Scarcity and Scale: Designing Water Markets for People and the Environment

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The water conditions experienced by society are not just physical. They result from the interplay between the climate system and the institutions that society has developed over time to deal with it.

Giulio Boccaletti - Water A Biography pg. 289

Apportion of Credit

The idea of pursuing a PhD had been in my mind since at least 2009. However, I could not have foreseen how this final product would materialize, even in 2018 when this journey began. The decision to take this leap was not easy; I left a job that I loved, with colleagues I greatly respected, doing work I was deeply passionate about to move across the Atlantic Ocean, away from my partner, and return to the life of a student.

The opportunity to study at Oxford was made possible by several members of the Global Water Team at The Nature Conservancy who had the faith and foresight to fund this work. I am forever grateful for the trust that Giulio Boccaletti, Andrea Erickson, and Tom Iseman placed in me to develop and fund the TNC Oxford Water Partnership. The idea of this partnership wouldn't have come to fruition without Dustin Garrick's strategic thinking and continuous support.

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My family's unwavering support deserves special mention. My parents supported my work even when they didn't always know where I was or what I was working on. My brother, as the first PhD in the family, set a high bar and his standard of

excellence in everything he does is contagious. However, I owe the most profound thanks to my sister, now Tía Jen, who traveled to Costa Rica several times for extended periods to help manage the homestead, enabling me to dedicate time to this dissertation, which might not have been completed without her support.

Finally, I am most thankful for my little family – which doubled in size during the PhD journey. Nela and I welcomed twins in 2021, which was transformational on every dimension I can think of. If I was honored to be your husband, and inspired by your passion for academia, I am immensely grateful to see you as a mother now. Many late nights, after putting the twins to bed, I was both physically exhausted and more driven than ever to continue advancing this work. This juxtaposition of fatherhood, with its added demands and responsibilities, fueled my determination to complete the work for our two sons.

I dedicate this thesis to the Blanco River, whose challenges with water scarcity mirror many of the pages in the dissertation, and to Dede, who passed away during the PhD but whose work ethic and support for education live on.

Abstract

Water scarcity is a pressing global challenge with far-reaching implications for economies and the environment. While the concept of water scarcity appears straightforward - a situation where demand surpasses available supply - the complexities associated with water supplies, and water demands and their dynamic socio-hydrological dimensions, underscore why solutions designed to address water scarcity have been elusive. Water scarcity is often characterized as a complex issue rooted in water governance. This complexity arises because the juncture where water demands surpass available supply, such as a city's reservoir level or a river's discharge, is intricately linked to a network of political, social, economic, and administrative systems that collectively shape the utilization and management of water - what scholars refer to as water governance.

Solutions to address water scarcity historically focused on augmenting water supplies, for example building more reservoirs or desalination plants. However, these approaches are exceedingly costly, carry negative environmental externalities, and struggle to alleviate water scarcity. On the demand side of the equation, economists have lobbied for incentives for decades to decrease water demand, including the use of water markets. Yet, despite decades of global experimentation, the outcomes have yielded mixed results. Recently, there has been increasing momentum to utilize incentives to drive sustainable water use. This shift is motivated by the recognition that the magnitude of the water scarcity challenge, both in the present and the near future, is substantial, and few traditional conservation tools offer the potential for scalability as effectively as incentives.

In this context, the aims and objectives of this thesis are motivated by the recognition that water scarcity is a function of the supply and demand of water and that a future marked by shifting water demands and variable water supply presents a significant challenge to both economies and the environment. Additionally, this thesis is driven by the observation that, to date, experiments with using incentives

for sustainable water use have struggled to meet their potential in terms of public and private benefits, and to respond at scale. The primary goal of this doctoral research is to identify viable pathways for market-based incentives to effectively address different types of water scarcity by reducing water demand and achieving a sustainable water balance that ensures sufficient water availability, at appropriate times, for both people and the environment.

This thesis contends that previous experiments with market-based incentives typically adopted a one-size-fits-all approach, utilizing a single type of incentive to address specific water scarcity challenges. However, in reality, water scarcity encompasses a variety of distinct types, each requiring a tailored toolkit for effective mitigation. Consequently, while there were sporadic successes, the alignment between the incentives and the specific type of scarcity often fell short. This misalignment led to a diminished perception of water markets as a scalable solution for addressing scarcity.

To support this argument, this thesis centers on identifying the drivers of water scarcity, evaluating the performance of water markets, and assessing the trade-offs associated with environmental water transactions. I embrace an interdisciplinary perspective and integrate a multi-scaled approach to address a hierarchy of questions focusing on the potential, performance, and pathways through which incentives can contribute to sustainable water use.

The thesis sets out with a global assessment of the various types of water scarcity, their geographical distribution, and the suitability of incentive-based approaches. This analysis links the characteristics of the drivers of water scarcity to the strengths of potential solutions and paints a more nuanced understanding of the various types of water scarcity on a global scale.

Next, I zoom in on Texas, a state in the Southwestern United States known for water scarcity challenges, and the institutional conditions to promote water markets. Drawing on an original transaction data set of over 2,300 transactions between

1987-2020, I assess the performance, as well as drivers of water market transactions across multiple basins by quantifying their private and public benefits. Results provide further depth to the canvas by demonstrating that different basins have used water markets to achieve different objectives, including providing water for the environment.

Finally, I zoom into one basin in Texas, the San Saba, which is notorious for competition between upstream and downstream users, each pointing fingers at the other for a dewatered river - a phenomenon with significant consequences for freshwater ecosystems. By triangulating data from groundwater wells, surface water rights, and transactions data, I assess the trade-offs associated with various environmental water transactions. This process involves evaluating the costs and benefits for both producers and the environment within a hydrologically interconnected system where groundwater and surface water are treated differently from a governance standpoint. These results add intricate layers and hues to the canvas. They reveal that the effectiveness of environmental water transactions is akin to a finely crafted painting, where success relies on precise spatial and temporal coordination within the context of unique hydrogeological settings and the diverse needs of water users.

In conclusion, these three layers collectively underscore the central insights of this thesis. They illuminate the challenges water markets face in delivering scalable benefits to both the environment and society. These challenges arise from the multifaceted values of water, which challenge its compatibility within a traditional market framework. This thesis posits that a one-size-fits-all approach is inadequate to address water scarcity effectively; instead, it advocates for the alignment of the type of scarcity with the design of the incentive and the intended objectives, be they private or public. This tailored approach is essential to harness the potential of water markets as a tool to drive sustainable water management. Water markets should not be seen as a standalone solution but rather as an in-

tegral piece in the mosaic of solutions. By matching the right incentive to the right scarcity type, water markets can complement other strategies, contributing to the achievement of Sustainable Development Goals (SDGs) or goals of a local irrigation district. It is not a matter of 'either-or,' but rather a matter of 'how to incorporate water markets' within the broader framework of solutions. Incorporating water markets into a broader framework of solutions can help mitigate key challenges in water governance, facilitating the transition from water scarcity to water security.

List of Publications

This thesis is comprised of work that has been published in or submitted to the following peer-reviewed journals:

- **Wight, C.,** Garrick, D., and Iseman, T. (2021). Mapping incentives for sustainable water use: global potential, local pathways., 3(4), 041002. *Environmental Research Communications*.
- **Wight,C.,** Garmany, K., Arima, E., Garrick, D. Texas water markets: taking stock of their trends, drivers, and future potential. *Submitted to Ecological Economics*.
- **Wight, C.,** Garmany, K., Smith, R., Garrick, D. Targets and Tradeoffs: Designing environmental water transactions to navigate compounding competition in the San Saba River of Texas. *Submitted to Water Resources Research*.

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Chapter 1

Introduction

1.1 Rationale and context

Reducing water scarcity was identified as a target in the Sustainable Development Goals in 2015 (Water, 2018), however with only seven years left, the world is off track to achieve this target (Sadoff et al., 2020). Water scarcity poses risks to people (Boretti & Rosa, 2019), economies (Rosa et al., 2020) and the environment (Pittock & Lankford, 2010). It is estimated that nearly two thirds of the global population experiences water scarcity at least one month per year (Mekonnen & Hoekstra, 2016) and freshwater biodiversity is vanishing at an unprecedented rate (Abell & Harrison, 2020). At the same time, water is an economic input in many sectors including energy and agriculture (Davis et al., 2016; Hoekstra & Mekonnen, 2012) which means that increases in scarcity in one region can propagate across sectors and scales (Dolan et al., 2021). The search for scalable solutions to manage water sustainably has been a struggle for water managers for over 50 years, and the evidence is clear that there are no panaceas (R. Meinzen-Dick, 2007; Ostrom, 2010).

Water scarcity in simple terms refers to an excess of water demand over available supply (Steduto et al., 2012). Measuring water scarcity has evolved over the last 40 years (Alcamo et al., 1997; Cosgrove & Rijsberman, 2000; Falkenmark, 1989; Gleick, 1996; L Ohlsson, 1999;

Rijsberman, 2006; Rosa et al., 2020), however only recently has corresponding attention been paid to the drivers of water scarcity (Brauman et al., 2016; D'Odorico et al., 2019; Marston et al., 2018). Understanding the drivers of water scarcity is critical for diagnosing the problem and designing solutions that address root causes. For example, water for irrigated agriculture consistently ranks as a leading driver for water scarcity and accounts for 73% of total water withdrawals, and in arid and semi-arid regions, for more than 95% (Döll et al., 2012). Water demand for agriculture faces unprecedented challenges balancing food and water security in the face of climate change and shifting demands (Davis et al., 2017; Foley et al., 2011; Wada et al., 2013). However, there are other types of competition driving water scarcity. Competition between cities and agricultural users is intensified by climate change and population growth and is projected to increase by 50-80% by 2050 (Flörke et al., 2018; World Bank, 2018).

Historically, investments in solutions to water scarcity have favored infrastructure and supply side solutions (Gleick, 2018). Reservoirs are an example of a supply side solution that saw exponential investment and adoption in the 21st century (Doll et al., 2009). Although these solutions provide benefits to certain communities, such as hydroelectric power, irrigated agriculture, and flood control (Gleick, 2003), they also have a measurable impact on the hydrology of the rivers on the planet (Chao et al., 2008; Grill et al., 2019). Building reservoirs is increasingly cost prohibitive (Petheram & McMahon, 2019), generates negative environmental externalities (McCartney, 2009), and can paradoxically exacerbate water scarcity (Baldassarre et al., 2018). Additionally, water infrastructure built during previous climatic conditions may not be prepared to face shifting supply and demand (Ehsani et al., 2017), especially in the absence of sufficient institutions or governance (Hall et al., 2014).

Against this backdrop, economists have focused on the potential of demand-side strategies to manage water scarcity, including pricing policies and water markets (Easter et al., 1999; Howe et al., 1986). Compared with pricing policies, water markets are considered favorable from a neoliberal economic point of view because they are a voluntary mechanism of trading water between users (Chong & Sunding, 2006). The economic argument of employing water

markets in water-scarce areas focuses on shifting the demand for water to its highest value use while providing gains from trade (Brooks & Harris, 2008; Easter et al., 1999; Hearne & Easter, 1997; R. S. Meinzen-Dick, 1998). Water markets require three regulatory elements that theoretically align with calls for local solutions for water management (Foster et al., 2013; Gupta et al., 2013): (1) a cap on water extraction, (2) the allocation of water rights, and (3) trading rules for reallocating water (Easter et al., 1999). However, evidence to date suggests that high-functioning water markets are the exception, not the rule (Debaere, 2014; Garrick & Svensson, 2017), and that, in practice, water markets require sound governance for water reallocation (Casado-Perez, 2015). Barriers for water markets originate in the unique attributes that make water generally non-substitutable, a high exclusion cost, and typically undervalued resource (Brouwer et al., 2009). As a result, most experiments with formal water markets have encountered stubborn political and financial obstacles, including high transaction costs (Ayres et al., 2018; Garrick & Aylward, 2012) which have impeded progress towards implementing and scaling water markets in response to water scarcity (Garrick et al., 2020).

The aims and objectives of this thesis are motivated by the recognition that water scarcity is function of the supply and demand of water (Falkenmark, 1989; Rijsberman, 2006), that a future with shifting water demands (Flörke et al., 2018; Garrick et al., 2019) and variable water supply (Connor et al., 2012; Padowski & Gorelick, 2014) poses a significant challenge to both economies and the environment, and that to date, experiments with using incentives for sustainable water use have struggled to meet their potential in terms of public and private benefits, and respond at scale (Garrick et al., 2020; Pahl-Wostl et al., 2021).

To achieve the aims and objectives of this thesis, I employ a multi-scaled approach consisting of three steps that correspond to the following research questions. These steps focus at the global, state, and basin scales, respectively. The findings resulting from these inquiries make unique contributions to the existing literature. Moreover, when considered together, they directly align with the overarching goals of this study.

1.2 Research Questions

Research Question 1 focuses on assessing the potential of market-based incentives at the global scale: What types of demand drive water scarcity? And which incentives and investments can address those drivers in the short term and long term?

Specific objectives:

- Develop a typology of water scarcity based on demands for water and their timing
- Produce a global map, whose unit of analysis is the sub-basin showing the types of water scarcity, including basins where types overlap
- Create an analytical framework links drivers of water scarcity to different incentives and investments

Research Question 2 focuses on analyzing water market performance in Texas. A state where water scarcity is prevalent, but whose experience with markets was underrepresented in the literature: where have formal water transactions occurred in the past 30 years? Which water users have been participating in water markets, including volumes and costs, and can we detect drivers for water market activity?

Specific objectives:

- Develop original transaction data set of 2,350 transactions
- Analyze trends of water markets performance at the basin scale: e.g., directions of water flows, volumes, prices.
- Develop a Poisson fixed effects regression model to test whether certain variables related to water supply (e.g., reservoir levels) or demand (e.g., population growth) are statistically correlated with increases in water transactions

Research Question 3 focuses on environmental water transaction design in a basin with compounding scarcity by asking a hierarchy of questions:

1. Which sections of river require intervention during times of scarcity to maintain flow targets? (i.e., priority reaches)
2. In these priority reaches, what are the spatial and temporal influences of natural (geologic) and anthropogenic (water use) drivers of scarcity?
3. What volumetric contribution can different portfolios of water rights paired with different types of EWT contribute to flow targets? And what are the costs and benefits associated with each portfolio?

Specific objectives:

- Synthesize results from gain-loss studies, and groundwater monitoring wells to identify spatial and temporal dynamics of groundwater-surface water interaction
- Calculate an estimate of mass water balance for the area of interest to quantify consumptive water demands of different sources of water (e.g. groundwater vs. surface water)
- Develop a model to compare the trade-offs, in terms of their financial costs and contribution to conservation objectives of different environmental water transactions

1.3 The Thesis Storyline

This doctoral thesis is motivated by an evident gap between two observations: (1) recognition that water scarcity increasingly affects both the environment and people (Brauman et al., 2016; Dolan et al., 2021), and (2) incentives, which offer a promising theoretical solution to balance the supply and demand of water, have struggled to provide significant environmental

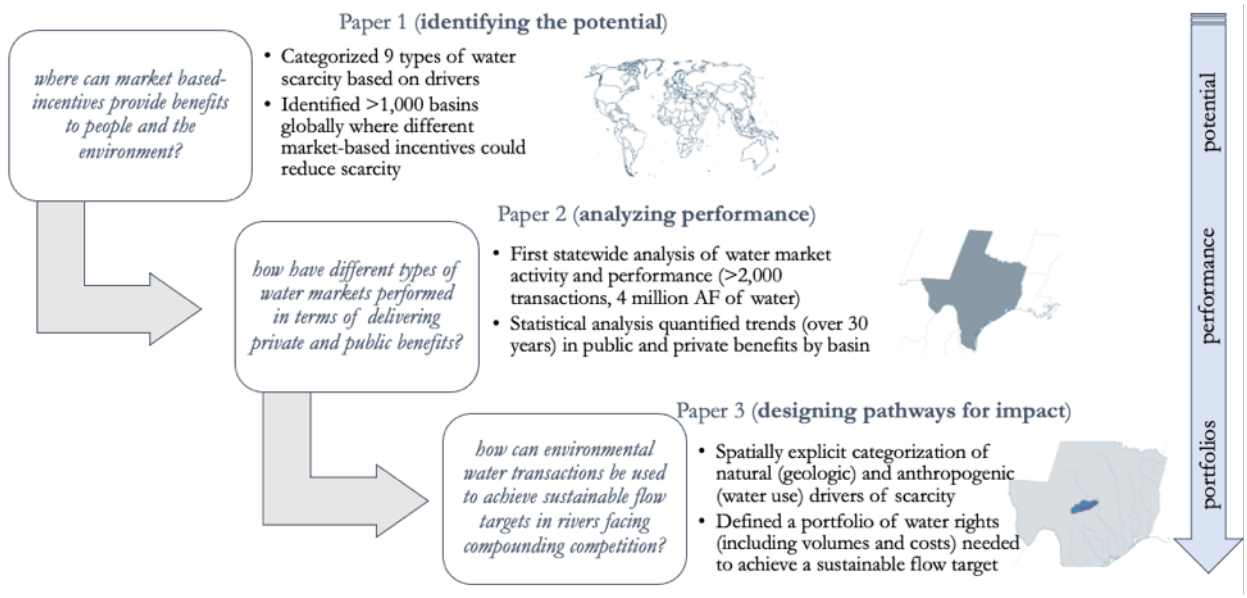

Figure 1.1: Systematic approach showing the sequencing between research objectives (in bold), the major insight (bullet points), and the follow-up question (blue) and how the findings support subsequent papers and the thesis objectives.

benefits (Bakker, 2014; Grafton et al., 2011; Kendy et al., 2018; Loomis et al., 2003; Pilz et al., 2017). To close this gap, between the theory and practice of incentives, this thesis takes a multi-scale, mixed methods approach and integrates literature from several disciplines. This thesis begins by asking the following questions: What types of water demands drive water scarcity? How are they distributed spatially? How do these variables vary temporally? Which incentives and investments can address these drivers in the short and long term? I draw on the literature to contextualize water scarcity in terms of water availability (Hoekstra, 2019) 2019) and the exacerbations in hydrologic variability due to climate change challenge water management and policy (D'Odorico & Bhattachan, 2012; Hall et al., 2014). I focus on water demands and differentiate consumptive use (Perry, 2007), water productivity, and comparative advantage (Debaere, 2014; Debaere & Kurzendoerfer, 2017), which allows me to develop a matrix to categorize water scarcity types. The results contribute to the literature on measuring water scarcity (Alcamo et al., 1997; Cosgrove & Rijsberman, 2000; Falkenmark, 1989; Gleick, 1996; L Ohlsson, 1999; Rijsberman, 2006; Rosa et al., 2020)) by linking the drivers of demand (spatial) with their timing. The maps produced from this model identify regional hotspots of

overlapping water scarcity types, which illustrates a novel level of nuance in the global water scarcity picture. This study also sets the stages for the following two studies. This includes providing a rationale for shifting from qualifying benefits (for global analysis) to quantifying benefits at the regional scale, **Chapter 5**, and incorporating environmental water needs in transaction design, **Chapter 6**. **Chapter 4** also recognizes the importance of governance and the feasibility of incentives, especially as it relates to environmental water needs, which creates a thread between the following two chapters, whose geographic focus is Texas.

Texas' experience with water markets has been built on the backdrop of hydrological conditions and political landscapes that favor markets for reallocating water. Although there is significant literature devoted to water markets in Texas (over 500 peer review articles since 1985), most studies are devoted to the spot and leasing markets of the agriculturally rich Rio Grande Valley (Debaere & Li, 2020; Leidner et al., 2011; Yoskowitzy, 1999). Considering the geographic diversity and drivers of scarcity across the state, I wanted to understand what we could learn about how water markets have performed in the past 30 years. **Chapter 5** starts by quantifying the private and public benefits of water markets across Texas. I employed a mixed-methods technique that combined transaction data analysis and statistical analysis. I discovered that formal water transactions were more ubiquitous across the state than the academic literature suggests, and since 2010, there has been a surge in transaction activity. I was motivated to understand if I could detect a correlation from either water demand or supply that could explain the increase in transactions. Therefore, as a final step, I asked: Is there a variable on either the supply side (e.g., drought, reservoir level) or the demand side (e.g., population increase, alternative supply costs), which can explain the increase in recent transactions? The results of the regression model demonstrated that reservoir levels, SPI, temperature, groundwater levels, and commodity prices for rice and cotton were statistically significant predictors of water transactions. **Chapter 5** concludes with several policy recommendations focused on incremental changes in existing water management practices to improve conditions for water markets and their contributions towards a water secure future for the people of Texas and their environment.

The academic literature focusing on using water transactions to improve environmental conditions, such as instream flows, has a considerable geographic emphasis in the United States over the past 20 years (Ferguson et al., 2006; Garrick et al., 2009; McCord et al., 2018; Neuman, 2004), in part because of the favorable enabling conditions for markets (Pilz et al., 2017). **Chapter 6** builds on the previous two papers to focus on designing environmental water transactions to help alleviate water scarcity driven by a combination of geologic and anthropogenic drivers. The geographic scope is the San Saba River, which is in the semi-arid transition zone between the Texas Hill Country and the Rolling Plains. This river basin exemplifies many of the challenges facing rivers in the United States West and abroad, including competition between water users, competition between water users and the environment, increasingly variable precipitation, and land fragmentation. Complicating these challenges is (a) a recognition of the need to protect freshwater species in one of the last undammed tributaries of the Colorado River and (b) a lack of evidence quantifying the interactions between surface water and groundwater. I develop a spatially explicit categorization of natural (geologic) and anthropogenic (water use) drivers of scarcity using data from gain-loss studies and monitoring wells, which I use to quantity offset of water use needed during different climatic (e.g., dry year) and irrigation time periods. Results develop a list of priority interventions that quantify the volume, location, costs, and impacts (on the river and producers) for specific EWTs. This chapter contributes to the literature by focusing on locally tailored solutions to water scarcity (R. Meinzen-Dick, 2007; Ostrom, 2010), and simultaneously offers a methodological contribution to the adaptation of a hydro-ecological spatial action mapping methodology to regions facing similar challenges and common contextual features.

1.4 Structure of the Thesis

This thesis, organized into seven chapters, follows an article-based format. The **first chapter** serves as a foundational introduction, establishing the research's context and rationale. It defines water scarcity as the result of an imbalance between water demand and available

supply, emphasizing its significance as a complex social-hydrological challenge. The chapter also underscores the far-reaching consequences of water scarcity on economies, ecosystems, and livelihoods. Here, the research questions guiding the remainder of the thesis are introduced, and the need for an interdisciplinary, multi-scaled approach that draws on hydrology, economics, and governance is justified.

In the **second chapter**, I conduct a critical review of existing conceptual and methodological research, providing the theoretical groundwork for this thesis. The conceptual review centers on the confluence of hydrology, economics, and governance, all of which contribute to both the emergence and potential resolution of water scarcity. In the methodological review, I present the reasoning behind the chosen approaches in this thesis. This encompasses the justification for adopting a systems approach, employing spatial analysis, utilizing econometric methods, and integrating these diverse approaches to comprehensively address the research questions.

The **third chapter** functions as a comprehensive exposition of the research design and methodology employed throughout this thesis. Within this chapter, I delineate the conceptual framework, methodological approach, and contextual constraints and assumptions that underpin the entire study. Subsequently, I provide a detailed outline of the methodological steps undertaken to address the three primary research questions discussed in subsequent chapters, namely chapters 4, 5, and 6.

The **fourth chapter** addresses the first research question by conducting a multi-scale assessment of water reallocation and conservation technology investment to understand their potential and limitations in addressing water scarcity drivers. It identifies sub basin-level drivers and explores two key responses, laying the groundwork for subsequent chapters.

