chapter 4's focus on administrative boundaries, socio-demographic data is available across each of the analysis scales. Thus, future research could be conducted into the characteristics of populations at risk from water insecurity, such as the role of poverty or inequality.

The relationship between water stress and water productivity studied in Chapter 5 can be improved primarily by separating out the different sub-indicators of water productivity (i.e. agricultural, industrial, and service), and testing each sectors' change in productivity to the change in water stress. This would allow for a more nuanced understanding of stress and productivity, but also test the usefulness of each sectoral productivity value. It could prove useful to test these relationships across scales to determine whether or not they remain consistent. The underlying empirical analysis could also be improved as more reliable data becomes available for each of the primary

indicators. Finally, more work needs to be done in terms of determining causation, since as of now, only the indication of a relationship exists.

This thesis has primarily focused on administrative boundaries and collecting secondary data. Yet, throughout the literature, individuals' perceptions of water are recognized to play an integral part in the creation of useful and effective policies (Jepson et al., 2017a; Koehler et al., 2018). There is also recognition in the literature that top-down approaches would benefit from bottom-up approaches (Conway et al., 2019), and this has been found in the water security literature (WWAP, 2012; Dadson et al., 2013; Garrick et al., 2020). The methods developed in this thesis (dashboard tool and multiscale assessment) could be complemented by bottom-up approaches. For example, through the multiscale assessment generated in Chapter 4, counties with high water insecurity could be identified. Household surveys and interviews could then be focused on these insecure counties in order to inform more effective policy.

Ultimately, this thesis strives to increase the dialogue surrounding water security as well as develop methodologies to better understand the complex concept. Yet, as demonstrated throughout this section, there is still a need for more evidence-based assessments to help navigate the path to water security. The suggestions above provide a way forward, but it is also important to remember that water is just one aspect of the much larger water-food-energy nexus. As Zeitoun (2011) points out, water security is not an isolated concept, but rather part of a larger web of security concerns. Thus, the importance of the evaluation and communication of water security is vital not only to decreasing water-related risk, but also to reducing broader societal risk as water is connected to reducing both food and energy insecurity.

APPENDIX D: CO-AUTHOR PAPER CONTRIBUTION STATEMENTS

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1. *A diagnostic dashboard to evaluate country water security*
2. *Assessing water security across scales: A case study of the United States*
3. *Water stress and productivity: An empirical analysis of trends and drivers*

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