The **fifth chapter**, focusing on Texas, addresses the second research question by analyzing water market activity using an original transactions database spanning 13 major basins. It reveals distinct transaction patterns and drivers among basins, highlighting their policy implications. The chapter emphasizes the role of past investments in water market institutions in

shaping basin-specific markets and underscores the importance of locally tailored institutions and governance.

The **sixth chapter** zooms further into the San Saba Basin in Texas to address the third research question by combining data from surface water and groundwater models to map how natural and anthropogenic factors drive scarcity across space and time. Further it demonstrates how spatially targeted environmental water transactions can provide water for dry sections of the river, and their associated costs and benefits.

The **seventh** and final chapter of this thesis provides a comprehensive discussion of the key findings and research contributions. It emphasizes the implications of the research for decision-making and policy, while also identifying the main limitations and areas ripe for future research

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Chapter 2

Literature Review

2.1 Literature Review

The first section of this chapter focuses on the **conceptual** advances that have shaped the research questions and themes in the thesis. The conceptual underpinning stems from the academic literature on hydrology, economics, and governance more broadly. The conceptual literature review begins with framing water scarcity as a function of two variables, supply and demand. I delve further into the subcomponents of each variable to explain why differences in drivers and scales of supply and demand affect variation and types of water scarcity. This deeper understanding of water scarcity as a function of supply and demand links with the second body of literature on incentives as a theoretical tool for alleviating water scarcity. This review discusses the challenges that managing water demand via incentives have posed by weaving between theoretical examples, and complementing them with empirical evidence of experiments across the globe. To conclude this segment, I offer a fresh perspective on the literature concerning water markets. This revisitation of water markets is twofold: firstly, it recognizes their resurgence in popularity and, secondly, it reevaluates them within the broader context of social-hydrological systems, encompassing institutions and externalities.

The second section of the is chapter reviews the **methodological** approaches to assess the po-

tential of incentives to address water scarcity, analyze the drivers and performance of a vibrant set of water markets that were previously not assessed, and finally design environment water markets by assessing their fit in the context of competition between water users and groundwater and surface water interaction. This methodological review begins with a recognition of relatively recent calls in the literature for multi-scalar, systems approaches for assessing social ecological systems and why this call aligns with the research questions and methodologies of this thesis. Each of the subsequent methodologies nest within a multi-scalar, systems scale framework. I provide an overview of different sub-areas of spatial analysis, demonstrating a unique value add to the study of water scarcity. Next, I review the literature on a select number of econometric models which have promise in the field of water market analysis, including fixed effects. I provide an overview of the landscape of current global scale hydrological models used to study water scarcity, including their associated trade-offs. Finally, I present a rationale for integrating methods and literature across the fields of hydrology, economics, and governance, how they answer my research questions, and in doing so which specific gaps in the literature I am helping to bridge.

2.2 Conceptual Review

2.2.1 Water scarcity as a function of supply of demand

Viewing the earth from space it is hard to imagine how billions of people, and millions of river kilometers could be affected by scarcity. For all intents and purposes, the overall water balance of the earth has been relatively unchanged during the Holocene. At a global scale, there is an enormous quantity of water stored in various forms and qualities. However, of the approximately 1.4 billion cubic kilometers of water, only a small fraction, less than 0.5% is available for human use (Gleick & Palaniappan, 2010; Postel et al., 1996). For example, rivers, historically the major source of surface water use for civilizations, constitute only 1/10,000th of one percent of total water. Moreover, the distribution of water fluctuates over space and time. For example, Asia, home to 60% of the human population today, only retains 9% of permanent

water and 35% of seasonal surface water (Pekel et al., 2016). In contrast, North America, home to just 5% of the human population, contains 52% of the planet's permanent surface water and 18% of seasonal water (Pekel et al., 2016)

At the same time, water use globally has shifted due to factors including urbanization, food production for a growing population, and higher standards of living. Since 1950, urban water demand has increased fivefold (Padowski & Gorelick, 2014; Richter et al., 2013). Irrigation for agriculture accounts for 73% of total water withdrawals and in arid and semi-arid regions, accounts for more than 95% of total withdrawals (Döll et al., 2012). Recent work revealing that water demand can decouple from economic measures (e.g., GDP) is helpful to demonstrate that there are pathways to reduce water use while without negatively affecting economic productivity (Richter et al., 2020) Nonetheless, the confluence of shifting demands and declining local water supplies produces water scarcity.

Water scarcity can be defined as an excess of water demand over available supply (Savenije, 2000; Steduto et al., 2012). Therefore, to better measure water scarcity we need to measure the balance of supply and demand of water at different scales. This is critical not only to identify water scarcity, but also to help reduce or alleviate it. For example, measuring the imbalance of supply and demand at a local stream may be important for residents, however, absent a larger governance context (e.g. watershed conservation) addressing scarcity at their local scale may not be possible. Likewise, measuring water scarcity at the continental scale consistently harbors blind spots based on model assumptions and resolution. However, policy at the continental or global scale could be a critical lever in terms of addressing water demands whose impacts transcend scales.

There are various approaches to quantify water scarcity, with many metrics encompassing elements related to both water supply and water demand. Measuring water scarcity poses theoretical and practical challenges which have persisted for decades. Water scarcity metrics at the global level can be traced to Falkenmark who examined changes in per capita water availability to capture water stress (Falkenmark, 1989). The Falkenmark "water stress index"

proposes thresholds for water requirements per capita. Countries whose renewable water supplies are below 1,700m3 are considered "water stress", below 1,000m3 are considered experiencing "water scarcity" and those below 500m3 are experiencing "absolute water scarcity" (Falkenmark, 1989). The Falkenmark indicator uses readily available data and its results are easy to understand. These factors have translated to its popularity as an indicator for water scarcity. There are however, serious limitations of the Falkenmark indicator including "(a) the annual, national averages hide important scarcity at smaller scales; (b) the indicator does not take into account the availability of infrastructure that modifies the availability of water to users; and (c) the simple thresholds do not reflect important variations in demand among countries due to, for instance, lifestyle, climate, etc." (Rijsberman, 2006).

Gleick expanded on the scarcity index recognizing variability in consumption (Gleick, 1996) and Ohlsson integrated adaptive capacity to consider socio-economic factors through the Water Stress/Scarcity Index (SWSI) (L Ohlsson, 1999). Alcamo et al. defined a "criticality ratio" of water withdrawals for human use to the total renewable water resources (Alcamo et al., 1997). This measure was widely used in proceeding global analyses including (Cosgrove & Rijsberman, 2000) and a similar definition was used in (Vörösmarty & Sahagian, 2000). Vörösmarty et al. (2000) evaluated global water scarcity from the perspective of production, assessing water scarcity for the domestic and industrial sectors (DI/Q), irrigated agriculture (A/Q), and their combined impact (DIA/Q) on an annual average basis.

However, the criticality ratio also presented serious limitations because (a) the data on water resources availability do not take into account how much of it could be made available for human use; (b) the water withdrawal data do not take into account how much of it is consumptively used (or evapotranspired) and how much could be available for recycling, through return flows; and (c) the indicators do not take into account a society's adaptive capacity to cope with stress" (Rijsberman, 2006). Recent studies have taken advantage of multiple spatial frameworks to quantify various stressors and account for downstream impacts for humans and biodiversity (Brauman et al., 2016; Vörösmarty et al., 2010). The common denominator

between the metrics above is that they are straightforward to compute with pre-existing data, but they lack the ability to adequately represent spatial and temporal variation associated with water scarcity.

Both blue and green water flows serve human productivity (Schyns et al., 2015). Blue water refers to the water that escapes evapotranspiration (Falkenmark et al., 2007). Blue water scarcity (BW) comes from an academic body of literature focused on water footprint accounting (Hoekstra & Mekonnen, 2012). Blue water footprints are calculated by measuring the consumptive use of ground- and surface water flows rather than water withdrawals, in an effort to account for the flows needed to sustain critical ecological functions and by considering monthly rather than annual values (Hoekstra & Mekonnen, 2012). Blue water scarcity (BWS) is defined as the ratio between societal blue water demand and renewable blue water availability (Rosa et al., 2020). Green water on the other hand refers to the water that sustains crop production (Rockström et al., 2009). Compared to blue water scarcity, the definition of green water scarcity (GWS) is more intricate and lacks unanimity. (Xu & Wu, 2018) provided a definition of green water scarcity as the proportion of remaining green water resources available for non-cropland managed ecosystem services, such as wood production and pasture, after fulfilling the demand for cropland. (Rosa et al., 2020) defined GWS as the ratio between irrigation water requirement and total crop water requirement. In contrast, (Schyns et al., 2019) defined a green Water Scarcity Index (WSI) as the ratio of green water flow allocated to economically valuable crops to the total green water availability. It is worth noting that this ratio reflects the portion of water used by plants in managed lands rather than the actual water constraints affecting economic services (W. Liu et al., 2022). To fill the gap between blue and green water scarcity, (W. Liu et al., 2022) developed an agricultural green + blue water scarcity index WSIAW and the resulting metric can help improve representation of water scarcity in regions where green water dominates agricultural water supply and demand.

While these ratio metrics are useful for quantifying disparities between water supply and demand in various geographical contexts, they have limitations when it comes to assessing

the multifaceted nature of the water scarcity challenge. Water scarcity is a complex condition and includes human deprivation marked by insufficient access to affordable and safe water for meeting societal needs, often at the expense of the environment (Rijsberman, 2006). Water scarcity can impact continents or singular aquifers, however, most severe consequences are typically borne by the most vulnerable populations (Delaney et al., 2018). This observation underscores the significant influence of economic and institutional factors in driving water scarcity and the need to measure its economic capacity instead of hydrologic constraints (Rosa et al., 2020).

Economic water scarcity (EWS) is defined as a situation in which renewable blue water resources are physically accessible, but societal ability to utilize this water is constrained due to economic and institutional limitations (Molden, 2013; Seckler et al., 1999). Early definitions of EWS emphasized countries with adequate renewable water resources but requiring substantial improvements in water development (Seckler et al., 1999). Traditionally, this approach centered on hydraulic engineering and infrastructure (Molle & Berkoff, 2009). However, it has faced criticism for its inability to adapt to changing socio-hydrological conditions and its environmental and societal consequences. Current research explores adaptive water governance, political ecology, water justice, and community dynamics to understand how institutional, political, and power factors influence access, restriction, and possession of water resources (Boelens et al., 2016; Huitema et al., 2009; Zwarteveen & Boelens, 2014). Until recently, there was an evident gap in the literature in terms of how EWS was integrated into agricultural development, prompting the agricultural economic water scarcity measure (Rosa et al., 2020). This condition arises when croplands exposed to GWS lack irrigation despite the presence of locally available renewable blue water resources sufficient for irrigation. These circumstances often result from various socioeconomic and political factors that hinder irrigation (Rosa et al., 2020).

In response to challenges of defining water scarcity, (Jaeger et al., 2013) proposed "the marginal value of a unit of water" as a definition of water scarcity to capture the complexity as a natural-

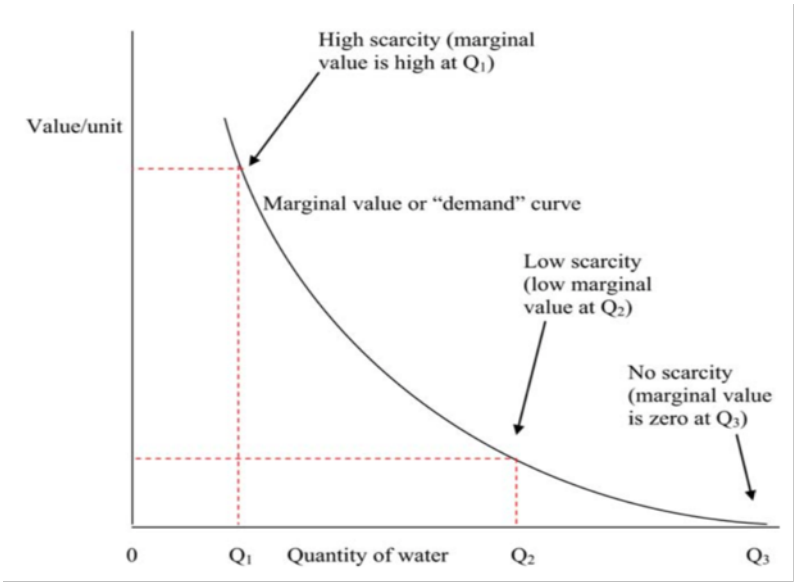

Figure 2.1: Scarcity as the marginal value of water at the level provided. Taken from (Jaeger et al., 2013)

human system. This definition allows individual units of water to have different values, and suggests water scarcity is a range of values defined across a domain of water units (Jaeger et al., 2013). In this framework, water scarcity is calculated as the value of allocating an additional unit of water to a user. This measurement of scarcity (opposed to previous metrics) accounts for human values in addition to the hydrological, biological, and technological contexts. Through the lens of a natural-human system, water scarcity can arise from changes in hydrology or by human actions (Jaeger et al., 2013). In this context, changes in the allocation of water between users in a system can increase or decrease water scarcity amongst users. For example, water trading as an allocation mechanism uses price signals to coordinate between willing buyers and sellers (D. Garrick, 2015). As illustrated below, the scarcity (or marginal value) of water may be high, low, or 0 depending on the allocation of water to a particular use:

Although this review focuses on the synergies between the hydrologic and economic perspectives of water scarcity, it is important to acknowledge alternative epistemologies of scarcity. For example, the social construction of scarcity helps to unpack historical pressure on water resources (Aguilera-Klink et al., 2000). Social perspectives of scarcity have engaged with

several disciplines including political ecology (Blaikie & Brookfield, 1987; Bryant, 1992) and Foucauldian discourse analysis (Peet et al., 2010). In addition to scholarly discourse, there are important implications of these alternative framings of water scarcity. These include how transactions of economic goods (e.g. water) are objects of property (Xenos, 1987), and how conflicts arise through competition for scarce resources (Homer-Dixon, 1994). The review highlights that variations in how water scarcity is measured, and the assumptions within those definitions, can be better suited for specific tasks or contexts, influencing the analysis. Additionally, this review underscores how the multidimensional aspect of water scarcity intersects with economics and governance, which has led to a significant body of literature focused on assessing incentives as a theoretical tool for addressing water scarcity.

2.2.2 Incentives as a theoretical tool for alleviating water scarcity

As water scarcity inherently revolves around the interplay of supply and demand, economists have argued that water markets and incentives can enhance efficiency. By facilitating gains from trade, which involves net benefits from voluntary trading, these mechanisms ensure that water is allocated to its highest valued uses in response to fluctuations in supply and demand. At least as early as 1959 gains from trade with water was mentioned in The Journal of Law and Economics that "if the public land or public water is to be parceled out on the basis of priority of application, some people will undoubtedly receive gains in the form of economic rent" (Milliman, 1959). This theory seemed to be supported by empirical evidence. The opportunity cost of water is high in diverse contexts (Laughland et al., 1993; Lu et al., 2018), and competition increases water's value (Flörke et al., 2018; Strzepek & Boehlert, 2010). Indeed many of the seminal articles promoting water markets as a tool to address water scarcity focused on the potential gains from trade (Chong & Sunding, 2006; Hearne & Easter, 1997; Horbulyk & Lo, 1998; Rosegrant & Binswanger, 1994). However, an important caveat is that transaction costs need to be lower than opportunity costs for institutional change to occur (Dinar & Saleth, 1999). Economic models have been capable of assessing potential gains from trade in developed and developing contexts (A. Garrido, 1998; Hearne & Easter, 1997; Pujol et al., 2006; Rosegrant

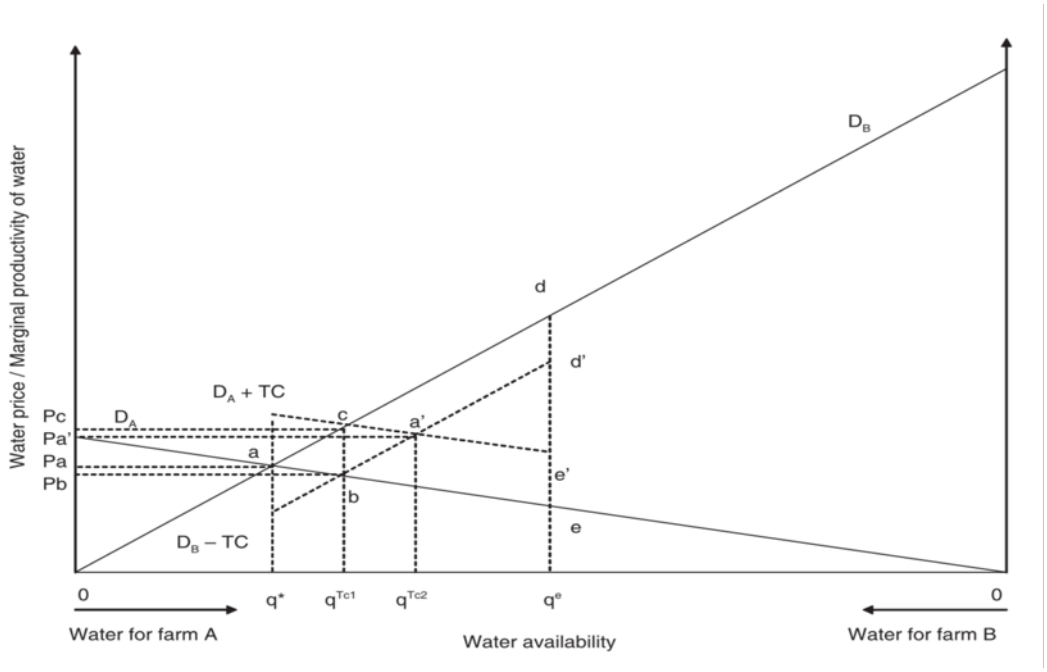

Figure 2.2: A theoretical framework for water markets with transaction costs from (Pujol et al., 2006)

& Binswanger, 1994). Indeed, the US National Water Commission identified water markets as a key part of the "future of water policy" in 1973. However, as (D. Garrick & Svensson, 2017) replied, "nearly forty five years later, many water-stressed regions are still waiting for the future to arrive".

The ability to trade water is a necessary precondition of a water market (Easter et al., 1999). However, accounting for transaction costs in a water market are imperative for understating trading potential. In the figure below, (Pujol et al., 2006) illustrates two farmers with equal amounts of water but different marginal productivity of water.

Imagine on the graph above the equilibrium level of reallocation initially is represented by the difference between qe and q* is fixed by transaction costs of both farmers. If we apply transaction costs, this alters the supply and demand curves so that supply from the low productivity farm (DA + TC) becomes more expensive, and therefore decreases the benefit to the high productivity farm (DB – TC). This example illustrates a very simple, theoretical exam-

ple of trading in a world of transactions costs. However, as water market programs increase in complexity to trade between private economic uses (e.g., irrigation) and public economic goods (e.g., instream flows) we find that technical and political hurdles present formidable barriers to trade. Indeed a significant body of literature has taken advantage of decades of experimentation with water markets and assess the challenges associated lack of trades including transaction costs (Ayres et al., 2018; D. Garrick et al., 2013; McCann & Garrick, 2014), lack of basin closer (Palomo-Hierro et al., 2015)lack of legal clarity in terms of riparian regimes (Dellapenna, 2005), and lack of administrative capacities (Grafton et al., 2011). Examples in the literature also include geographic breadth and range from Spain, Canada, Mexico, the United States, Australia and Chile (A. Garrido, 1998; R. Q. Grafton & Horne, 2014; Hearne & Easter, 1997; Horbulyk & Lo, 1998; Neuman, 2004).

These studies have yielded concordant results:

First, that gains from trade in these geographies can occur based on:

- diversity of uses of water (Young, 1986) and
- the marginal value of water varies in an area (Easter et al., 1999).

Second, that potential gains from trade is consistently not realized because:

- transaction costs exceed opportunity costs (D. Garrick & Aylward, 2012) and
- poorly defined property rights (Chong & Sunding, 2006).

This gap between expectations and reality has emerged over the past two decades proving that water market allocation reforms are more complex than initially anticipated (Neuman, 2004). Combined with the observation that high transaction costs can pose as barriers to realizing the gains from trade in water reallocation (D. Garrick, 2015), trading activity remains a fraction of the potential suggested in the 1990s (D. Garrick & Svensson, 2017).

2.2.3 Historic challenges with scaling water markets

Despite their potential, high-functioning water markets are more often the exception than the rule (D. Garrick et al., 2023). Coase emphasizes the necessity of fully specified, exclusive, transferable, and enforceable water rights for optimal market functionality (Coase, 1960). However, research reveals persistent inequalities in pricing across users due to high transaction costs, administrative regulations, and the manipulation of market power by participants, especially evident in intersectoral water trading scenarios (Ayres et al., 2018; D. E. Garrick et al., 2017).

Fully specifying water rights, especially in developing countries, proves challenging, as illustrated by the experiments with water markets in China and Mexico (Reis, 2014; J. Zhang, 2007). Even converting riparian rights use-based rights as a creative solution to this challenge, the persistent linkage between land and water rights acts as a barrier to trade, e.g. in Southern Spain (Giannoccaro et al., 2015). Stakeholder perceptions and values, notably among farmers who predominantly hold water entitlements, play a crucial role in resisting the commoditization of water through market mechanisms (Bjornlund, 2003; D. E. Garrick et al., 2017). This resistance contributes to the overestimation of benefits in theoretical water market models (Giannoccaro et al., 2015; Tisdell & Ward, 2003).

Related is the challenge of valuing water, a task which has been deemed ”difficult but necessary” (D. E. Garrick et al., 2017). This is especially challenging in accounting for non-economic valuations of water. However there may be signs of progress. For example, Australian scholars in particular have focused on incorporating Aboriginal values and perspectives of water into water management and policy (Moggridge & Thompson, 2021). This is particularly important in the context of this thesis as Australia is know for its water scarcity and water markets (Quentin Grafton et al., 2016). Understanding these diverse cultural values is essential for sustainable water management too. However, as others have pointed out, national level water laws may provide the foundation to engage with Indigenous peoples diverse water values, but in practice, the institutional infrastructure is poorly developed (Jackson et al., 2012).

Third-party effects, including environmental concerns, present additional obstacles to scaling water markets. While water reallocation can serve environmental goals, including environmental flows (H. Liu et al., 2005), it also generates opposition and legislation prohibiting water transfers that would cause 'unreasonable impact on fish, wildlife, or other instream uses' (Rosegrant & Gazmuri S., 1995). Reallocation of water can disrupt the temporal pattern of instream flows and reservoir releases, thus negatively impacting other uses—especially ecosystems that require a very particular flow regime (Marston & Cai, 2016). This is a particularly interesting test for water markets in the context of the United States Endangered Species Act (ESA). On the one hand, the ESA was a catalyst for the Edwards Aquifer water market in the 1990s (Votteler, 1998). Recent water mandates supporting listed species under the ESA and interstate compact compliance have created demand (requiring water instream) and provided funding for transactions in the Colorado River Basin (Womble & Hanemann, 2020). On the other hand, the ESA was once seen as a litmus test of the extent to which existing water-use patterns in the American West can accommodate contemporary environmental values (Moore et al., 1996) and today models indicate a more efficient allocation of curtailments that account for ESA environmental flow requirements could reduce the costs of water shortages by as much as $362 million dollars per year or 4.4% of the net agricultural revenue in California (Arellano & Bonhomme, 2011).

Transaction costs emerge as a common theme among these challenges, encompassing various expenses associated with information acquisition, negotiation, third-party mitigation, and enforcement (D. Garrick & Aylward, 2012; Rosegrant & Binswanger, 1994). Furthermore, power dynamics within water markets significantly influence efficiency gains and benefit distribution, as demonstrated in studies examining groundwater trading and the presence of market power (Bruno & Sexton, 2020; Tomori et al., 2021). In summary, the historic challenges with scaling water markets are multifaceted, spanning regulatory, environmental, and social dimensions, with transaction costs and power dynamics playing pivotal roles in shaping market outcomes.

2.2.4 Water markets and the importance of "fit"

Water markets enable the buying and selling of water rights (or entitlements or licenses) and allocate water to its highest value user by establishing price signals (Wheeler et al., 2020). The preceding review section primarily emphasized formal water markets. Nevertheless, it is important to acknowledge that water markets are neither novel nor uncommon, with historical evidence of water trading dating back centuries in regions such as Oman, Spain, the United States, and Australia (D. Garrick et al., 2023; S. Garrido, 2011; Wilkinson, 1977). In fact, an expanding body of literature is dedicated to unveiling informal water markets, which can emerge in regions with relatively abundant water resources as a response to inadequate infrastructure or governance for supplying drinking water (Whittington et al., 1989, 1991; Wutich et al., 2016). The divide within the literature on formal and informal water markets became evident with the publication of two reviews in 2019. One asserted the rarity of water markets (Leonard et al., 2019), while the other emphasized their proliferation (O'Donnell & Garrick, 2019). Scholars familiar with the water markets literature recognize that both perspectives can be accurate, as formal water markets remain uncommon in comparison to their informal counterparts (D. Garrick et al., 2023).

Another rift in the literature is between proponents and critics of water markets. Scholars who focus on water markets from an economic perspective tout their efficiency in terms of reallocating a scarce resource (Brennan, 2008; Xu & Wu, 2018), while policy and environmental scholars proclaim their potential to improve environmental conditions (Erfani et al., 2015; Murphy et al., 2009). On the other hand, critics highlight that water markets can lead to adverse consequences within communities where water trading occurs. For example, water markets have the potential to exacerbate existing challenges and may perpetuate historical injustices by marginalizing or excluding Indigenous peoples ((Hartwig et al., 2022). This occurs through the reinforcement of legacies tied to colonization and dispossession, which have historically restricted the formal allocation of water rights (Hartwig et al., 2020; Prieto, 2022; Sanchez et al., 2020).

Although defining water markets may splinter semantically, (D. Garrick & Svensson, 2017; Rosegrant & Binswanger, 1994; Wheeler et al., 2020) they converge on necessary enabling conditions: scarcity, a "cap" on water extractions to set the limit on how much water is available for use, water rights allocated to water users, and rules for reallocation and mediating disputes ("About the Editors", 2017; D. Garrick et al., 2020; Hanak, 2003). These enabling conditions, and the water markets they support exist within a broader socio-hydrological framework and include institutions and externalities.

2.2.5 Unpacking Water Markets

Institutions

There is an established academic lineage devoted to markets and private property governing access to natural resources (Anderson & Leal, 2001; Hardin, 1968; Thompson Jr, 2000). As competition for water supplies increases, institutions – prescriptions that humans use to organize all forms of repetitive and structured interactions (Ostrom & Basurto, 2009) – are required to manage the resource. However, water's complexity as an economic good has complicated its management across interdependent private and public uses (D. Garrick, 2015).

In this context, institutional analysis has played an important role in the literature on addressing water scarcity. The theoretical analysis of institutions is based on three pillars: (a) frameworks, (b) theories, and (c) models (Ostrom, 2011). The Institutional Analysis Development (IAD) is a popular framework that has been used in a wide range of academic fields to identify the "interactions of an action situation and the resulting patterns of interactions and outcomes, and evaluating these outcomes" (Ostrom, 2011). A graphical representation provided in figure 2.3:

Theories make assumptions and usually multiple theories are compatible within one framework. Examples of theories compatible within the IAD framework include: economic theory, game theory, transaction cost theory, and common-pool resource (CPR). Agent-based models, experimentation, and simulation are examples of models which aim to test assumptions on a

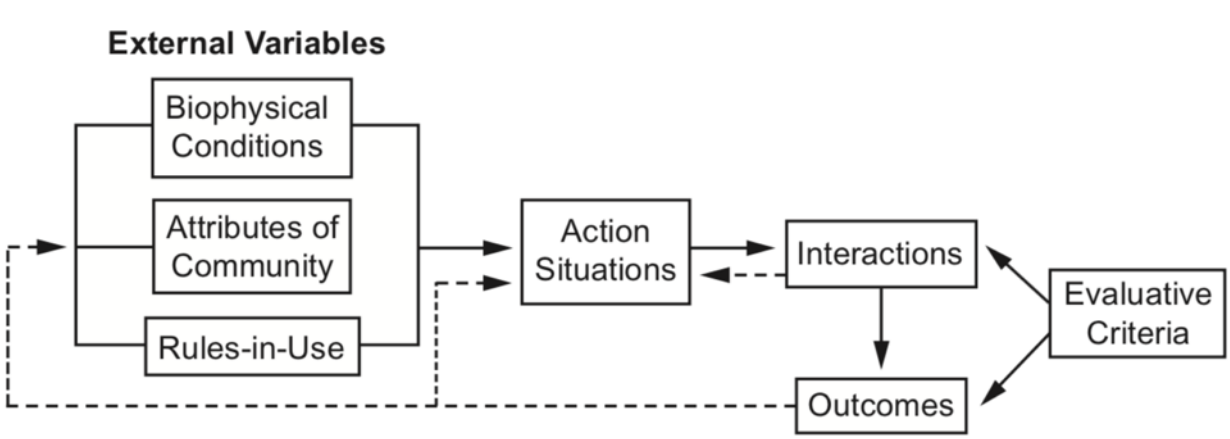

Figure 1. A Framework for Institutional Analysis.
Source: Adapted from E. Ostrom (2005, p. 15).

Figure 2.3: IAD framework from (Ostrom, 2011)

limited set of outcomes. Early work by (Weissing & Ostrom, 1991) employed a series of models to explore consequences of different physical and institutional combinations of irrigators.

The application of institutional analysis for water markets historically focuses on four pillars: First, the recognition of the importance of strong property rights and operational rules (Gray, 2002; Ostrom, 1991). Second, the ability for institutions to respond to conflict resolution (Kimmich, 2013). Third, monitoring systems to improve the effectiveness of water allocation and trading (J.-L. Zhang & Zhang, 2008). Finally, because water institutions operate at multiple scales, nested governance is a necessary lens for mapping the three previous pillars (Crase et al., 2011; D. Garrick et al., 2011; Ostrom, 2010).

At the same time, water allocation in water scarce areas has been identified as a large-scale collective action dilemma (D. Garrick, 2015)p.201. Although the search for panaceas to solve water-management problems has persisted for the last 50 years, many scholars have argued going beyond single-policy solutions and embracing the complexities associated with this challenge (Anderies et al., 2007; Meinzen-Dick, 2007; Ostrom, 2010). The IAD is a tool designed to handle the complexities associated with water allocation in scarce environments

because it is built to systematically analyze collective action and the commons with a focus on institutions. Especially important to water scarcity, IAD is designed to integrate multi-scale analysis and is able to integrate social ecological systems (SES).

Externalities

Recognition of negative externalities associated with water markets has been present in the literature since at least the 1980s (Bauer, 1997; Chong & Sunding, 2006; Howe et al., 1986). Examples of negative externalities associated with water markets included hydrological, for example saltwater intrusion and groundwater drawdown (Knapp et al., 2003; Lefkoff & Gorelick, 1990). Additionally, some researchers have placed emphasis on the concept of return flow externalities, which can detrimentally affect downstream stakeholders who are not directly participating in upstream transactions (Pérez-Blanco et al., 2020). This includes the impact on environmental processes through reduced water supplies (Perry, 2011).

Another area of research related to externalities and water markets is devoted to intra-basin water markets and return flow externalities. These studies typically use economic modeling to evaluate the consequences of uneven adoption of irrigation technology on water consumption and return flows (Grafton et al., 2011; Qureshi et al., 2010; Wheeler et al., 2017). These analyses identify potential adverse feedback loops that can impact downstream water availability. This can occur through reallocating water to more efficient irrigators, heightened consumption, and diminished return flows in other areas. Recent advances in extending hydro-economic modeling to inter-basin externalities, (Pérez-Blanco et al., 2020) calculate and compare trade-offs between trading and return flows.

Another crucial consideration in the realm of water markets involves third-party effects, which arise when a water transaction between two individuals has an impact on a third party. This problem is quite pervasive in water markets because "rarely can a change in the time, location, or manner of use of a water occur without affecting other water users" (Draper, 2005). This observation primarily applies to multiple water users engaged in or potentially participating

in a water market. Nevertheless, it is essential to recognize that even non-market participants (or individuals who do not directly use water) can be influenced by indirect third-party effects. These impacts can manifest directly, such as a reduction in in-stream flows below the point of diversion during a water transfer, or indirectly, like the loss of jobs in the agribusiness sector within an agricultural region when farmers and landowners decide to transfer their water supplies. The potential for externalities arises from the conflict between market objectives aimed at maximizing private benefits and the consideration of public values or benefits. This challenge is exacerbated in regions where legal authority over water resources is unclear. Equally concerning is the possible loss of legal authority and control over a nation or state's internal water resources, a situation that has led some to raise concerns about the erosion of sovereignty over a state's or a nation's surface and groundwater (Dellapenna, 2007; Draper, 2005).

Social- Hydrological Systems

Traditionally, social scientists viewed environmental influences as constant and minimal while natural scientists focused on natural interactions, perceiving pristine environments where human actions are external and rarely influenced (J. Liu et al., 2007). However, mounting evidence demonstrating the significant impact of human activity on our planet has led scholars to propose that we have entered the Anthropocene era. Consequently, there has been a concerted effort to bridge the gap between social and natural sciences, particularly in the context of scholarship devoted to water (Wesselink et al., 2017). This integration has given rise to several related bodies of literature, including socio-ecological systems (SES), human-environment systems, human-nature systems, and Coupled Human and Natural Systems (CHANS) (Alberti et al., 2011). In particular, socio-hydrology has emerged to explore the interconnected and reciprocal interactions between humans and water systems (Di Baldassarre et al., 2013; Di Baldassarre et al., 2015; Sivapalan et al., 2012) and builds on significant bodies of literature from Coupled Human and Natural Systems (CHANS) and Social-Ecological Systems (SES).

Analyzing water markets within the context of social-hydrological systems is of paramount

importance, as the design, implementation, and management of these markets are inherently entwined with both social and hydrological elements. To visually represent this conceptualization, I have included an original figure (with aesthetic assistance from Karla Vázquez Mendoza) below. Figure 5 provides a graphical depiction of how this thesis envisions water transactions and water markets. Within this framework, it becomes evident that water transactions, a focal point in much of the water market literature, are but one facet of a larger, intricate system.

In Figure 5, we observe the diversity of sellers and buyers, each engaged in distinct types of water transactions, influenced by the varying characteristics of the water itself, including its source (surface water or groundwater) and the infrastructure used for conveyance (e.g., canals or reservoirs). These transactions occur within different institutional arrangements, which can range from formal to informal, guided by a set of overarching rules that serve as signals for market participants.

Beyond the transactional layer lies the broader social-hydrological system, representing the intricate relationship between society and the environment. This system is unique to each location and is shaped by a complex interplay of factors, including hydrology, culture, economics, governance, and value systems. Recognizing and studying these multifaceted interactions is essential for a comprehensive understanding of water markets and their real-world implications.

CHANS Approach

The Coupled Human and Natural Systems (CHANS) approach builds upon a long-standing tradition of scholarship dedicated to understanding the intricate interactions between human and environmental systems (J. Liu et al., 2007). CHANS scholars engage deeply with research communities exploring various aspects of human-environment interactions, encompassing human-environment systems, social-ecological systems, ecological-economic systems, and population-environment systems (Alberti et al., 2011). What sets the CHANS approach apart is its explicit acknowledgment of the inextricable linkages between human and natural systems

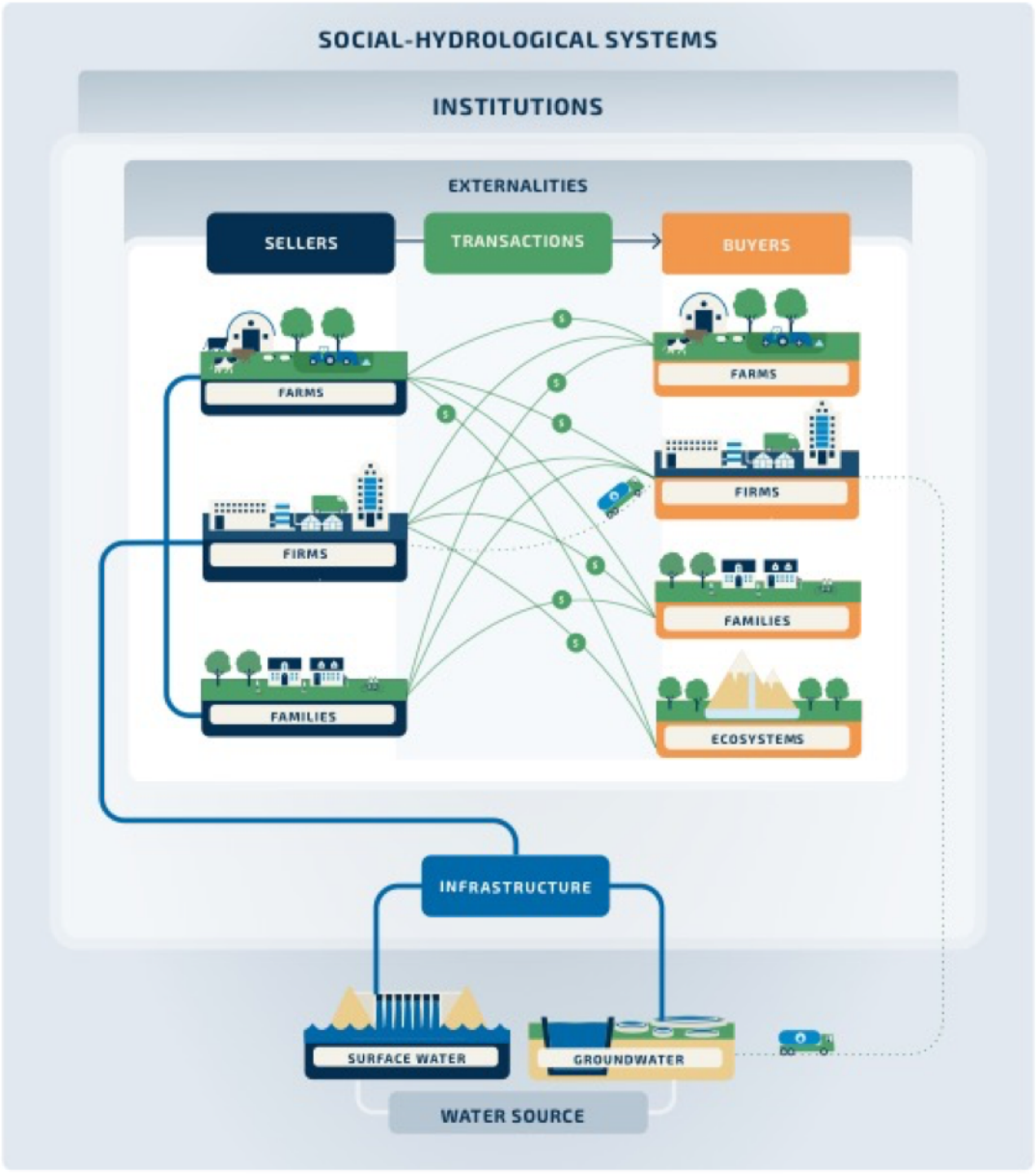

Figure 2.4: A conceptualization of water transactions nested inside externalities, institutions, and social-hydrological systems

through reciprocal interactions, including the flow of materials, energy, and information. This approach encompasses concepts such as feedback loops, nonlinear dynamics, critical thresholds, time delays, enduring legacy effects, path dependence, and the emergence of new phenomena (J. Liu et al., 2007) (Liu et al., 2007). Researchers in the CHANS field aim to unravel this complexity by developing coupled models that accurately represent both human subsystems (e.g., economic and social) and natural subsystems (e.g., hydrological, atmospheric, and biological) (Alberti et al., 2011; Fitzhugh et al., 2019). The focus is on capturing the dynamic interplay between these subsystems, particularly in the context of water management (Giuliani et al., 2016; Motschmann et al., 2022; Yin et al., 2021).

SES Approach

The Social-Ecological Systems (SES) perspective views interconnected systems that encompass human society and the natural world (Ostrom, 2009). The graphic below (figure 6) comes from Ostrom's 2009 Science article (Ostrom, 2009).

SES emphasizes that humans are integral components of the environment rather than separate entities, echoing the sentiment of scholars such as (Berkes et al., 1998). A social-ecological system can be characterized by several key attributes, the four characteristics below come from (Redman et al., 2004) which was inspired by previous work by (Burch Jr & DeLuca, 1984; Machlis et al., 1999):

1. It is a coherent amalgamation of biophysical and social elements engaged in consistent, resilient interactions.

2. This system operates across multiple spatial, temporal, and organizational scales, which may be interconnected in a hierarchical fashion.

3. Critical resources, spanning natural, socio-economic, and cultural domains, are governed by a combination of ecological and social systems.

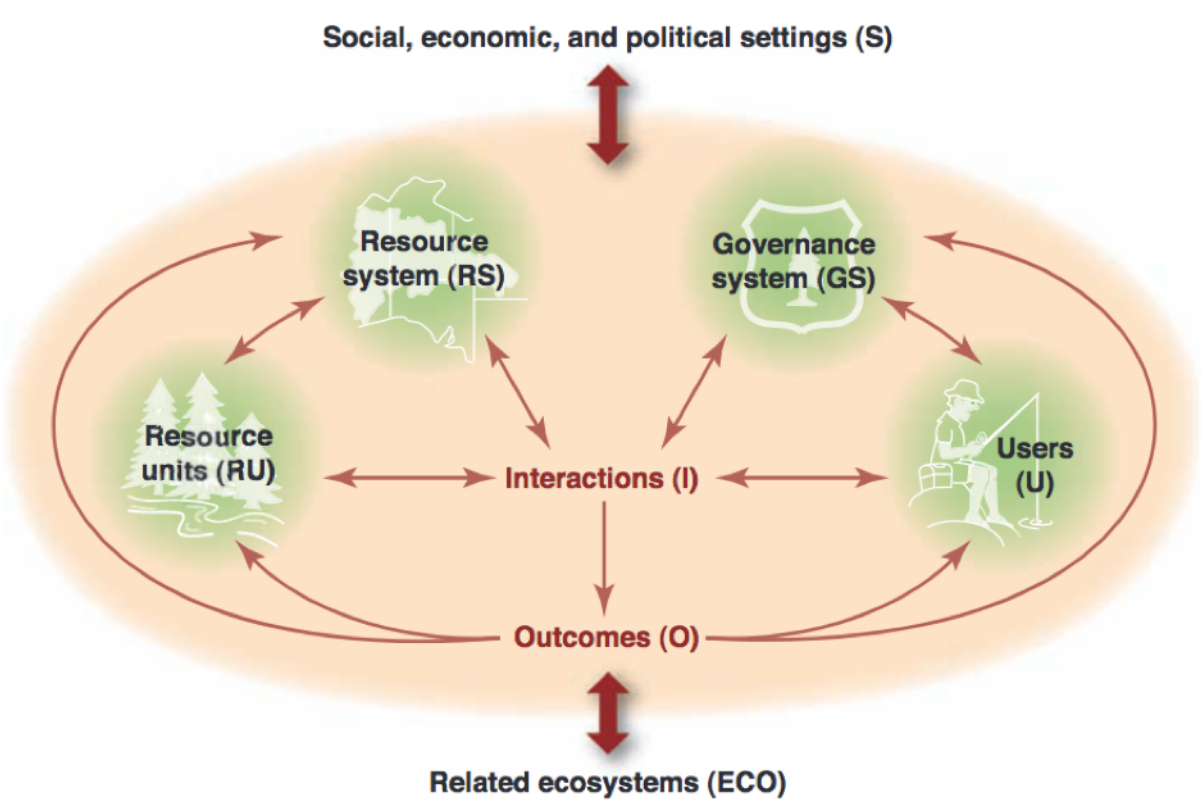

Fig. 1. The core subsystems in a framework for analyzing social-ecological systems.

Figure 2.5: An illustration of a framework for analyzing SES from (Ostrom, 2009)

4. It represents a perpetually dynamic and complex system that constantly adapts to evolving circumstances.

The SES perspective underscores the notion that the demarcation between social and ecological systems is artificial and arbitrary. Both social and ecological components exhibit characteristics of resilience and complexity, further highlighting their intricate and intertwined nature (Cote & Nightingale, 2012; Folke et al., 2010). SES has a significant body of literature devoted to water management, dating back to Elinor Ostrom's work (Ostrom, 2009) which later integrating the Institutional Analysis Framework (IAD) is designed to integrate multi-scale analysis and is able to integrate social ecological systems (SES) (Ostrom, 2011). Because of this link between institutional analysis and SES, the SES theory saw a significant amount

of literature production specific to water governance (Gain et al., 2021; Godden & Ison, 2019; Janssen et al., 2010; Trimble et al., 2021; Van der Brugge, 2009).

2.3 Methodological Review

2.3.1 Multi-scalar, systems approach

A multi-scalar systems approach is pivotal in addressing environmental and societal challenges, and this recognition has garnered support from scholars, practitioners, and policymakers (Horton et al., 2017; Micheli et al., 2014; Sala & Torchio, 2019). Water scarcity, as a multifaceted issue, demands the integration of both natural and social sciences, highlighting the relevance of a systems approach (Aguilera-Klink et al., 2000; Jaeger et al., 2013).In this context, multi-scalar analysis becomes indispensable because incentives operate across various scales (Baulenas et al., 2021; Qureshi et al., 2010). For example, the allocation of water supplies often extends beyond political boundaries, as evidenced in the Colorado River basin (Booker & Young, 1994; Goemans & Pritchett, 2014). Furthermore, water demands, influenced by exogenous factors like commodity prices or endogenous factors such as population changes, exhibit complex dynamics that span different scales. This necessitates high-resolution analyses, particularly crucial for econometric models (Colby et al., 1993; Hansen et al., 2014).

To respond effectively to this challenge and harness the full potential of a multi-scalar systems approach, I have structured Chapters 4, 5 and 6 to progressively shift from a global scale to statewide and then to a basin scale. Each of these scales comes with its unique set of trade-offs concerning data availability, suitable analytical methods, and resulting insights. For instance, in **Chapter 4,** I employed a global water scarcity dataset, WaterGAP3, which was well-suited for a global-scale analysis (further elaborated in Global scale: prioritization modeling to assess potential). However, it would have been inappropriate to simply downscale this model to the San Saba region, as explored in **Chapter 6**, for groundwater-surface water interaction analysis. Conversely, conducting the econometric analysis carried out in Chapter 5 at the continental

or global scale would have required a large, multi-year research effort.

Nevertheless, these scale-related limitations inherent to specific chapters seamlessly dissolve when the chapters are integrated, as demonstrated in this thesis. For instance, **Chapter 4** furnishes a list of geographic regions with a high potential for using incentives to address water scarcity. Using these results as a guiding framework, I zoom into the context of Texas in **Chapter 5**. Here, by pursuing different yet complementary research questions, I gather state-specific data pertaining to factors that could influence transaction activity. Finally, at an even finer scale, honing in on the San Saba River sub-basin in Texas (**Chapter 6**), I continue to address this hierarchical set of questions by focusing on the design of specific subsets of incentives tailored to mitigate water scarcity.

2.3.2 Spatial Analysis

The application of Geographic Information Systems (GIS) and spatial analysis has significantly advanced the modeling of interactions between water supplies and demands, providing spatially explicit representations (Dobson et al., 2020; Gain & Wada, 2014; J. Liu et al., 2017; Long & Pijanowski, 2017). Spatially explicit hydro-ecological models offer compelling illustrations of the advantages associated with incorporating spatially explicit modeling into efforts to address water scarcity (Esteve et al., 2015; Expósito et al., 2020; Jaeger et al., 2017; Ward et al., 2019). These models establish meaningful connections between hydrology and economics within a spatial framework, effectively showcasing the benefits of such an approach. Specifically, the spatially explicit approach provides multiple advantages, including improved visualization and communication, more accurate identification of water scarcity hotspots, and enhanced support for decision-making processes.

In each of the three substantive chapters (4, 5, and 6), spatial analysis techniques and GIS are used to address distinct research objectives. For instance, in **Chapter 4**, spatial joins are employed to amalgamate basin-level data from various models, forming a comprehensive matrix that characterizes different types of water scarcity. Meanwhile, **Chapter 5** leverages GIS to

organize extensive tabular time-series data across numerous variables, effectively categorizing it by specific basins. This organized data serves as the foundational dataset for subsequent econometric modeling. Finally, in **Chapter 6**, a range of GIS techniques are applied to transform point-specific hydrological data into river reaches, distinguishing between those gaining and losing reaches. Additionally, this chapter introduces a novel aspect by constructing longitudinal profiles of the basins, creating graphical representations that elucidate the relationship between rivers and underlying geology, thus enhancing our understanding of aquifer contributions to streamflow and vice versa.

2.3.3 Econometrics

Econometrics, a subfield of economics, employs a robust toolkit of statistical and mathematical techniques to systematically align economic theory with empirical evidence (Baltagi & Baltagi, 2011; Maddala & Lahiri, 1992). This discipline plays a pivotal role in enhancing our understanding of economic phenomena by quantitatively assessing how theoretical models correspond with observed real-world data. In the context of water markets, where a significant disparity often exists between theoretical expectations and empirical observations, econometrics emerges as a promising avenue for analysis (Colby et al., 1993; Isaaks & Colby, 2020; Jones & Colby, 2010). Its potential lies in its ability to decipher extensive transaction data, provided such data are readily accessible. By subjecting these datasets to rigorous econometric analysis, researchers can uncover underlying patterns, relationships, and dynamics within water markets, shedding light on how economic principles manifest in this specific domain. The application of econometrics serves as a crucial bridge that spans the divide between economic theory and real-world market behavior. By applying econometric methods to water market data, researchers can quantify the validity of economic theories, identify deviations from idealized models, and gain valuable insights into the factors influencing supply, demand, pricing, and trading behaviors in the complex realm of water markets. In doing so, econometrics can contribute to a more accurate and nuanced understanding of how economic principles operate in practice, facilitating informed decision-making and policy development in the field of water

resource management.

I explored various types of econometric analyses when trying to answer the final research questions associated with **chapter 6**. Interestingly, the initial study design did not incorporate econometric analysis. It was only upon assembling the original transactions database and visualizing the count of transactions (comprising both sales and leases) over time that a notable surge in transactions since 2012 caught my attention. This question promoted a serious investigation into econometric analysis and specifically which type of econometric analysis could answer the research question while using the transaction data. After significant research, it was determined a fixed effects model would be most appropriate considering the data and research question. Fixed effects models can account for differences between (in this case) basins, making them a valuable tool for several reasons:

1. Entity-Specific Effects: Fixed effects models allow you to account for unobserved, time-invariant differences or characteristics specific to each basin. In the context of your analysis, different basins may have unique characteristics or factors that influence water market transactions but remain constant over time. By including fixed effects for each basin, you control for these factors, ensuring that your analysis focuses on the changes within each basin over time.

2. Addressing Heterogeneity: Basins can vary significantly in terms of size, geography, hydrology, and other characteristics. Fixed effects help control for this heterogeneity by capturing the differences between basins that are consistent over time. This ensures that your regression coefficients reflect changes within each basin rather than variations between basins.

3. Controlling for Time Trends: Fixed effects models can also account for time trends that affect all basins similarly. For example, there may be global economic factors or regulatory changes that influence water market transactions across all basins. Fixed effects models allow you to control for these common time trends, isolating the unique effects

within each basin.

4. Statistical Efficiency: When you have multiple basins and limited data for each basin, fixed effects models can provide more statistically efficient estimates than a single pooled regression. They take advantage of the within-basin variation over time, making better use of the available data.

5. Interpretable Results: Fixed effects models yield interpretable results because they isolate the effects of time-varying variables within each basin. This can help you understand how specific factors or changes impact each basin individually

There were a couple of challenges with using the transactions data in a fixed effects model: (a) relatively small n (2,352 transactions), (b) it was time series, or panel data necessitates specific considerations. After extensive iterations, peer reviews, and testing, the Poisson fixed effects model was determined to be the most appropriate choice. However, to ensure robustness and facilitate broader understanding, I also present results from OLS, linear fixed regression, and the Poisson fixed effects model. Additionally, I developed an Arellano-Bond dynamic model estimator to account for the situation where T>N. Across various iterations, the statistical significance of each variable consistently aligned, as did their directional impact (positive or negative), contributing to a comprehensive analysis of the research question.

2.3.4 Global Hydrological Modelling

There is a rich body of literature devoted to global hydrological modeling, underscored by several recent review articles that take stock of its rapidly advancing scholarship (Bierkens, 2015; Pandi et al., 2021; Sood & Smakhtin, 2015).

Some of the earliest global hydrological models can be traced back to the late 1960s by a model developed in the atmospheric science community using a “bucket” model that generated runoff when full and had crude parameters for soil moisture and regional atmosphere (Manabe, 1969). Nonetheless, the bucket model paved the way for future models which integrated vegetation

layers, canopy interception, and two-layer soil hydrology (Deardorff, 1978). This set the stage for land surface models (LSM) in the 1980s (Dickinson & Henderson-Sellers, 1988; Sellers et al., 1986) and continued a decades long effort that evolved into land earth system models (LESMs) which combined hydrology, vegetations, carbon, and climate models (Best et al., 2011; Clark et al., 2011; Lawrence et al., 2011; Milly et al., 2014).

During the late 1980s and early 1990s hydrologists were focusing increasingly on quantifying water resources by trying to calculate both water availability and water demands at the global scale (Falkenmark et al., 1989; Gleick, 1996; Shiklomanov, 1997) and initial efforts in hydrological modeling relied on water use statistics and meteorological/hydrological observations. The first macroscale hydrological models (MHM) emerged in the late 1990s, including WaterGap, WBM, and MacPDM (Alcamo et al., 1997; Arnell, 1999; Vörösmarty et al., 1998). These models calculated blue water (surface water and nonrenewable groundwater) availability by accumulating runoff over stream networks. Water demand was also factored in, particularly in WaterGap and later versions of WBM, to assess water stress (Falkenmark, 1997). Additionally, (Fekete et al., 2002) utilized WBM output and discharge observations to create global runoff maps. Subsequently, blue water availability was determined by routing runoff from land surface models over global stream networks (Nijssen et al., 2001; Oki, 1997).

MHMs like WaterGap and WBM introduced a groundbreaking aspect: the integration of a water use model. Inspired by integrated assessment modeling work, they parameterized domestic and industrial water use based on average income per country (GDP/capita) (Alcamo et al., 1994). This allowed for global water use calculations, historical reconstructions, and future projections, considering factors like population growth and economic development. Additionally, irrigation water withdrawal and consumption were determined using a map of irrigated areas, considering irrigation water requirements (crop-specific potential evapotranspiration minus available soil water) and country-specific irrigation efficiencies (Döll & Siebert, 2000, 2002). These models, explicitly accounting for water use, are referred to as Global Hydrology and Water Resources Models (GHWMs). GHWMs have become central to global wa-

ter resource assessments conducted by organizations like the Global Water Systems Project (GWSP), UNESCO World Water Assessment Program, and UNEP Environmental Outlook. In Vörösmarty's 2000 Science article, they leveraged these foundational advances to illustrate that the impact of population growth on water scarcity outweighed that of climate change (Vörösmarty & Sahagian, 2000). GHWMs have undergone continuous enhancement in the last 20 years thanks to significant advances in computing, server-side processing, and higher resolution remote sensing resulting in improved functionality and higher model resolution. Notable GHWMs developed after 2000 include the integration of reservoir operations (Hanasaki et al., 2006), hydrodynamic routing (Van Beek et al., 2011), floodplain inundation modeling (Yamazaki et al., 2011), and monthly-scale assessment of water scarcity to consider intra-annual variability in availability and demand (Wada et al., 2011). Models such as Hydro-JULES offer further promise by offering three-dimensional, open source, models of the terrestrial water cycle which can support hydro-meteorological risks quantification and monitoring (Dadson et al., 2019). Beyond their original purpose of global water stress assessment, GHWMs and MHMs have found application in various areas, such as modeling global freshwater temperature,assessing global flood hazard and risk, tracking groundwater depletion, estimating the impact of terrestrial water stores on global sea level change, and providing medium-range to seasonal streamflow forecasts (Pappenberger et al., 2012; van Beek et al., 2012; Wada et al., 2010, 2012; Yossef et al., 2013). In light of the proliferation of models and applications, recent work has focused on fit of models (Horton et al., 2022; Waseem et al., 2017) and similar to recommendations in other disciplines the choice of the model should be guided by the research question, available data, and analysts to navigate the trade-offs associated with different models.

This thesis adopted a multi-scalar approach, ranging from the global to basin scale. Currently, there is no hydrological model available with parameters that can accurately scale up and down to the level of precision required for my research inquiries. While online tools like WWF Water Risk Filter and WRI Aqueduct use a global hydrological model and enable users to obtain results at the basin level, my research, particularly for the second and third papers,

demanded a higher level of precision than what global models could provide.

For my first paper, I employed the Water Global Analysis and Prognosis (WaterGAP3) model, developed at the University of Kassel (Germany) and computes water flows and storage across all continents except Antarctica. This model accounts for human impacts on natural freshwater systems through activities like water abstractions and dam construction. WaterGAP's modeling outcomes have significantly contributed to various international assessments of the global environmental landscape, including the UN World Water Development Reports, the Millennium Ecosystem Assessment, UN Global Environmental Outlook reports, and have been featured in reports by the Intergovernmental Panel on Climate Change. Additionally, it has been cited in several influential publications (Davis et al., 2017; Flörke et al., 2018; Greve et al., 2018; X. Liu et al., 2019; van Vliet et al., 2017; Vetter et al., 2017).

More comprehensive information regarding the models and methodologies for each chapter is provided in their respective methods sections.

2.3.5 Rationale for Integrating Approaches

The rationale for integrating approaches in this thesis is deeply rooted in the conceptual and methodological foundations that have been laid out in the preceding sections of this chapter. The conceptual framework, which draws from hydrology, economics, and governance literature, establishes the understanding of water scarcity as a complex interplay between supply and demand variables. By delving into the subcomponents of these variables and recognizing their diverse drivers and scales, we gain insight into the various manifestations of water scarcity. Furthermore, the conceptual framework also embraces incentives as a critical theoretical tool for addressing water scarcity. It acknowledges the challenges of managing water demand through incentives, supported by both theoretical examples and empirical evidence from global experiments. Additionally, a renewed exploration of water markets, in the context of a growing wave of popularity and as integral components of larger social-hydrological systems, forms a vital part of the conceptual foundation. The methodological approaches, discussed

in the second section of this chapter, align seamlessly with this interdisciplinary perspective. They respond to recent calls in the literature for multi-scalar, systems-based assessments of social-ecological systems. Within this framework, various methodologies, including spatial analysis, econometric models, and global-scale hydrological models, are explored for their unique contributions to the study of water scarcity. The rationale for integrating these diverse methods and literature across hydrology, economics, and governance becomes apparent when considering how they collectively address the research questions posed in this thesis. By synthesizing insights from different disciplines and employing a multi-scalar, systems-scale approach, we aim to bridge specific gaps in the existing literature. This integration is not merely an academic exercise; it is a strategic approach to generating holistic and actionable knowledge that can inform effective solutions for managing and mitigating water scarcity challenges. In doing so, this thesis seeks to foster a more comprehensive understanding of water scarcity and its practical applications in the real world.

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Chapter 3

Methodologies

3.1 Methodologies

This chapter serves as an overview of the overarching research design and methodology employed in this thesis. It delineates the conceptual framework, methodological approach, and contextual constraints and assumptions that guide the study. Subsequently, I outline the methodological steps taken to address the three primary research questions. The first question focused on mapping the potential of incentives to address water scarcity is addressed through a comprehensive global spatial analysis, the findings of which are expounded upon in Chapter 4. Moving forward, an original transactions database is constructed, serving as the foundation for spatial and econometric analyses presented in Chapter 5, addressing the second research question on performance. Finally, focused on portfolios for the third research question, this thesis employs a triangulation approach, integrating data from groundwater wells, surface water rights, and transactions records to assess the trade-offs associated with various environmental water transactions. For a more detailed examination of each aspect, please refer to Chapters 4, 5, and 6, respectively. This chapter provides only concise methodological overviews.

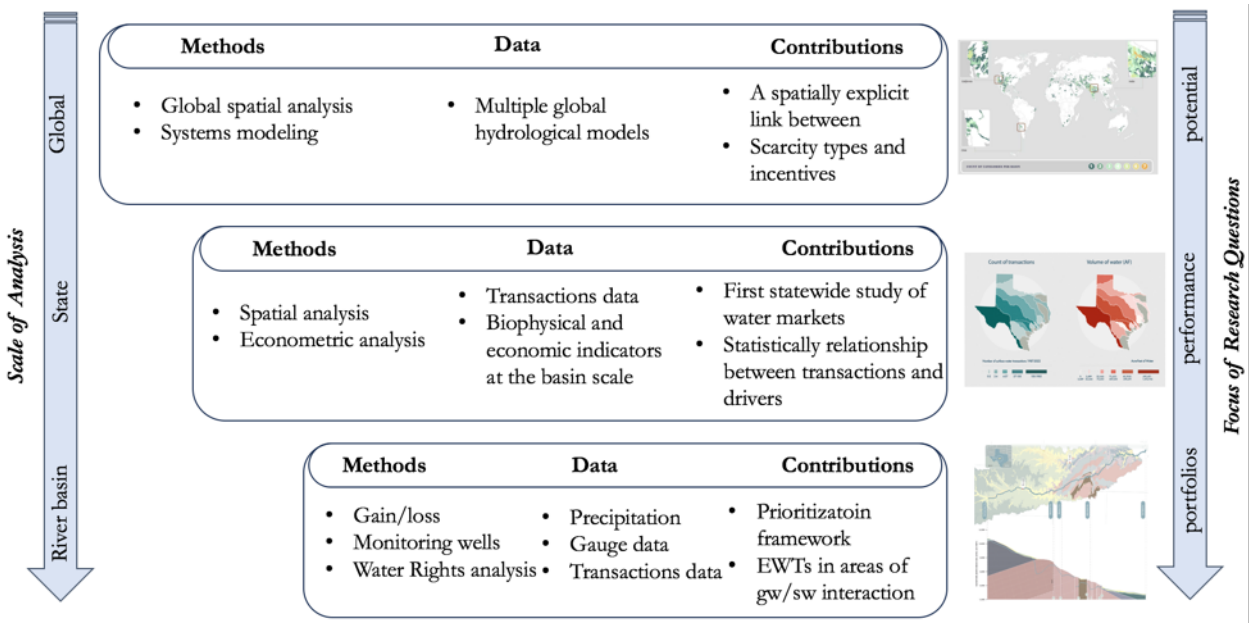

Figure 3.1: Overarching methodological approach taken to achieve the aims of the thesis.

3.1.1 Research Design

This thesis addresses the overarching question: where and how can water markets contribute to sustainable water management? To answer these questions, this thesis explores the potential, performance, and portfolios of incentives to address water scarcity employing an interdisciplinary, systems approach at three different scales. A conceptual diagram is presented below in Figure 3.1. On the left-hand side, I show the scale of analysis, going from global to river basin, which reflect the order of chapters 4, 5, and 6, respectively.

3.2 Scope of Thesis: Limitations and Assumptions

3.2.1 Conceptual Boundaries and Assumptions

Interdisciplinary scholarship: a trade-off of breadth and depth

This thesis seeks to bridge disciplines, specifically hydrology, economics, and governance to answer the research questions. As argued in the conceptual review, I believe an interdisciplinary perspective is necessary to bridge the gap between the theory and implementation of

incentives to address water scarcity. Nonetheless, there are also associated tradeoffs with an interdisciplinary thesis. For example, I made a concerted effort to position hydrology in the context of water resources management hydrology, which takes into account water uses and water demands and therefore links to economics and governance. However, there are other sub disciplines of hydrology which could also offer opportunity to improve incentive conditions, for example the link between atmospheric science and hydrology for climate change modeling.

Likewise, my sub-focus on water markets focuses on a subset of economic scholarship related to property rights, transactions, and externalities because there was a direct link, theoretically and empirically to water scarcity (Pérez-Blanco et al., 2020; Young, 1986). Even exciting new fields of economics, for example market design which could contribute to the work on incentives were not explored fully (Borenstein et al., 2019; Roth, 2008, 2018).

Similarly, my focus on governance and institutional analysis was strongly guided by Ostrom's work on common pool resources (CRP) because there was an explicit link to the management of water resources as a social-hydrological system (Ostrom, 1993, 2011; Ostrom & Basurto, 2009). The ability for water governance to be analyzed within larger social-hydrological systems prioritized this sub-field of governance for this thesis (Cody et al., 2015; Cox, 2015; Ostrom, 2010)). Nonetheless, there are additional lineages of scholarship that focus on additional aspects and epistemologies of water governance, including ethics, cultural water governance and indigenous water governance that deserve equal attention (Leonard et al., 2023; O'Donnell et al., 2023).

The complex values of water: conceptual challenges associated with mapping and modeling

In a 2018 paper published in Science, a group of influential water scholars highlighted the challenging yet crucial task of valuing water for sustainable development (D. E. Garrick et al., 2017). This challenge is rooted in the multifaceted nature of water, encompassing economic,

political, and physical attributes (as discussed in the chapter by Hanneman in (Rogers et al., 2005). This thesis grapples with the conceptual challenge of understanding water's value, considering it both as a public good and a commodity. Traditionally, water markets have treated water as a commodity, while environmental water transactions aimed to derive public benefits from market-based exchanges (Ayres et al., 2018; Brooks & Harris, 2008). Consequently, the results presented in chapters 4, 5, and 6 inherit this tension and each seeks to address it based on the respective research question.

For instance, in chapter 5, I compare the value of water transactions between rural users (representing a private benefit associated with using water as an economic input) and transactions dedicated to enhancing instream flows (representing a public benefit to improve baseflows). In reality, the values associated with water are more complex and dynamic than a simple dollar-to-acre-feet value. However, in this case, there were not enough environmental water transactions to segregate the database for a detailed comparison based on water users involved in the transactions, though this area holds potential for future research. Dedicated scholarship has explored the tension between water as a public good and a commodity (Baer, 2014; Deacon, 2009; Perry et al., 1997). Nonetheless, while existing research has focused on valuing water for specific purposes, such as water supply reliability or water quality (Egan et al., 2009; Griffin & Mjelde, 2000), the challenge of valuing water for multiple uses across diverse scales, cultures, and political boundaries remains a promising avenue for future scholarly exploration.

3.3 Methodological boundaries and assumptions

This thesis designed and employed a series of models to help answer a hierarchy of questions and multiple scales. All of the models carried their own set of assumptions which to the extent possible were carefully designed to mitigate the impacts on the particular analysis. In the global model that links types of scarcity to types of incentives, I encountered a challenge related to the diversity of water use. To address this, I needed to establish a proxy measure for water use diversity that could be consistently applied on a global scale. Given the limi-

tations, I opted to use crop type as a proxy because it was the most readily available metric with high-resolution global coverage. It is important to acknowledge that this choice comes with certain limitations. I am aware that the assumption underlying this proxy, i.e., that crop type represents diversity in water use universally, may not hold true in all cases. Water's marginal productivity can vary even within a basin dominated by a single crop due to various factors affecting crop productivity. Nevertheless, the model treated basins with higher variation in crop production value as more suitable candidates for incentive-based water reallocation, while those with near-homogeneous production values were assumed to have less incentive for water reallocation. Of course, exceptions exist, particularly when other factors of production exhibit high variation. For a comprehensive list of additional model assumptions, please refer to the supplementary material in the published article. **Chapter 5** involves a methodological assumption related to groundwater level data in different basins. To compile groundwater level data spanning 30 years, I thoroughly examined available state and national well data for Texas. Unfortunately, there was a significant scarcity and paucity of data, both temporally and spatially, within the monitoring well records. Consequently, I had to select wells with the most comprehensive datasets while still ensuring sufficient spatial diversity to serve as proxies for groundwater levels in each basin. This assumption rests on two key considerations. First, it presumes that monitoring wells with the best records provide the most accurate indicators of groundwater levels within the specific surface water basin under investigation. Second, it acknowledges the well-established existence of groundwater-surface water interactions in Texas rivers (as discussed in **Chapter 6**). However, due to computational constraints and data availability limitations, I could not collect monitoring well data for all aquifers underlying each surface water basin. The hypothesis I tested using groundwater levels in the econometric models posited that declining groundwater levels corresponded to an increase in surface water transactions. Nonetheless, it is possible that groundwater levels in different (minor) aquifers within the basin may not closely align with data from the selected monitoring wells. Consequently, certain trading decisions based on groundwater levels may not have been detected in the econometric analysis. **Chapter 6** presents yet another

methodological assumption, this time concerning sample sizes in both the gain-loss study and groundwater well monitoring. A famous 1904 Texas Supreme Court case characterized the ”movement and course” of underground water as ”so secret, occult, and concealed” that it defies easy comprehension (Mace et al., 2004). For many decades, monitoring groundwater was not a priority, as there was no incentive for either the state or private landowners to engage in such efforts. Consequently, substantial knowledge gaps persist regarding surface-groundwater interactions, an area where **Chapter 6** makes a valuable empirical contribution. However, for the purposes of addressing the research questions and, more pragmatically, for spatially targeting environmental water transactions (EWTs), it was not imperative to have a perfectly modeled representation of groundwater-surface water interactions. Ideally, access to more than three wells would have allowed for a better demonstration of the variations in hydrological relationships among precipitation, streamflow, and groundwater levels. Unfortunately, the historical lack of emphasis on installation and maintenance of monitoring wells in Texas meant that access to additional wells was not available.

3.4 Global scale: prioritization modeling to assess potential

Chapter 4 develops a framework and a geospatial model for linking water scarcity with incentives and investments focused on the interaction of human and natural components of water (Jaeger et al., 2013; Srinivasan et al., 2012). This link is created using three steps:

1. Map the drivers of water scarcity by analyzing at the intersection of (a) types of demand and (b) their timing using spatial analysis.

2. Define different types of incentives and investments, their strengths, and weaknesses, limiting factors, and enabling conditions based on a literature review.

3. Compare how certain incentives and investments impact water scarcity (e.g., change in

use, increase economic productivity, increased environmental flows, etc.) drawing on the literature.

3.4.1 Step one: Map the Drivers of Water Scarcity

WaterGAP3

WaterGAP3 classifies 15,084 basins globally into even divisions of consumption-to-availability water depletion categories. The metric of water depletion has been used in a growing number of recent articles which seek to interrogate implications of water scarcity (Davis et al., 2017; Flörke et al., 2018; Greve et al., 2018; van Vliet et al., 2017; Vetter et al., 2017). The model further defines seasonal and dry-year depletion based on the number of times a basin meets a depletion threshold within their time series of 1970-2000. Importantly for our purposes, WaterGAP categorizes water use by sector and includes: agriculture, domestic, industrial and livestock. More information on WaterGAP3 can be found in (Brauman et al., 2016). WaterGAP3 outputs inform at least part of every one of our nine scarcity typologies, and its basins represent the spatial extent of all of our maps presented in this article. I used WaterGAP3 for defining the thresholds of the competition of water matrix as well as the seasonal and chronic thresholds on the timing of scarcity matrix. For the competition matrix, I employed a threshold of 75% depletion. This threshold is consistent with the thresholds employed in WaterGAP3 categories. While sensitivity analysis was indeed considered, feedback indicated that deviating from the established threshold introduced more arbitrariness into the process. For example, if agricultural water consumption within a basin was 75% or more of the total depletion within a basin, then that basin was categorized as agriculturally driven competition. For the timing of scarcity matrix, I combined the predetermined seasonal and dry-year categories developed by (Brauman et al., 2016). In their model, they define seasonal depletion as occurring when annual depletion is below their 75% threshold but at least one month has consumption-to-availability ratio greater than 75%. Dry-year is defined as a basin which "experiences one month more than 75% depleted in at least 10% of years during the historic period but on average are not annually

or seasonally depleted" (Brauman et al., 2016). In my matrix, chronic timing of scarcity refers to depletion levels above seasonal and dry-year in WaterGAP3 which correspond to 75-100% and over 100% depleted.

Aqueduct Water Risk Atlas

Aqueduct Water Risk Atlas is a platform developed by World Resources Institute designed to organize spatial information on water-related risks and assess exposure to different variables including: water stress, water depletion, interannual variability etc. An updated technical note on the platform can be found here: (Hofste et al., 2019). The model output uses HydroBASINS level 6 hydrologic sub-basins globally. I used Aqueduct to inform typologies 3,6,9 because I needed a comparable dataset to inform the anticipated timing of scarcity. I relied on the Water Risk Atlas, Future 2030, Business as usual, Water Stress indicator to inform our analysis. The water stress indicator measures "the ratio of total water withdrawals to available renewable surface and groundwater supplies. Water withdrawals include domestic, industrial, irrigation, and livestock consumptive and non-consumptive uses. Available renewable water supplies include the impact of upstream consumptive water users and large dams on downstream water availability. Higher values indicate more competition among users" (Hofste et al., 2019). I performed spatial analysis to identify any WaterGAP3 basin which was overlaid by an Aqueduct Water Stress indicator (Future 2030, BAU) of high or extremely high. Depending on the typology I then further filtered either the WaterGAP3 basins or the City Water Map intakes.

City Water Map The City Water Map (CWM) (McDonald et al., 2014) is a database which identifies the water sources of over 500 cities globally. The database has been used recently to study water competition between cities and agriculture (Flörke et al., 2018) and the data has been featured as a contribution to the urban water security literature (Hoekstra et al., 2018). The CWM data was used to inform typologies 4, 5, and 6, and 7, 8 and 9 in our matrix. Specifically, I performed spatial analysis to find city intake point within WaterGAP3 basins or Aqueduct Water Risk basins depending on their depletion levels or stress levels, respectively. I assigned an attribute to each WaterGAP3 basin where a CWM withdrawal point was located

within the basin boundary. Each of the typologies analyzing competition of urban uses relied on (a) the withdrawal point was in a water scarce basin and (b) was neighbored by water scarce basins where 75% of depletion came from another user.

Crop Prices

SPAM's cross entropy starts with prior knowledge of where crops may be grown and to which extent. It assumes that farmers, given a choice of different crops, will grow those which generate more revenue. And this is where crop prices come in. I use a different price for every crop, but the same price for all countries: 2004-2006 average international price, as used by FAO to compute the Value of Production. More details available: https://www.mapspam.info/methodology/

Process

First, I identify basins where competition for water is driven by irrigated agriculture where 75% or more of depletion is attributed to irrigated agriculture using WaterGAP3 (cells 1-3 in figure 1). Second, I identify basins where water scarcity is driven by competition between agriculture and urban users by identifying basins where a city's water intake (City Water Map) falls within a scarce WaterGAP3 basin OR their neighboring basin is scarce (cells 4-6). Finally, I identify competition between urban and industrial users as drivers of scarcity when a WaterGAP3 basin where urban and industrial use exceed 25% of water availability in the same basin (cells 7-9)

Next I developed the timing axis by categorizing the timing of scarcity within a basin as either seasonal, chronic, or anticipated. For seasonal scarcity I combined the predetermined seasonal and dry-year categories developed by (Brauman et al., 2016). Chronic timing of scarcity was given to basins where depletion levels were either 75-100% or ¿100%. For anticipated scarcity I relied on the WRI Water Risk Atlas, Future 2030, Business as usual, Water Stress indicator.

This classification scheme is not able to explicitly account for infrastructure constraints (Pad-

owski & Gorelick, 2014), and assumes that they are captured at coarse resolution by the underlying data in WaterGAP3 and Aqueduct.

3.4.2 Step two: Define Different Incentives

Finally, a third tier of examples from the literature also exists. For example, for incentives: spot markets (Calatrava, 2005; Yoskowitzy, 1999), formal water markets (D. Garrick et al., 2009; Grafton et al., 2011), and environmental water trusts (Montilla-López et al., 2016; Neuman, 2004) reveal a patchy history of successes and challenges . For irrigation water-use efficiency: sprinkler to drip irrigation conversion (Liu & Kang, 2006; MacDonnell, 2012), and canal lining (Meijer et al., 2006; Scheierling & Tréguer, 2018) also feature prominently in the literature and practitioner experience.

3.4.3 Step three: Compare how Incentives Impact Water Scarcity

For irrigation water-use efficiency, I use crop value of production as a metric for potential applicability for irrigation water-use efficiency. I use data from the 2010 Spatial Production Allocation Model (SPAM) (Yu et al., 2020) to organize the value of production for all crops (food and non-food) across all basins from the nine types of water scarcity. Value of crop production is an important metric because it relates to the value of water and the potential for gains from trade. I used ArcGIS 10.7 to calculate Getis-Ord Gi* statistic to identify statistically significant spatial clusters of high values and low values (i.e. hotspots) within each basin. Next I identified basins where there were more hotspots (using 99% confidence value) of either low value or high value crop production than non-hotspots. I considered the basins containing high counts of hot spots of low or high value production, which indicate heterogeneous values of crop production, as better candidates for transactions than those without hotspots. I assumed that basins with near homogeneous values of production have less incentive to trade and may be better served by irrigation water-use efficiency. For a graphical display of how this set of rules was applied to the nine water scarcity categories, see Figure 1 in Chapter 4.

3.5 State Level: Spatial analysis and econometrics to detect drivers

For chapter 5, I employed a mixed methods approach, including spatial and statistical analyses, leveraging an original water transactions database to examine water market dynamics and performance. One of the significant challenges in water market research is obtaining robust transaction data. To address this, I compiled a database, which, to the best of my knowledge, is the most extensive record of transactions in Texas (n=2,352) from 1987 to 2020.

3.5.1 Data Collection

This database integrates surface water transaction data from various sources, including the Water Transfer Database (WTD), WestWater, and The Nature Conservancy. The WTD, spanning from 1987-2010, draws data from Water Strategist, providing information on transaction volumes, prices, types, and directions for 335 transactions in Texas up to 2009 (Hendricks and Peterson, 2012) WestWater contributed data for 147 sales and 1,836 leases from 2009 to 2022 (Regnacq et al., 2016), while The Nature Conservancy added 34 transactions since 2015, including 10 benefiting the environment (Bigelow et al., 2017). Though not exhaustive, my database offers substantial temporal (1987-2022) and spatial (13 basins) coverage, making it a valuable resource for analysis.

3.5.2 Statistical Analysis

To understand transaction patterns, I utilized fixed effects and Poisson regression models (Brookshire et al., 2004; Colby et al., 1993). Fixed effects regression helps control for factors like selection bias and unobserved differences that remain constant across time and entities (K. W. Jones & Lewis, 2015; Mummolo & Peterson, 2018).This method has a history of application in social science research and is particularly valuable for panel data analysis, such as water transactions (Brown et al., 2013). Econometric analysis has been a staple in water market research for years, including the study of externalities and trading behavior (Shiferaw

et al., 2008).

3.5.3 Econometric Model Selection Rationale

Choosing the right econometric models depends on research questions, data characteristics, and assumptions. While previous studies have employed different models, my research opted for fixed effects regression to account for basin-level variation (Ghosh, 2019; Hansen et al., 2014). Poisson regression was chosen to focus on transaction counts, allowing for a better understanding of market activity, especially at the basin level, while normalizing for volumes and prices across basins (Isaaks & Colby, 2020; L. Jones & Colby, 2010).

These methodologies build upon existing studies by offering a basin-level perspective, leveraging high-resolution remotely sensed data, and providing a nuanced analysis of water market behaviors and outcomes.

3.6 Basin scale: spatial targeting to navigate groundwater-surface water interaction

In river basins experiencing water scarcity, water demands for freshwater ecosystems and water users increasingly compete with one another. Environmental water transactions (EWT) offer a mechanism for resolving this competition via a voluntary agreement in which existing water users are paid to modify the time, place and/or volume of their water right to provide an environmental benefit. However, inconsistencies in how water governance manages surface water and groundwater have challenged the implementation and scaling of EWTs. I specifically focus on the San Saba River, a tributary of the Texas Colorado River, and the finest scale of my thesis. Water scarcity in San Saba is driven by multiple types of scarcity, which can be exacerbated by a local hydrogeology that facilitates high groundwater-surface water interactions. This has challenged traditional water management tools and given rise to increased competition between downstream and upstream water users. Additionally, several stretches

of the river can become dry and imperil native freshwater species. In this context, chapter 5 focuses on a hierarchical set of questions designed to disentangle the mismatch between the governance and hydrology of the San Saba, and use that information to spatially target EWT portfolios:

1. Which sections of river require intervention during times of scarcity to maintain flow targets? (i.e., priority reaches)
2. In these priority reaches, what are the spatial and temporal influences of natural (geologic) and anthropogenic (water use) drivers of scarcity?
3. What volumetric contribution can different portfolios of water rights paired with different types of EWT contribute to flow targets? And what are the costs and benefits associated with each portfolio?

I focus on triangulating data between a gain-loss study, groundwater monitoring wells, and state data on surface water rights.

To identify priority reaches, I relied on a gain-loss study that took place between 2018-2021 in the section of the San Saba in Menard County. Gain-loss studies are an example of a physically based model and are used to quantify interactions between groundwater and surface water within a system (Harte & Kiah, 2009; Slade Jr et al., 2002). Measurements of streamflow are taken at various locations in the main channel. The channel gain or channel loss is computed for each sub-reach between measurements by comparing the inflows and outflows plus flow gain or flow loss in the sub-reach. I employed a gain-loss study because (a) I needed to identify reaches in the river that were losing and gaining to ensure I could meet the conservation objective; (b) the results allow us to unpack the anthropogenic and hydrogeological influences on the system; and (c) because there is a growing interest in the state of Texas to understand groundwater/surface water interaction considering the legal and governance implications (Foster et al., 2021; Smith et al., 2015). For the San Saba, a gain-loss study was

performed in June 2018 where streamflow was measured at 14 locations in Menard and McCulloch Counties to identify (a) where groundwater contributes to streamflow and (b) where water use may be reducing streamflow. The locations of the study were based on a previous study in July 1933 (found in(Slade Jr et al., 2002) and focused on the reach between the headwater springs and Paleozoic outcrop. This reach is where most irrigation takes place and is composed of complex interactions with underlying aquifers. The flow measurements were collected by TNC, Texas Parks and Wildlife Department, and WSP USA. All measurements were made with a Sontek FlowTracker following USGS protocols and measured twice at each location. June 2018 corresponded with very dry conditions immediately before a period of heavy rainfall in fall of 2018. Low flow periods provide an advantage for gain-loss studies because interactions between the river and the bedrock geology are more observable.

3.6.1 Monitoring wells uncover interactions between groundwater and surface water based on sources of water and geographic location

To understand the interactions between streamflow, precipitation, and groundwater levels, I relied on gauges from well data. Six In-Situ Model 400 Level-TROLL transducers were installed in local alluvium and Edwards-Trinity groundwater wells on June 28th and July 27th, 2018. These transducers record semi-hourly water level changes. On July 20th, 2018, two Model 100 Rugged-Troll transducers were installed at Fort McKavett Springs and Clear Creek, two locations previously measured by the U.S. Geological Survey. The long-term goal with monitoring both surface water and groundwater levels are to identify gains and losses in both irrigation, and non-irrigation seasons to (a) understand how the system responds to pumping and (b) identify specific EWTs strategies that respond to the system and protect habitat.

3.6.2 Developing an estimate of mass water balance for the area of interest helps quantify consumptive water demand

To estimate the consumptive use of water in Menard County, I developed a model to estimate the volume of consumptive groundwater and surface water used during the irrigation season.

For surface water demand, I used a water availability model (WAM) run 8 scenario and selected water rights in Menard County (n=83) (Wurbs, 2005). Run 8 of the model is current conditions and simulates recent (last 10 years) surface water demands. Therefore, I assume that volumes from users were consumptively used during this time period and do not account for return flows. I took the sum of the volumes from the WAM model for the months of March to October to represent the irrigation season. The volume of water, which I call the surface water demand irrigation season, is equal to 7,484 AF of water, which is 31.18 AF/day or 15.72 cubic feet per second (cfs) for 8 months.

For the groundwater demand of the model, I filtered groundwater wells inside Menard County. I then used data from the Texas Water Development Board (TWDB) which calculated the consumptive water demand of groundwater wells. I mapped the demand curve of the surface water demand irrigation season to the groundwater wells to provide an estimate of consumptive demand during the irrigation season. The volume of water, which I call groundwater demand irrigation season, is equal to 440 AF of water, which is 1.83 AF/day or 1 cubic feet per second (cfs) for 8 months.

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Chapter 4

Mapping Incentives for Sustainable Water Use: Global Potential, Local Pathways

Abstract

Competition for freshwater resources is intensifying water scarcity and its impacts on people, economies, and the environment, posing a growing challenge for sustainable development. Meeting these challenges will require incentives to encourage sustainable water use. Prior calls to shift from supply-driven solutions to a soft path of demand management (pricing, markets, behavioral changes) have encountered stubborn obstacles. We undertake a multi-scale assessment of water reallocation and investment in water conservation technologies to understand their potential and limits for addressing different drivers of water scarcity. Our model identifies what drives water scarcity at the sub basin scale, and examines two prominent responses to these drivers. Our analysis distinguishes different types of water scarcity based on the demands for water and their timing, creating nine (9) categories of water competition, which can overlap. Water demand within agriculture contributes to scarcity in 94% of the basins experiencing scarcity, concentrated in the central USA, Spain, and India. Urbanization has led to competition between cities and agriculture in 1,596 of 3,057 subbasins (52%). We examine how different institutional mechanisms (incentive-based water reallocation) and technologies (investment in water conservation technologies) can address these different types of water scarcity. This study builds on several local and high-resolution models demonstrating the potential to increase the economic efficiency (and marginal productivity) of water use. The gap between potential and implementation is high, however. Efforts to bridge this gap in priority geographies can link modeling advances with the design of pathways that combine incentives with robust water accounting, caps on water extraction, and enforcement capacity at multiple scales.

4.1 Introduction

The World Economic Forum's global risks survey has identified water scarcity as one of the top five global risks affecting people's well-being (WEF, 2020). Water supply variability, exacerbated by climate change, is already a significant challenge for food growing regions (Connor et al., 2012; Hanjra & Qureshi, 2010) and cities (Padowski & Gorelick, 2014; B. D. Richter et al., 2013). Water demand globally has increased due to multiple, interrelated factors includ-

ing urbanization, changing diets, and a growing population. As a result, water abstraction today is nearly six times greater than it was 100 years ago (Wada et al., 2014). Historically, water policies and investments have favored supply-side solutions like dams, desalination and groundwater development (Baldassarre et al., 2018; McEvoy, 2014). However, incentive-based approaches to manage demand—including improved water allocation policies—consistently rank among the lower-cost options to enhance water security (Bank, 2016; E. L. O'Donnell & Garrick, 2019). This article focuses on the question: which types of incentives and investments can address different types of water scarcity? This requires us to first understand what drives scarcity, and then evaluate appropriate incentives and investments that match the type of water scarcity.

4.1.1 What drives water scarcity?

Water scarcity can be defined as an excess of water demand over available supply (Steduto et al., 2012). Within this definition are several important components. Freshwater supply or availability depends on precipitation over land which divides into either runoff or evapotranspiration (Hoekstra, 2019). Water availability fluctuates over space and time, and exacerbations in hydrologic variability due to climate change challenge water management and policy (D'Odorico & Bhattachan, 2012; Hall et al., 2014). There are also different types of water demands and uses. Consumptive use (evaporation or transpiration) can be beneficial (e.g. intended for a cooling plant or irrigation) or non-beneficial (e.g. evaporation from a lake) (Perry, 2007). Water consumption can either be recoverable (e.g. return flows from sewage systems) or non-recoverable (e.g. flows to the sea) (Perry, 2007). Economic policies and technological changes respectively, influence the demand and supply curves of water. Economic policies (e.g. trade policies, subsidies) drive changes in water use which affect water productivity (Debaere & Kurzendoerfer, 2017) and comparative advantage (Debaere, 2014).

Studies demonstrate that agriculture is the largest water consumer (Falkenmark & Rockström, 2006; Tuninetti et al., 2019) and that globally, the area equipped for irrigation has expanded

fivefold over the 20th century (Siebert et al., 2015). Urban water demand is projected to increase 80% by 2050 and competition between cities and agricultural users could affect hundreds of millions of people (Flörke et al., 2018). Competition between hydropower and agricultural users (Zeng et al., 2017) and industrial water users (Strzepek & Boehlert, 2010) also occurs. Water demands for the environment should be considered as well, as environmental flow requirements and management play an important role for freshwater conservation (Poff et al., 2010). However, over 40% of global irrigation water use occurs at the expense of environmental flow requirements, (Jägermeyr et al., 2017) and groundwater pumping has already resulted in environmental flow limits being reached in a substantial number of watersheds (Graaf et al., 2019).

There are also differences in how water scarcity is measured, and the assumptions in those definitions affect the analysis. Both blue water and green water are affected by water scarcity. Blue water scarcity (BWS) is defined as the ratio between societal blue water demand and renewable blue water availability (Rosa et al., 2020). Green water scarcity (GWS) is defined as the ratio between irrigation water requirement and total crop water requirement (Rosa et al., 2020). Within the literature, blue water scarcity has received significant attention, in part because it represents competition between water users (Brauman et al., 2016; Rosa et al., 2020). Studies on green water scarcity lag behind (Rockström et al., 2009; Schyns et al., 2015) even though accounting for GWS is critical for agricultural production (Aldaya et al., 2010) and represents opportunities for reduced water use and increased water productivity (Davis et al., 2017; Molden et al., 2010). There are also important differences in measuring water scarcity in terms of livelihoods (Srinivasan et al., 2012), natural-human systems (Jaeger et al., 2013) or biophysical definitions (Brauman et al., 2016). Here we focus on a biophysical definition of water scarcity defined by (Brauman et al., 2016) as depletion, i.e. the fraction of available renewable water consumptively used by human activities within a watershed.

4.1.2 Which incentives can address different types of water scarcity?

There are multiple types of incentives for addressing water scarcity. The literature is extensive and inconsistent in its terminology for what counts as an incentive, and whether incentives should be considered strictly 'demand-side' given their heavy reliance on supply infrastructure. We examine economic instruments for water management drawing on typologies developed through recent work in the European Union (Rey et al., 2019), environmental conservation organizations (Springer et al., 2021), and irrigation technology for water conservation (Pérez-Blanco et al., 2020). We focus on incentive-based reallocation (which can be coordinated by markets or negotiation) and investment in water conservation technologies (which involves technology adoption and behavior changes). Incentives and investments designed to address competing water uses require an increase in the economic productivity of water (Debaere, 2014) i.e. the value of product over volume of water extracted. Specifically, we assess how the policy and technological changes required for water reallocation and water use efficiency can address different types of competition for water.

We map incentives for sustainable water use by addressing two gaps: (1) What types of demand drive water scarcity? and (2) Which incentives and investments can address those drivers in the short term and long term? To answer these questions, we take four steps. First, in this section (above), we reviewed the literature on the drivers of water scarcity and the role of different incentives and investments. Second, in the methods, we construct a basic typology of water scarcity that considers the types of demand driving water scarcity and their timing. Third, we formulate a rules-based logic for matching incentives and investments with different types of water scarcity. Fourth, we map the drivers of water scarcity and potential incentives globally, and illustrate the sub-national heterogeneity in the context of Mexico.

Our analytical framework links drivers of water scarcity to different incentives and investments. This framework needs to be tailored by water managers for application at different decision-making scales. The initial objective is to understand where, and how, different incentives can respond to water scarcity. Matching the type of scarcity to appropriate incentive-

based tools can help identify priorities for policy reform and investment.

4.2 Methods

Our framework for linking water scarcity with incentives and investments focuses on the interaction of human and natural components of water (Jaeger et al., 2013; Srinivasan et al., 2012). We create this link using three steps:

1. Map the drivers of water scarcity by looking at the intersection of (a) types of demand and (b) their timing.

2. Define different types of incentives and investments, their strengths and weaknesses, limiting factors, and enabling conditions.

3. Compare how certain incentives and investments impact water scarcity (e.g. change in use, increase economic productivity, increased environmental flows, etc.).

4.2.1 Step one: map the drivers of water scarcity

We develop a typology of water scarcity built on two axes: (1) types of demand and (2) timing of water scarcity (figure 1 below). The two axes reflect trends in literature that competition (Flörke et al., 2018; Kendy et al., 2018) and timing (Hanasaki et al., 2013; Schewe et al., 2014) are critical attributes for understanding water scarcity. To develop the types of demand axis, we examine three types of demand that can drive water scarcity in the context of limited water supply using WaterGAP3 (Brauman et al., 2016) and City Water Map (McDonald et al., 2016) (described in supplementary material (available online at stacks.iop.org/ERC/3/041002/mmedia)). First, we identify basins where competition for water is driven by irrigated agriculture (figure 1: Types 1–3) . Second, we identify basins where water scarcity is driven by competition between agriculture and urban users (figure 1: Types 4–6). Finally, we identify competition between urban and industrial users (figure 1: Types

7–9). Future iterations should consider environmental flows (Richter et al 2012) which would highlight additional layers of competition within basins and aquifers.

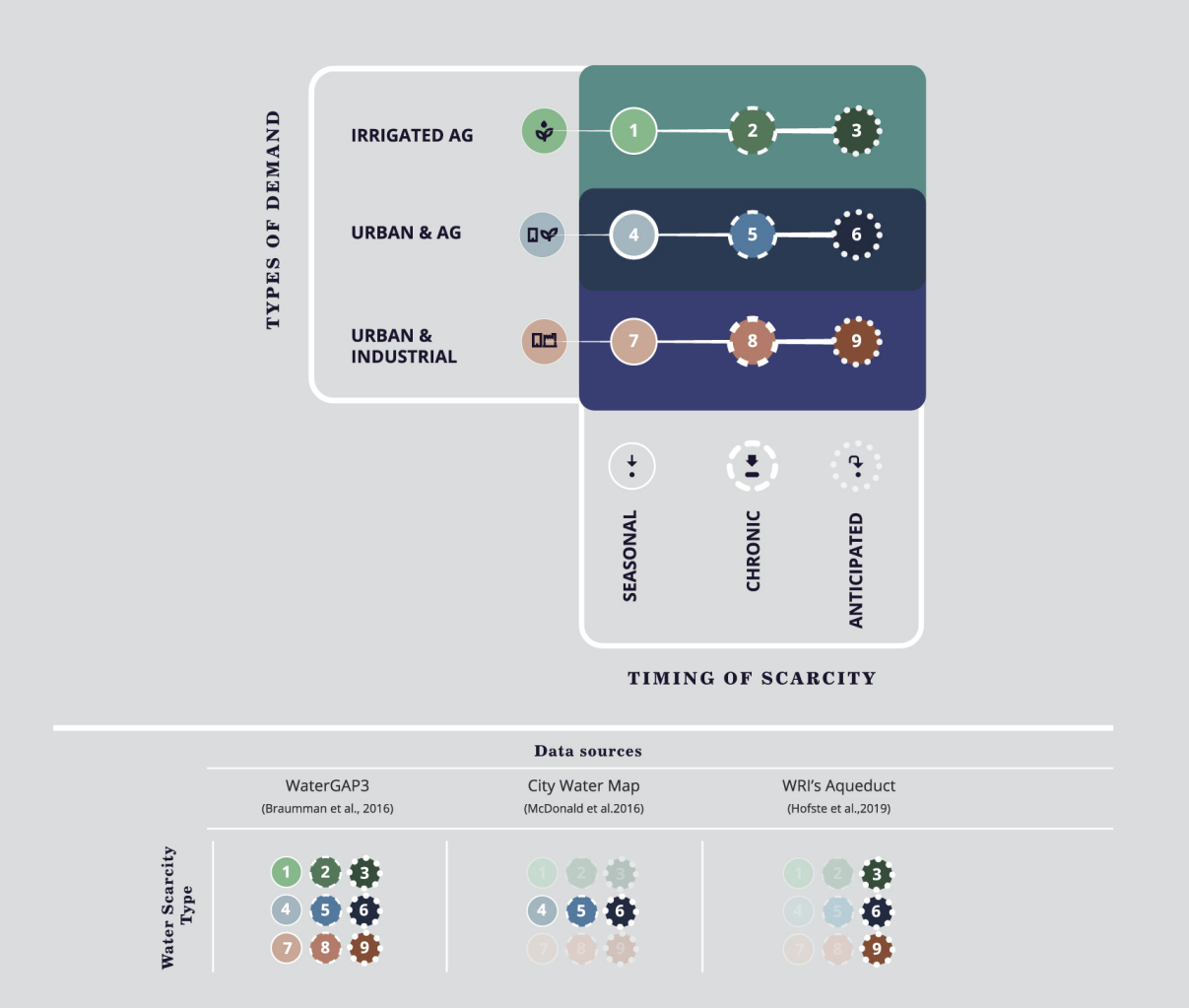

Figure 4.1: The matrix to categorize types of water scarcity. The resulting 3 × 3 matrix shows 9 types of water scarcity.

Next, we develop the timing axis by categorizing the timing of scarcity as either seasonal, chronic, or anticipated. For seasonal and chronic scarcity we rely on existing categories developed by (Brauman et al., 2016). For anticipated scarcity we rely on the WRI's Water Risk Atlas, Future 2030, Business as usual, Water Stress indicator (Luck et al., n.d.).

Combining the drivers and timing of water scarcity results in a 3 × 3 matrix categorizing 9 types of water scarcity based on the relationship between competition and timing. Each of the

9 types of scarcity identifies what drives water scarcity in a given basin. For example, basins with type 5 water scarcity are characterized by competition between urban and agricultural users, and the timing of scarcity is chronic.

4.2.2 Step two: define different incentives and investments

Incentives for sustainable water use need to be matched to local contexts and designed based on available legal and regulatory frameworks, and the underpinning. However, as a first step in assessing locally relevant metrics we focus on incentives and investments associated with water reallocation (exemplified by transactions) and investments in water conservation technologies (WCTs). We identify basins which can be served by either water reallocation, WCTs, or both. WCTs may apply anywhere there is or could be irrigation, while reallocation applies where it is legal, and there are heterogeneous uses particularly agricultural to urban, hence differences in the marginal productivity of water. The decision to focus on this narrower suite of tools is driven by the observations that: (a) significant investments and research has been given to both, and specific theoretical attention has been paid to their potential to scale; (b) both have decades of empirical evidence outlining their strengths and weaknesses in terms of performance; and (c) there are case studies found globally, which aligns with the geographic scope of this chapter. Future work could focus on additional tools and technologies (e.g. water reuse, improved efficiencies in industrial, commercial, thermoelectric power generation, and residential users), however, a more appropriate geographic focus would likely be limited to the United States or Europe where data availability would be appropriate.

The ability to reallocate water (via transactions, other incentive-based mechanisms, and even some administrative procedures) can create incentives that can increase the marginal productivity of water by forcing water users to consider the opportunity cost of water in alternative uses (Thobanl, 1997). A classic example includes neighboring farms with differing marginal productivity of water; the ability to reallocate water forces the farm with the lower marginal productivity to consider whether using the water is more profitable than selling it to the neigh-

bor. However, water reallocation depends on regulatory limits to water extraction based on sustainability criteria, well-defined property rights to water, adequate water accounting, and associated governance mechanisms for enforcement, stakeholder inclusion and conflict resolution (Easter et al., 1999). For our model, we focus on two considerations: (i) legal permission to reallocate water under specified conditions and (ii) the heterogeneity of water uses, which implies the potential for economic gains from reallocation. Legal permission for water reallocation is interpreted more narrowly than stipulated above, and includes documented formal water allocation reforms and the separation of land ownership and water rights and is assessed at the national level (water laws are set at the sub-national level in some countries). There are 74 countries where water reallocation has been authorized and implemented based on data from prior publications (Endo et al., 2018) and the OECD's Water Resource Allocation report (OECD, 2015). Basins in countries where reallocation is either not yet authorized or documented can only use WCTs.

Water conservation technologies can increase the economic productivity (in terms of yields per unit of water) and typically focus on increasing physical irrigation efficiency. However, WCTs can only lead to a net reduction of water consumption when paired with the following: limits to water extraction, clearly defined and enforced property rights to water, and attention to the water balance and accounting (R. Q. Grafton & Wheeler, 2018; Pérez-Blanco et al., 2020). The heterogeneity of crops produced within a basin offers a proxy for diversity of use, although the marginal productivity of water can vary even within a basin dominated by a single crop due to effects of other factors of production on crop productivity. We use data from the 2010 Spatial Production Allocation Model (SPAM) (Yu et al., 2020) and identify variation in the value of crop production within a basin. We consider the basins containing higher variation in the value of crop production as better candidates for incentive-based reallocation than those with lower variation. We assumed that basins with near homogeneous values of production have less incentive to reallocate water, although there will be exceptions when there is high variation in other factors of production.

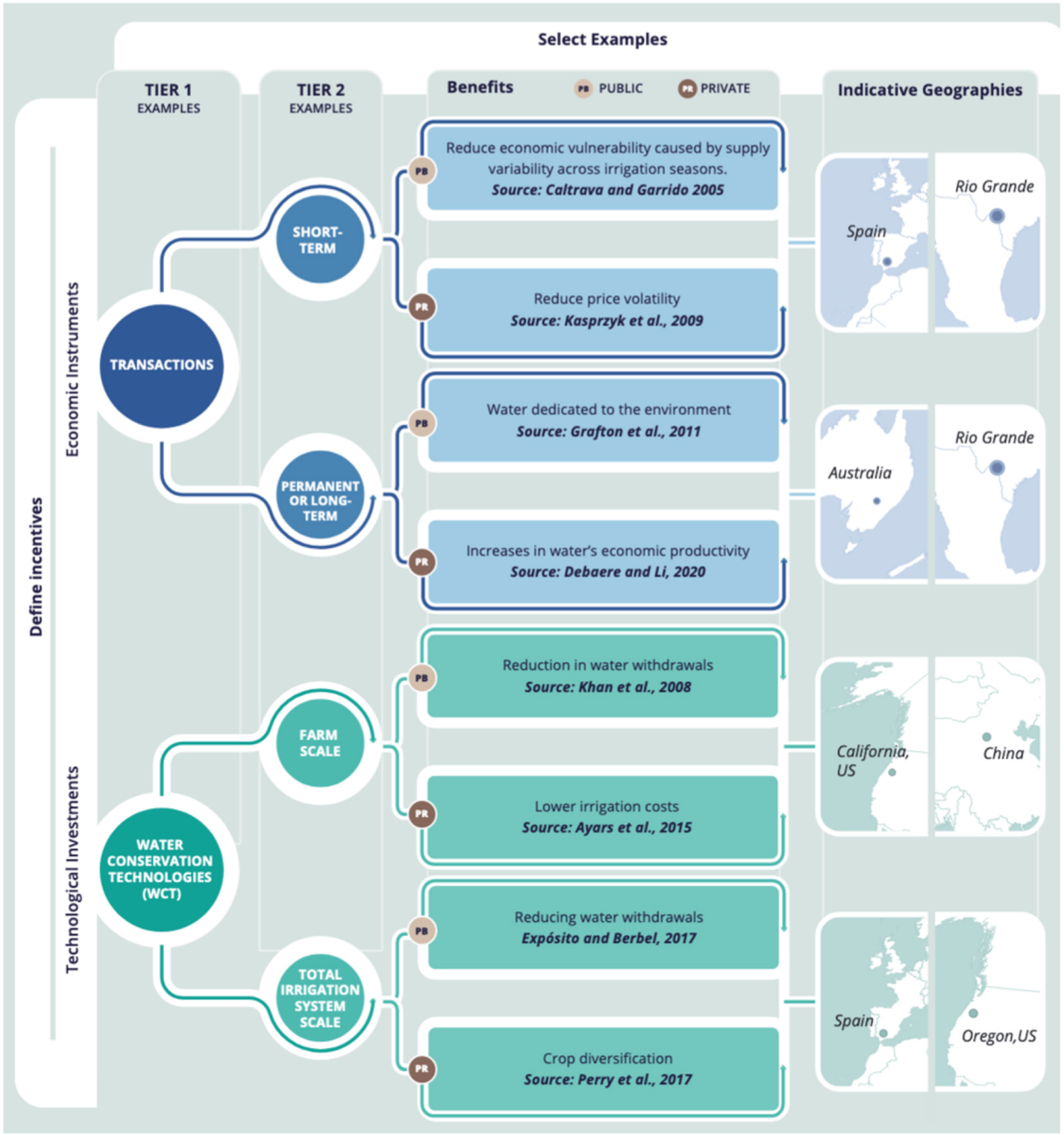

Figure 4.2: A graphical display of indicative benefits (public and private) of different types of incentive-based tools.

4.2.3 Step three: compare how incentives and investments impact water scarcity

The applicability of incentives involves legal and institutional criteria as well as economic costs and benefits. While transactions costs (D. Garrick et al., 2013) and the paradox of irrigation ef-

ficiency (R. Q. Grafton & Wheeler, 2018) impede reallocation and WCTs respectively, the short and long-term costs and benefits are an empirical matter, and shaped by historical, cultural, technical and other contextual factors.

For example, water consumption usually increases with water conservation technologies unless combined with limits on water extraction and clearly defined and enforced entitlements to water, underpinned by water accounting (Pérez-Blanco et al., 2020). Although WCT projects may involve public investments (R. Q. Grafton & Wheeler, 2018; B. Richter & Orr, 2017), decentralized and private investment by farmers and agribusiness hinge on risk perceptions, access to finance and economic decisions. Valuing water (D. E. Garrick et al., 2017) and water pricing (Davidson et al., 2019; Hellegers & Perry, 2006) will shape the incentives for both water reallocation and investing in WCTs. In practice reallocation and WCTs are interrelated and can be synergistic (e.g. legal permission to reallocation water can create incentives for private investments in WCTs) or counterproductive (when legal permission to reallocate water or public investments in WTCs ignore social and environmental externalities), meaning these results should be interpreted with caution and then downscaled with high resolution data on costs, benefits and behavioral responses. Figure 2 represents an indicative assessment of benefits (private and public) (Pannell, 2008) different incentives can provide. Different drivers of scarcity require different types of incentives.

4.3 Results

Our spatially explicit model demonstrates how geographic patterns of water scarcity reflect the types of demand and their timing. On the global scale, our model highlights a total of 1,275 basins that are categorized by one or more of the nine scarcity types. A single basin can have multiple types (median = 2, mean = 2.3). Hotspots of multiple types are prominent in central California, northern India, north eastern China, and central Mexico (see figure 3).

Water demand for irrigated agriculture remains the most significant driver of water scarcity

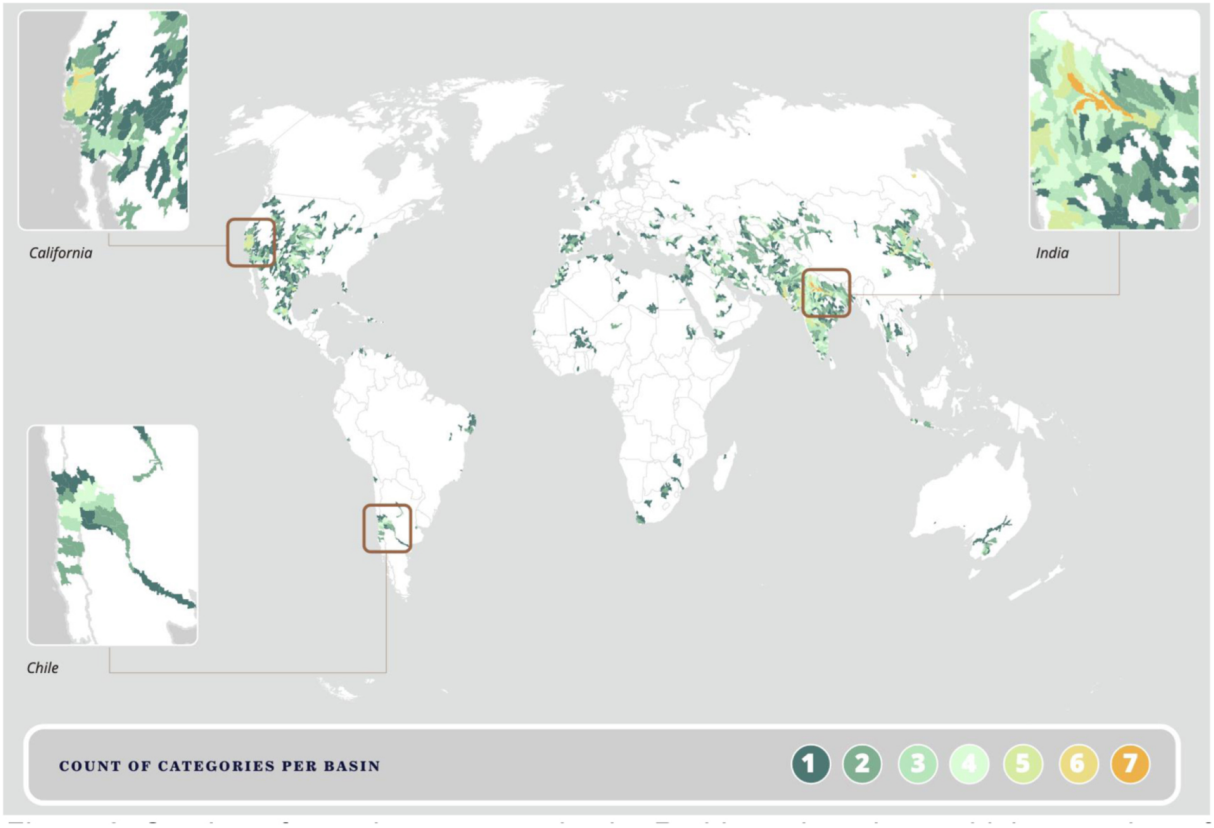

Figure 4.3: Overlap of scarcity types per basin. Redder colors denote higher numbers of overlap and may suggest multiple pathways for sustainable water use.

in our model, echoing recent literature (Davis et al., 2017; Perry et al., 2017). The scarcity type with the highest count (n = 1,119) was type 4: urban and agricultural competition in seasonal scarce basins, adding to the evidence that competition between agriculture and urban users is a significant challenge (Flörke et al., 2018; D. Garrick et al., 2019).

In terms of the timing of scarcity axis, basins categorized as seasonal scarcity (types 1,4 and 7) had the highest number of basins (n = 1,763) followed by future scarcity (n = 995), and then by chronic scarcity (n = 299). That chronic basins featured considerably less than future and seasonal is a reflection of the WaterGAP3 model, which has demonstrated similar results in previous work (Brauman et al., 2016). Along the types of demand axis, urban and agriculture (types 4, 5 and 6) were the most prevalent (n = 1, 596), followed by demand within agriculture (n = 1,271), followed by demand between industry and urban users (n = 190).

The graphic below (figure 4) shows areas characterized by each type of water scarcity in our matrix

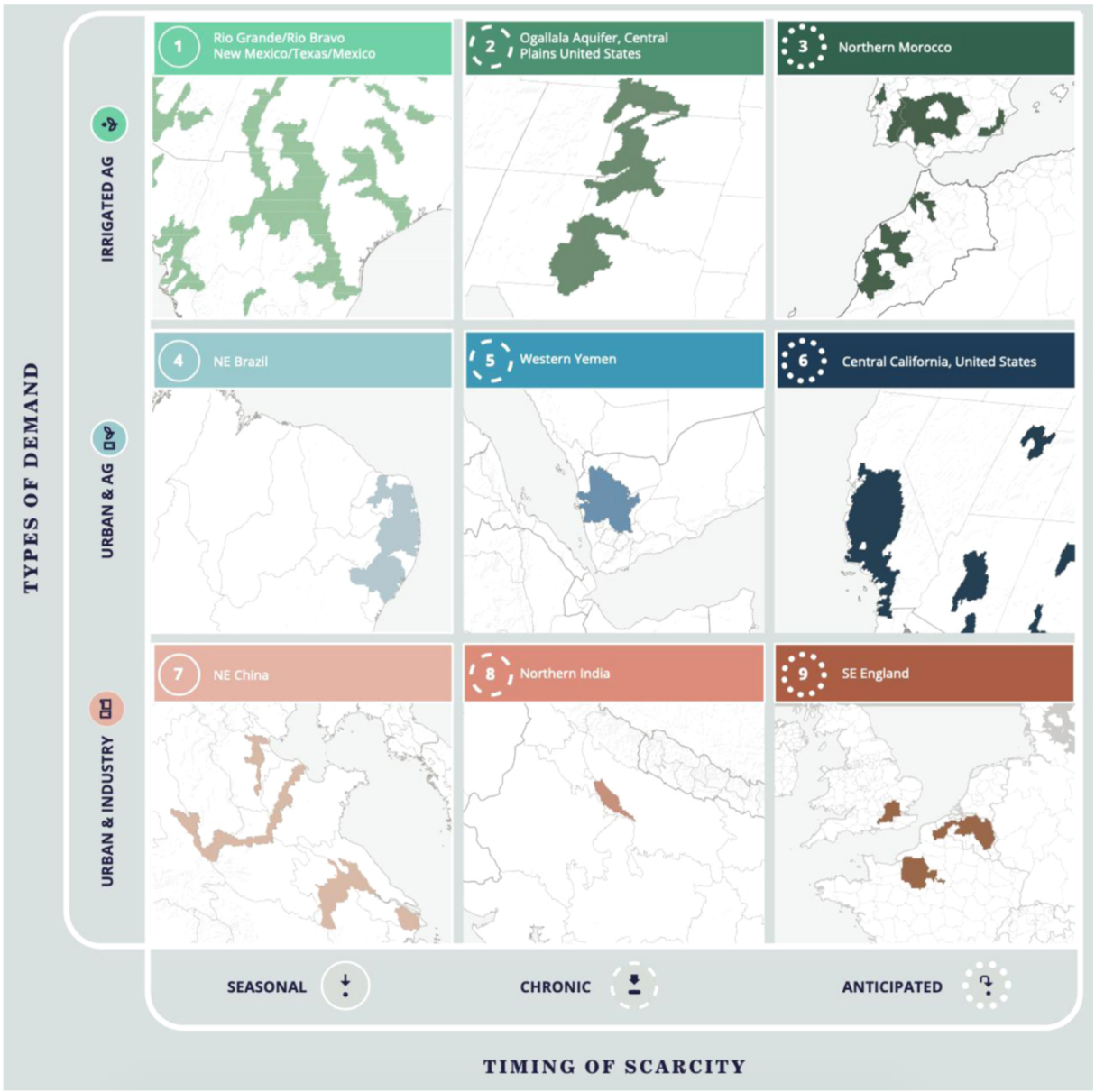

Figure 4.4: The 9 water scarcity types in our analysis. The interaction between competition of users and timing of scarcity provides a more nuanced picture of global water scarcity. Note areas represent the overlaying basin boundaries, not the aquifer boundaries.

We find that globally, 601 basins are potentially suited for water reallocation, 464 are potentially suited for WCT incentives, and 424 meet the criteria for either water reallocation or

WCTs, although technically WCTs are feasible and potentially applicable anywhere there is irrigated agriculture. The map below (figure 5) shows the geographic extent of the three portfolios.

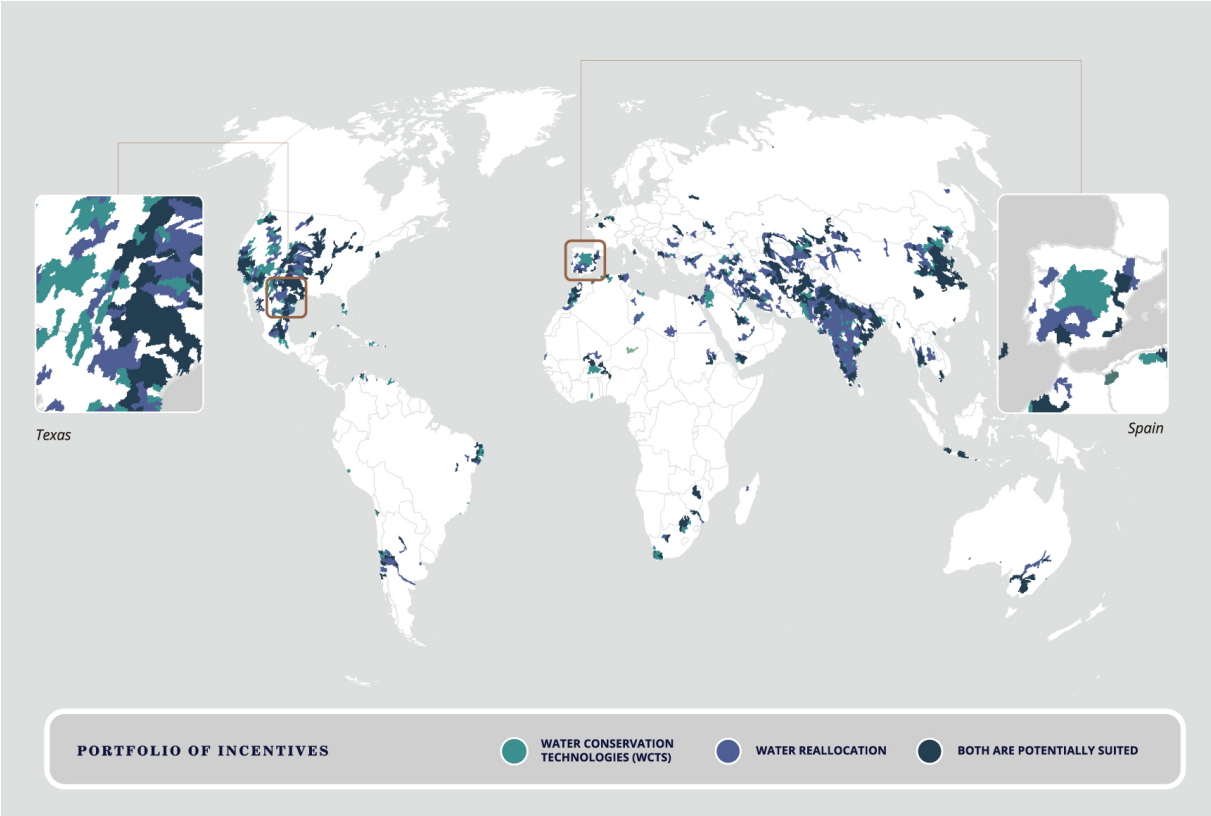

Figure 4.5: Linking the type of scarcity with a portfolio of incentives designed to respond to the specific type of scarcity in a basin.

The global analysis shows the spatial variation which can be seen across countries and also within them. For example, Mexico (figure 6) illustrates the different types of demands that drive scarcity in the short and long term. Northern Mexico is dominated by seasonal scarcity and competition among agricultural uses and users, and between agriculture and urban users. This includes the Río Bravo/Grande agricultural valleys as well as major cities like Monterrey, Ciudad Juarez, and Tijuana. Central Mexico is categorized as a mix of several scarcity types including competition between urban and agricultural users in chronic and anticipated scarcity regimes. We find that the ten most-populated cities in Mexico (home to approximately 30 million people) are located within watersheds experiencing one or more types of water scarcity.

4.4 Discussion

Water scarcity has human and hydrological components. Bridging these elements helps identify potential pathways for evaluating impacts and responses to water scarcity via incentive-based tools. We find that 73% of the water-scarce sub-basins in our model are located within national boundaries where documented legal water reallocation has occurred. This suggests there is additional potential for strengthening institutions supporting water reallocation, which may in turn drive investment in WCTs and enable reallocation between sectors. Different drivers of scarcity will require different incentives. Integrating multiple incentives can include synergies with existing green and gray infrastructure projects that facilitate the movement of water.

One contribution of this article is to demonstrate that (a) different types of water scarcity are present and emerging, and (b) linking types of water scarcity to specific incentives and investments that may help address water scarcity. We also propose that our three-step approach (map, define, compare) needs to be tailored to local contexts.

As a first step, we chose to illustrate the framework for mapping incentives for sustainable water use at the global scale to understand the global potential. However, as mentioned, local variability can drastically shape the applicability, feasibility, costs, and benefits of incentives. There is a many to many relationship between drivers of water scarcity and applicable incentives, i.e. many options for addressing a given driver. Therefore, as a next step, it is critical to move from the global potential, which overestimates the potential applicability of incentives and investments, to local pathways that consider costs, benefits, and technical and political feasibility (Werners et al 2021). Realizing the local pathways can be informed by (1) downscaling our matrix of types of demand and timing of water scarcity, (2) quantifying benefits and costs of specific priority incentives, and (3) focusing on governance, public/policy priorities, and feasibility. All three steps require local high-resolution data and sustained engagement with local stakeholders. Recent research in decision scaling for sustainable water management may offer frameworks for operationalizing potential incentives based on local factors (Brown

et al., 2012; Poff et al., 2016). Additionally, it will be critical to closely evaluate and measure the unintended consequences to the environment (e.g. return flows).

4.5 Downscaling

Our results illustrate how water scarcity manifests as a result of the dynamics between competing uses and the timing of scarcity. However, an important next step is to test our analytical approach by downscaling to priority geographies. For example, our global model identifies priority geographies including Mexico, India, and California, which suggest their water scarcity types are conducive to incentive-based mechanisms for addressing water scarcity. However, the current resolution of global datasets is not sufficient for prioritizing areas within those geographies for intervention. Downscaling aligns with recent trends in the literature for matching decisions to the scale of the challenge (Brown et al., 2012) as well as accounting for the spatial dynamics at appropriate scales (Dobson et al., 2020). This will include the need to account for infrastructure and institutional arrangements.

4.6 Moving from qualifying to quantifying

There is extensive literature on the costs of different kinds of incentive-based programs for water allocation, and include specific costs like transaction costs and monitoring costs (D. Garrick et al., 2013; Marshall, 2013). Likewise, many local factors influence these costs which are highly associated with institutional capacity (Grafton et al., 2011). As a first step, we were interested in qualifying different benefits associated with specific incentives. As a next step, we need to quantify specific benefits of priority incentives. One approach is by linking the Total Economic Value (TEV) framework to a private and public net benefits framework for choosing policy mechanisms (Pannell, 2008). In addition to benefits, it is important to quantify specific costs associated with the transactions of different incentives. This includes special attention to transactions costs (Erfani et al., 2014; D. Garrick et al., 2013) as well as gains from trade (Brooks & Harris, 2008; Zekri & Easter, 2005), and the cost-effectiveness of reallocation, WCTs

and different hybrids. There is also opportunity to expand on the types of public and private values to include new legal rights (e.g. for rivers) (E. O'Donnell & Talbot-Jones, 2018) as well as indigenous water justice (Robison et al., 2017).

4.7 Focusing on governance and feasibility

Future work will focus on understanding institutional arrangements as a critical step in assessing feasibility. At present our analytical framework is designed to answer the question: where, and how, can different incentives respond to freshwater scarcity? However, missing in this assessment is the feasibility of specific priority incentives. Institutional capacity is critical for achieving sustainable water use (D. E. Garrick et al., 2017) and especially with incentives like water markets (Casado-Perez, 2015). Efforts to combine institutional analysis (Ostrom, 2011) and market design (Teytelboym, 2019) will play an important role in closing the gap between the theory and practice of incentive-based solutions for water scarcity.

4.8 Conclusions

Water scarcity already impacts billions of people and over half of the world's rivers and their aquatic habitats (Mekonnen & Hoekstra, 2016; Vörösmarty et al., 2010). Changes in population and climate indicate that the imbalances between the supply and demand of water will be exacerbated in the future (Flörke et al., 2018). The inability to close the supply-demand gap has serious consequences for economic and environmental outcomes and jeopardizes our chances of meeting SDG 6.4. Policy-enabled incentives via water reallocation and technology-induced incentives via investment water conservation technologies have been presented as scalable solutions to mend the imbalances of supply and demand for water. However, decades of international experience demonstrate that their success is elusive. As a first step in quantifying the potential of incentives, we developed an analytical framework to demonstrate how certain incentives can match different water scarcity types and meet specific objectives. At the global scale, the results indicate that over twelve hundred unique basins present enabling

conditions for at least one incentive for responding to water scarcity. We propose that defining the scarcity type, quantifying the impacts on water scarcity, and calculating the costs and benefits (both public and private) of priority incentives can help water managers examine the tradeoffs of different incentives. Basing decisions on these metrics can help close the gap between the theory and practice of incentive-based mechanisms for water reallocation. Doing so can maximize the chances for incentives to succeed in their local contexts, thus providing a set of cost-effective solutions for achieving SDG 6.4.

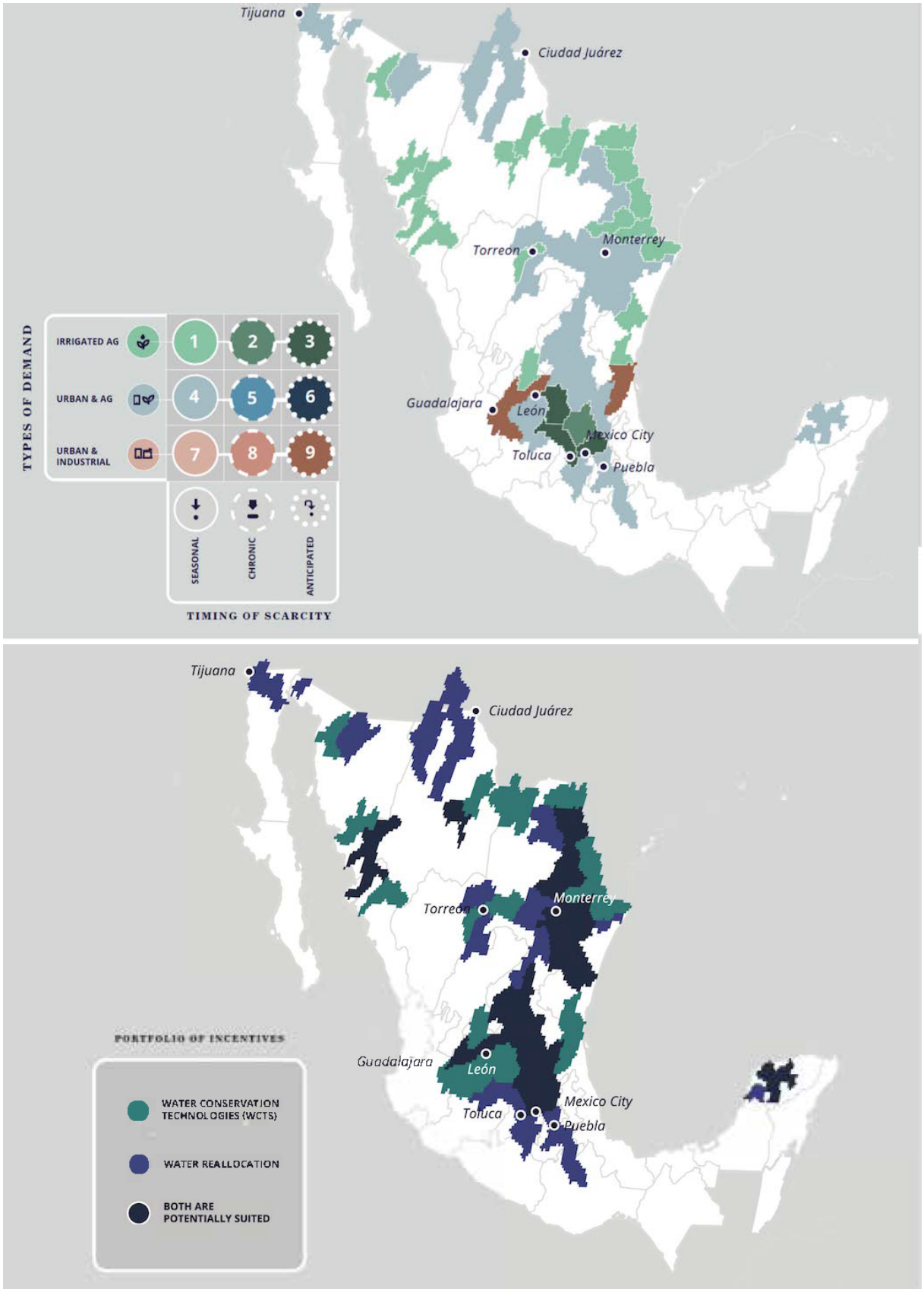

Figure 4.6: (a) Zooming into Mexico highlights different types of water scarcity based on the interaction between competition of users and timing of scarcity (b) Linking the type of water scarcity to a portfolio of incentives designed to respond to the specific type of scarcity in a basin.

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Chapter 5

Texas Water Markets: Taking Stock of their Trends, Drivers, and Future Potential

Abstract

Water scarcity and competition between water users in Texas have been driven by shifting demands and variable supplies for decades. Despite water scarcity in many parts of the state, the scholarly literature focuses primarily on the Rio Grande and Edwards Aquifer markets. With urban water demand projected to outpace agriculture for the first time by 2060, this article examines water market activity across Texas to better understand where transactions have occurred, the scale of transactions, and the factors driving transactions. We construct an original transactions database of over 2,350 individual surface water transactions between 1987 and 2022, spanning 13 major basins and reallocating over 4 million acre-feet (AF) of water at a total price of $1.3 billion USD. We design a Poisson regression model to test the statistical relationship between different types of variables, such as biophysical factors (e.g., drought, precipitation) and social factors (e.g., commodity prices, population growth), with water market activity. Results demonstrate that transactional activity has increased over the past decade, and it has also spread across diverse contexts. We illustrate how different basins have different "signatures" of transactions, namely different mixes of drivers and patterns of trade, which have implications for policy. We find that reservoir levels, SPI, temperature, groundwater levels, and commodity prices for rice and cotton are significant predictors of water transactions. By examining the diverse water market activity in Texas, this study shows how past investments in water market institutions have enabled the establishment of markets tailored to basin characteristics, while also emphasizing the need for institutions and governance arrangements that fit well with local conditions.

5.1 Introduction

Water markets have been a decentralized tool for reallocating water and water rights in Texas for more than 100 years (Chang & Griffin, 1992). Economic theory predicts that water markets can provide incentives to improve water use efficiency and encourage reallocation to higher value uses thereby mitigating the impacts of water scarcity (Bjornlund, 2003). Water markets rely on three regulatory elements: a cap on extractions, the allocation of water

rights on a legal basis, and the creation of trading rules to facilitate reallocation (Easter et al., 1999). Economists have promoted water markets for decades as a tool for alleviating water scarcity by incentivizing gains in efficiency (Rosegrant & Binswanger, 1994) and economic gains from trade (Hearne & Easter, 1997). However, international experiments (Grafton et al., 2011; Libecap, 2009) demonstrate that the three regulatory elements are necessary but insufficient enabling conditions for water markets to address scarcity at the scale that economist envisioned (Garrick et al., 2020; Meinzen-Dick, 2007).

Water markets require water scarcity and legal conditions that facilitate reallocation through voluntary transactions. Texas has both. Water scarcity in Texas is driven by dynamics between competing water demands (e.g., within agriculture and between urban and rural users), increasingly variable water supplies, and a precipitation regime gradient that decreases in places away from the Gulf of Mexico and towards the west (Nielsen-Gammon et al., 2020; Wight et al., 2021). Texas' political leaning toward decentralized water management and local governance has legal reforms and regulatory frameworks that enable water trading. Figure 1 captures the legal reforms that set the stage for water markets in the state [1] . Major droughts in the late 1800s, the drought of record in the 1950s, and the 2011 drought prompted legislative changes to enable water reallocation via market exchanges. This legislative history illustrates that water markets in Texas have been decades in the making. The original constitution for Texas did not include the necessary institutions and legal frameworks to establish water markets. Instead, these were developed as a response to a series of legislative priorities that followed severe droughts, which had a crippling impact on the state and its economy. However it was not until the mid 1980s that Texas established environmental flow protections which meant that few of the several thousand allocated water rights considered environmental flows (Wurbs, 2017). Even in the wake of landmark legislation like Senate Bill 3 (SB3), which established environmental flow standards in 2007, environmental water demands still go unmet (Anchor and Hoffpauir, 2021).

[1]For a more detailed summary of Texas water law over time, see Timothy Brown's piece: A primer for understanding Texas water law (2006)

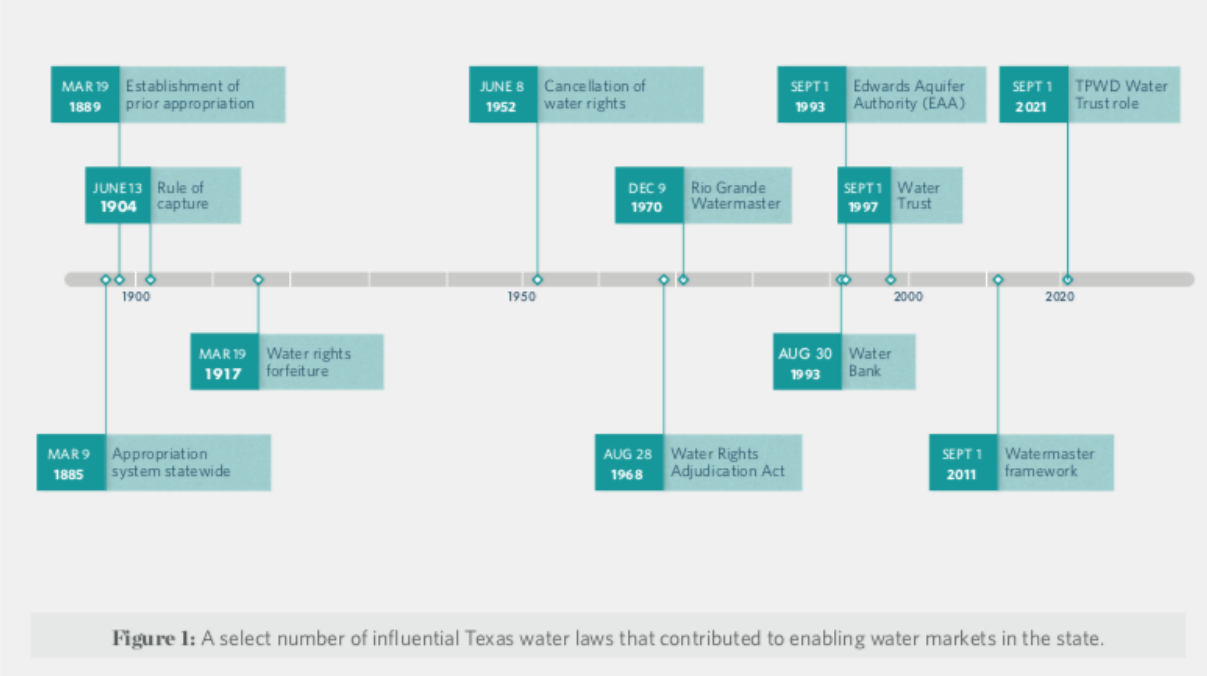

Figure 5.1: A select number of influential Texas water laws that contributed to enabling water markets in the state

The state of Texas is at a pivotal moment in terms of managing water resources. According to the Texas Water Development Board (TWDB), projected water demand will rise over 18 million acre-feet (AF) by 2030 (TWDB, 2022) and for the first time in the state's history, demand for municipal uses is projected to exceed water demand for irrigation by 2060 (TWDB, 2022). While certain areas may benefit from additional infrastructure projects, such as reservoirs, and technological solutions like desalination or aquifer storage and recharge (ASR), which aim to increase water supplies, these options tend to be significantly more expensive per volume compared to water conservation or demand management strategies. For example, for an additional 5,000 AF, brackish groundwater desalination can cost $2,690/AF/year, while conventional groundwater **costs** $1,119/AF/year. Alternatively, smart water meters can provide the same amount of water with an annual **savings** of $2,800/AF (City of Austin, 2018). As a result, there is a renewed interest to review demand management strategies, including water markets and related incentives.

Our article contributes to the academic literature on water markets by (a) building an original dataset, (b) identifying the drivers of water trading and how they vary across diverse contexts in the state, and (c) ruling out the possibility that all basins have the same drivers (e.g. non-significant results). Together these point to insights about patterns of water markets in Texas and their pathways forward as competition for water intensifies which offer lessons to other water scarce geographies.

We ask the following questions:

1. Where have water transactions occurred in the past 30 years?

2. Which water users have been participating in water markets?

3. Can we detect drivers of water market activity?

5.2 Water Markets in Texas

Formal water markets have gained increasing attention in academic literature since the 1980s, but the practice of trading water, both informally and formally, has been observed for centuries, spanning from New Mexico to Spain (Cox, 2014; Garrido, 2011). Despite the diverse academic disciplines studying water markets, including economists, hydrologists, and governance scholars, the core definition revolves around decentralized trading of water products, whether temporary or permanent, under a set of established trading rules (Garrick et al., 2023; Quentin Grafton et al., 2016). The global experience of using formal water markets to balance consumptive water use has seen waves of experimentation initially led by Australia (R. Q. Grafton & Wheeler, 2018; Hadjigeorgalis & Lillywhite, 2004; Hearne & Easter, 1997), and the United States (Howe et al., 1986; Young & Brozovic, 2019). In the 1990s countries like Mexico (Reis, 2014) and Spain (Palomo-Hierro et al., 2015) struggled with trading, while analysis of water market experiments in China are still emerging (Svensson et al., 2021). Using water markets to provide environmental benefits has been even more limited with most pockets of

success being found in the western United States and Australia (Garrick et al., 2009; Kendy et al., 2018).

Similar to the global experience, academic literature on water markets in Texas has steadily increased over the past 30 years (see figure 5.2 below) fueled by increased attention to water scarcity (R. C. Griffin, 2012; Nielsen-Gammon et al., 2020) and favorable legal enabling conditions (Gervais, 2015; R. C. Griffin, 1998). However, most studies focus on only two water markets in Texas – the Rio Grande (Booker et al., 2005; Debaere & Li, 2020; Ward et al., 2007; Yoskowitzy, 1999), and the Edwards Aquifer (Gillig et al., 2004; J. M. Griffin, 2021; Votteler, 1998).

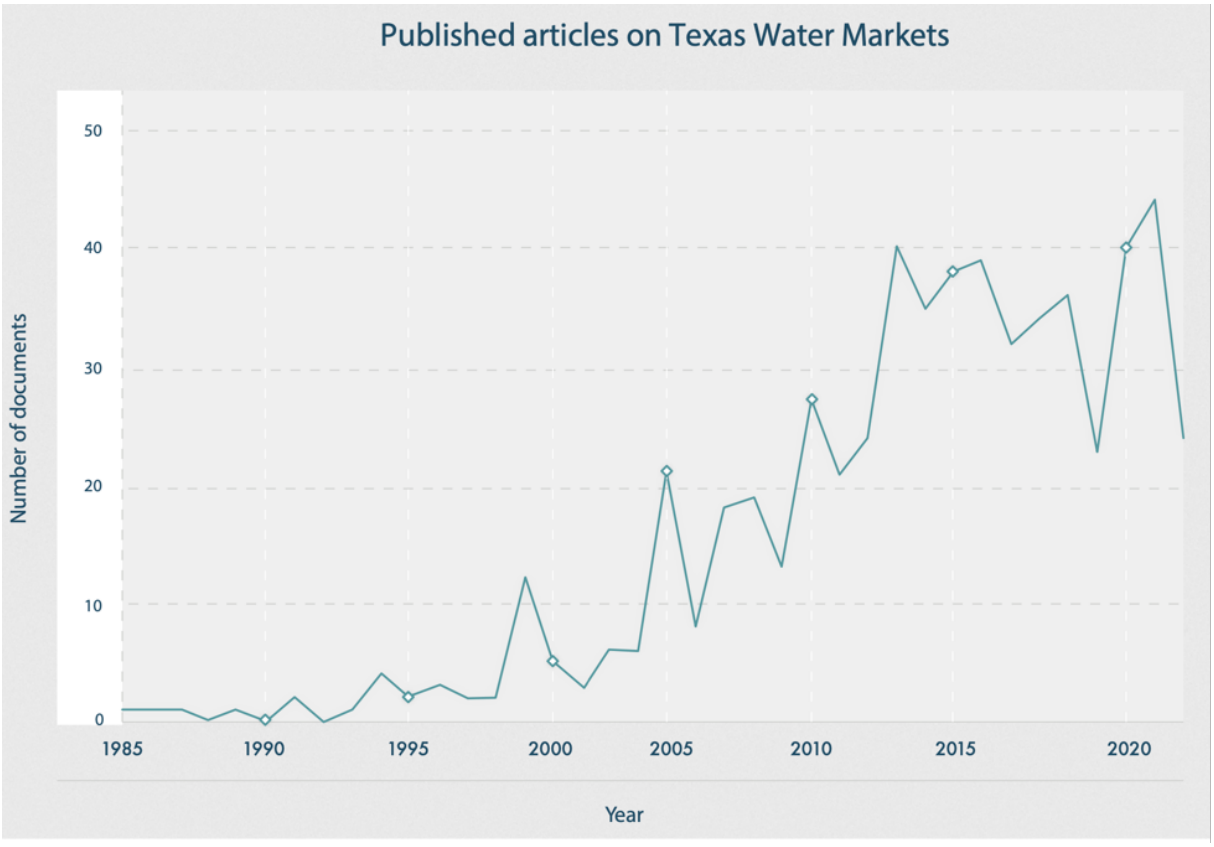

Figure 5.2: Analytics from Scopus searching (Texas OR TX) AND “water markets”; n= 518. May 2023

The Rio Grande water market is the most active in Texas and exemplifies many of the enabling conditions that economic theory predicts facilitate water trading: a well-defined cap, rules for

trading, scarcity, and ability to move water effectively (Garrick et al., 2020). Although the basin is shared by Mexico and New Mexico, the following characteristics are specific to Texas. The basin is operated through a combined reservoir pool and fluctuates based on storage in the reservoirs creating an annual cap. After a 15-year adjudication process ending in 1971, the Rio Grande market design offered several unique features. First, there are two exceptions to the amendment procedure: (a) the rule prohibits transfers from the Lower or Middle Rio Grande to a point above Amistad Reservoir; and (b) the requirement for public notice is not necessary due to negligible third party impacts (Chang & Griffin, 1992). Second, the water rights within the market possess equal priority, reducing the need for extensive evaluation of reliability and consequently streamlining the assessment of their value. This contrasts with systems of prior appropriation, where varying priorities are assigned based on seniority, particularly during periods of scarcity. Finally, water is accessed through a set of contracts and actively monitored by water masters (Chang & Griffin, 1992). Although these exceptions have helped increase the number of transactions in the basins, there are areas for improvement in terms of conserving water, including water transfer restrictions, insecure rights to conserved water, and land ownership and arrangements (Ward et al., 2007). Nonetheless, recent studies demonstrate that the market has been effective in shifting producers to higher valued and less water intensive crops, especially in times of drought (Debaere & Li, 2020).

The Edwards Aquifer water market is also unique for Texas in that it was designed to protect endangered species (Kaiser & Phillips, 1998; Ward et al., 2008). The aquifer itself boasts unique characteristics that have enabled trading in a state where a landowner has the right to pump water from beneath their property, even at the expense of their neighbor (i.e. rule of capture)(Drummond et al., 2004): (a) an incentive to conserve endangered species at the state level mandated by a federal law (Votteler, 1998), (b) a well-funded groundwater management district (Barton Springs and Edwards Aquifer Conservation District, 2004) and (c) an aquifer that is well modeled (Scanlon et al., 2003; Smith et al., 2005). Additionally, the karst geology in the Edwards Aquifer provides very high porosity, permeability, and transmissivity (Painter et al., 2007). High transmissivity provides flexibility for pumping which means there is one

market encompassing two pools of water, with low transaction costs and third-party effects (J. M. Griffin, 2021). Management of the Edwards also includes some pumping caps as well as cutbacks on some permits in times of drought. As a result of these favorable enabling conditions, decreased water supplies from recent dry conditions, and increasing municipal demands in central Texas, there were over 2,400 short term (less than 3 years) lease transactions (which are not included in our database) between 2005-2016 in the Edwards Aquifer water market (J. M. Griffin, 2021).

Although the Rio Grande and Edwards water markets have shown to be active based on thousands of transactions, other water markets in Texas have been slower to develop. There have been several factors proposed for explaining the lack of market activity outside of the Rio Grande and Edwards, including that (a) water scarcity is generally a bigger problem in western half of the state; (b) Texas (compared to states like California) lacks natural and built conveyance for transporting water; (c) water right enforcement is spotty; and (d) river authorities tend to monopolize power and water within basins which decreases market activity (R. C. Griffin & Characklis, 2011). However, despite the increasing number of peer reviewed studies, most of the literature we reviewed tends to cluster – either geographically (e.g., Rio Grande and Edwards), or by type of water market (e.g., surface water, spot market, groundwater market), and the market activity is analyzed from a specific academic perspective (e.g., institutional analysis (Chang & Griffin, 1992) or public policy (White et al., 2017). These clusters in the literature have created blind spots in our understanding of water markets, limiting our ability to improve policy and enabling conditions for water markets beyond the narrow goals of each market design. Previous studies often focused on potential, localized cases, and often lacked long term data. Therefore, a more integrated and comprehensive approach to studying water markets is needed to advance our understanding of their potential and limitations. Our transactions database takes a first step at shedding light on additional markets throughout the state, to help quantify the diversity of existing markets that may not resemble either the Rio Grande or the Edwards Aquifer.

5.3 Methods

We employed a mixed methods approach including spatial and statistical analyses designed to develop an original water transactions database, and then analyze water markets activity. We were explicit in our literature review and methodological development to embrace perspectives from multiple disciplines and draw synergies between hydrology, economics, and governance to continue to challenge the historical perspective of water markets as a panacea (Meinzen-Dick, 2007; Ostrom, 2010).

We combined surface water transactions data from the Water Transfer Database (WTD), WestWater, and The Nature Conservancy. The WTD was developed by the University of California Santa Barbara (Bren School) and drew all its data from the private company, Water Strategist from 1987-2010. This dataset contains information on volumes, prices, year, type, and direction of transaction of 335 transactions for Texas between 1987-2009. WestWater provided data for 147 sales and 1836 leases from 2009-2022. The Nature Conservancy provided 34 transactions since 2015, including 10 of which provided water to the environment. We recognize our database is not an exhaustive list of all surface water transactions in Texas, because (a) data on water transactions is historically difficult to obtain and (b) any informal transactions are not recorded as they happen without administrative approval and typically within irrigation districts or among neighbors. However, we believe 2,352 individual transactions to be an appropriate sample size given its temporal (1987-2022) and spatial (13 basins) coverage, and are unaware of any database with a higher count of transactions for Texas.

We employed fixed effects and Poisson regression models to examine the impact of individual-specific fixed effects on the dependent variable, which in our case is the number of transactions. These models are particularly valuable for analyzing panel data, such as water transactions, where observations are collected over time for multiple entities (Brüderl & Ludwig, 2015). Fixed effects regression is widely used in social science research as it allows for the control of factors like selection bias and unobserved heterogeneity that remain constant across time and entities, including both observable and unobservable biases (K. W. Jones & Lewis, 2015;

Mummolo & Peterson, 2018). By accounting for these factors, researchers can obtain more accurate estimates of the effects of variables on outcomes of interest. Econometric analysis has been used by scholars working on water markets for decades (Brookshire et al., 2004; Colby et al., 1993; Hadjigeorgalis & Lillywhite, 2004) including specifically analyzing externalities (Shiferaw et al., 2008) and costs and trading behavior (Regnacq et al., 2016). Poisson regression, a statistical technique, is particularly suitable for modeling count data, where the outcome variable represents the frequency of events within a fixed time or space (Cameron & Trivedi, 2013; Coxe et al., 2009). It is especially valuable when analyzing datasets with discrete, non-negative outcomes, and can estimate the relationship between one or more predictor variables and the count outcome (in this case sales and leases of water). In the realm of water transactions, econometric models, including fixed effects, have been utilized to examine various factors, including climate impacts on water security and the responses of third parties to water markets, particularly in the southwestern United States (Bigelow et al., 2017; Brown et al., 2013; Hagerty, 2019; Hanak, 2005; Hendricks & Peterson, 2012). Reviewing the literature, we organized a list of variables which relate to both the supply and demand of water (see table below):

Choosing econometric models requires careful consideration of multiple factors including the research question, nature of the data, and the assumptions. Two recent studies (Ghosh, 2019; Hansen et al., 2014) who employ different econometrics models using a similar data set from the Water Strategist illustrate this point. In the case of (Hansen et al., 2014) researchers chose to use a binary discrete choice model (specifically a maximum likelihood logit model) to test the relative effects of different variables on the decision to buy or lease a water right(Hansen et al., 2014). Alternatively, to analyze the effects of drought on the volume of water transferred, (Ghosh, 2019) used an instrumental variable regression. While these methods fit the specific research questions of the researchers (i.e., analyze binary outcomes, and estimate causal relationships while addressing endogeneity, respectively), we chose to use a fixed effects regression to better control for unobserved time-invariant differences across basins, and then a Poisson regression to focus on the count of transactions as the unit of analysis because it is a

	variable	name	explanation	scale	source
supply	annual precipitation	precip	total annual precipitation averaged at the basin scale	basin	CHIRPS, UCSB
	groundwater levels	gwlevels	monitoring groundwater wells with the most complete historical record used	well to basin	TWDB
	reservoir storage	dams	annual average of % full of all reservoirs in a basin	basin	TWDB
demand	population	pop	county level population estimates for every year between 1987-2022 aggregate to the basin sacle	county to basin	census.gov
	commodity prices for rice	rice	producer price of rice for each year is the price received by farmers for primary crops as collected at the point of initial sale	United States	FAOSTAT
	commodity prices for cotton	cotton	producer price of cotton for each year is the price received by farmers as collected at the point of initial sale	United States	FAOSTAT
	commodity prices for cattle	cattle	producer price of cattle for each year is the price received by farmers as collected at the point of initial sale	United States	FAOSTAT
	commodity prices for maize	maize	producer price of maize for each year is the price received by farmers as collected at the point of initial sale	United States	FAOSTAT
	commodity prices for sorgum	sorgum	producer price of sorgum for each year is the price received by farmers as collected at the point of initial sale	United States	FAOSTAT
	annual average mean temperature	temp	a mean annual temperature in F	basin	PRISM
	Palmer Drought Severity Index (PDSI)	PDSI	a measure of the severity and duration of drought conditions based on precipitation, temperature, and soil moisture data	basin	GRIDMET DROUGHT UC Merced
	Standardized Precipitation Index	spi	a measure of how anomalous the precipitation in a specific location is compared to the long-term average	basin	GRIDMET DROUGHT UC Merc
	Maximum daily vapopur pressure deficit	vpdamx	VPDmax, or maximum vapor pressure deficit, is related to the demand of water by plants. It represents the point at which the air is so dry that transpiration from plants is limited by the atmospheric demand for water rather than the supply of water in the soil.	basin	PRISM

Figure 5.3: A list of variables used in the fixed effects model including how we categorized them conceptually in terms of how they related to the demand of supply of water

metric that normalizes for volumes and prices across basins and is a better measure of market activity. Previous studies, including (Ghosh, 2019; Hansen et al., 2014; Isaaks & Colby, 2020; L. Jones & Colby, 2010) develop models at the state level, however, we were interested in understanding market variation (e.g. volume, count, type (sales vs. leases) and performance at the basin level, therefore fixed effects is more appropriate for accounting for basin-level variation in our sample, especially considering the high resolution remotely sensed data we employed (Wang, 2021).

5.4 Results

5.4.1 Summary Statistics

Transactions are not limited to the Edwards Aquifer and Rio Grande. A notable finding from our analysis is the broadening of the geographical coverage of water transactions in Texas and the significant volume of water reallocated across the state. Figure 3 depicts this phenomenon, with the count of transactions displayed on the left and volume of water (measured in acre-feet (AF)) on the right. Even in basins with only a few transactions (e.g., Nueces), the amount of water reallocated exceeded 60,000 AF. Moreover, despite being only 3% of the size of the Colorado Basin, the Guadalupe Basin had twice as many transactions over the last three decades. These insights underscore the importance of studying water markets at the basin level and considering unique factors that may drive water transactions in each region.

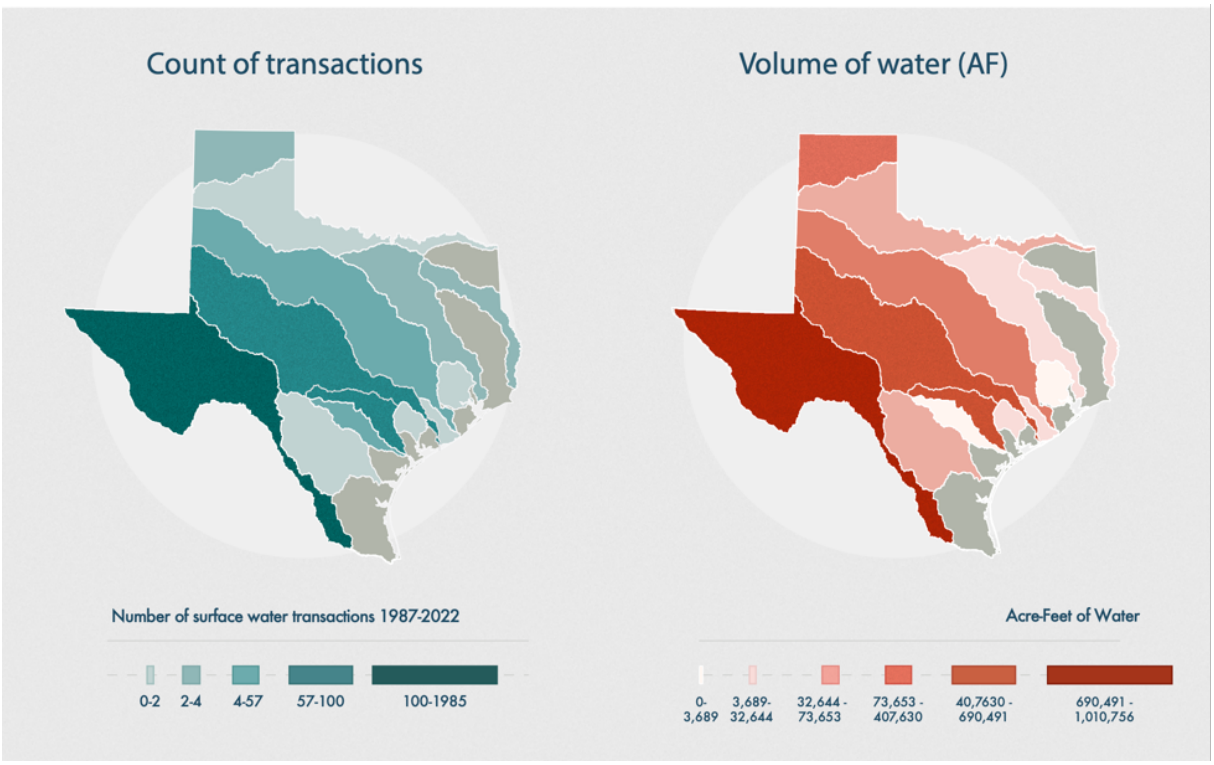

Figure 5.4: Maps of counts of transactions (left) and volume of water in acre-feet (AF) (right) both categorized by natural breaks

The statewide coverage illustrates variations in price and quantity across basins. Figure 5.5 be-

low presents a graphic displaying the number of transactions (color-coded by lease and sales) and a table summarizing the price per transaction and price per unit (acre foot) for transactions in the four main basins in our study: the Brazos, Colorado, Guadalupe, and Rio Grande, which together account for 2,198 transactions or over 93% of our database. It is important to note that figure 5.6 (bottom) does not use a log transformation on the y-axis (volume), which can better display data with a wide range of values (e.g. Figure 5.6 top). Examining the Colorado River (Figure 5.5 b), we note the occurrence of several significant transactions (over 300,000 AF) around the turn of the 21st century. During this period, the Lower Colorado River Authority (LCRA) acquired senior irrigation water rights downstream to enhance its water supply portfolio. The interquartile range (IQR) for transaction volumes in the Colorado River is 244,865. In contrast, the Rio Grande (Figure 5.5 D) which experiences a significantly higher number of transactions (n=1,985), has never recorded a year in which the transaction volume exceeds 150,000 AF.

The above summary statistics provide valuable insights into the variation across the state in terms of sales and leases, and their associated prices and volumes. However, our database offers further analysis on the buyers and sellers involved in these transactions, as highlighted by (Brewer et al., 2008). By utilizing an alluvial plot visualization (Figure 5.7), we identify the types of water users involved in the transactions and examine how water moves within and across sectors (e.g., from one agricultural user to another or from agriculture to other sectors) (Brunson, 2020). One noteworthy trend that aligns with existing literature is the focus on rural-to-urban water transfers (Flörke et al., 2018; Garrick et al., 2019). Figure 5.7 illustrates that both sales and leases contribute to this trend, with sales representing a larger volume of water moving from rural to urban areas.

The graphic also highlights a crucial aspect: water transfers to the environment. While numerous studies have explored environmental water transactions in the US West, documentation in Texas has been limited until now (Kendy et al., 2018; Neuman, 2004; Richter et al., 2020). These results reveal that over 250,000 AF (acre-feet) have been transferred, primarily through

Figure 5.5: Graphic showing count of transactions (by lease and sales) and a table showing summary statistics for total price and price per AF of transactions

leases, to benefit the environment. However, it is important to note that not all environmental water transactions are based on ”firm” water, meaning they may not be able to deliver the full leased volume during drought conditions.

5.4.2 Trends per basin

Figure 5.8 below presents a summary of the variables examined in our regression models for each basin from 1985-2022. Each basin is presented individually, accompanied by its respective variables. The top portion of the graphic displays the Standard Precipitation Index (SPI) values, color-coded as black for negative values (indicating drought conditions) and grey for

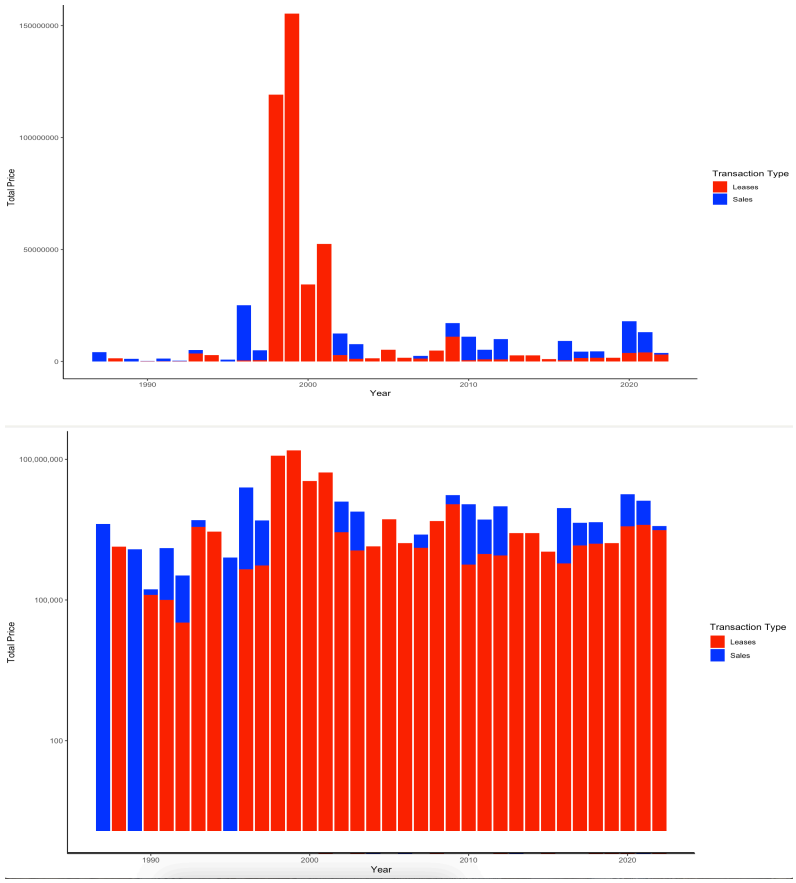

Figure 5.6: Two graphics showing total price of sales and leases. Note the bottom graph does a log10 transformation to better compare the relative changes in price across the dataset

positive values (indicating wet years). Next, precipitation is summarized at the basin level, along with the percent full of all reservoirs within the basin. Groundwater levels, with higher values indicating decreased groundwater levels, are also included. Additionally, VPDmax, a metric representing crop stress, is depicted. For a comprehensive perspective, the graphic also presents the number of transactions by year in blue, combining both sales and leases. This information sheds light on the changing frequency of water trading over time. By examining these variables at the basin level, we gain a deeper understanding of the distinctive characteristics and challenges specific to each basin in terms of water management and trading.

The basin-level graphics presented in this section offer a detailed view of the variables exam-

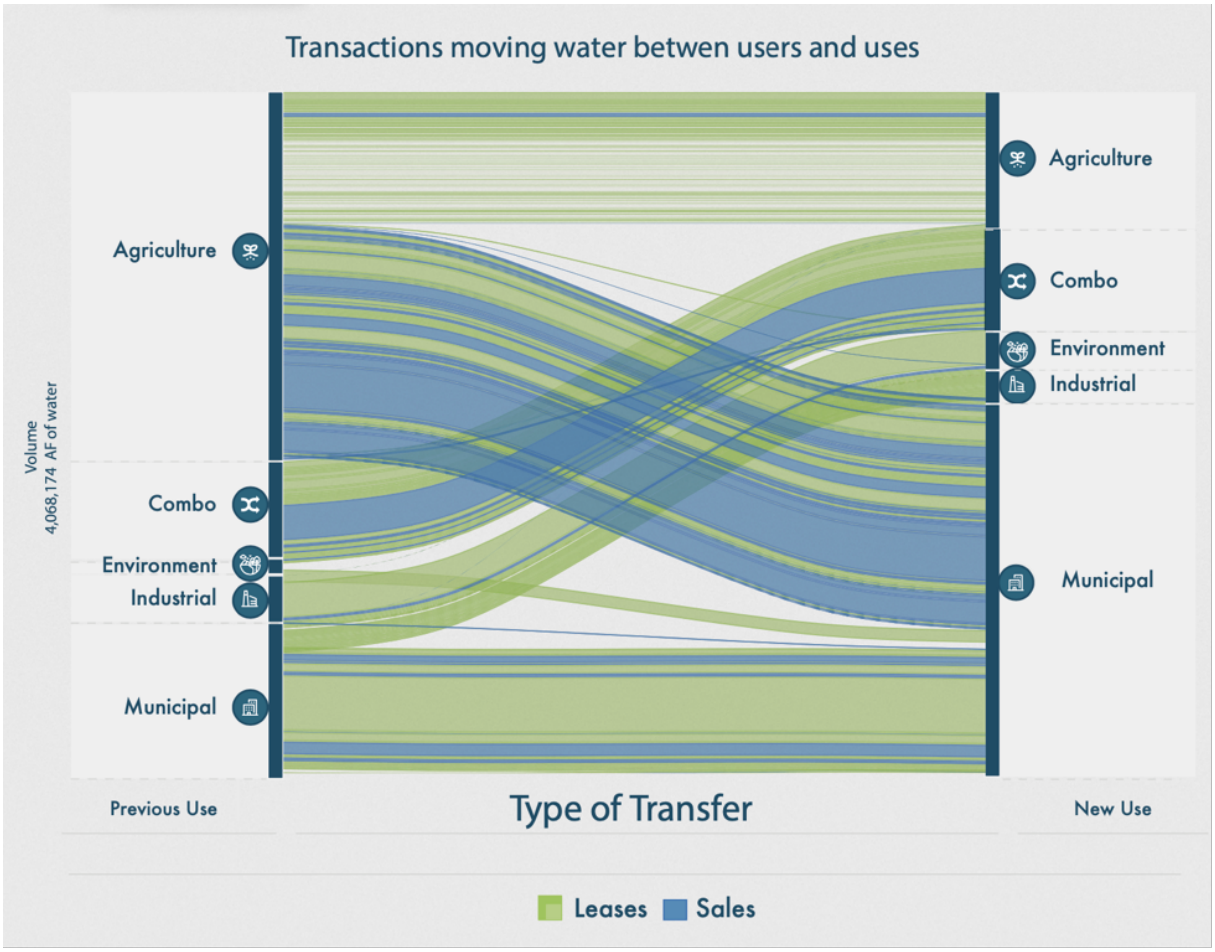

Figure 5.7: An Sankey plot displaying the amount of water reallocated between the previous use (left-hand side) and its new use (right-hand side), with the thickness of the flow representing the volume of water. The plot uses blue for sales and green for leases, with color coding indicating transaction type. Flows of transactions are displayed as volume, and are proportional in this graphic, e.g., "new" municipal use is over 50% of all new uses. "Combo" refers to multiple new uses.

ined in our fixed effects regression, highlighting differences that may affect water trading. By analyzing these variables at the basin level instead of summarizing at the state level, we obtain a more nuanced understanding of the spatial variability of water availability and demand among neighboring basins, which may influence water market outcomes. For example, examining the SPI (Standardized Precipitation Index) values presented in the top row (in black and grey) and the transaction counts depicted in the bottom row (in blue) across all basins, it is evident that despite similar trends in annual SPI (e.g., a drought from 2010 to 2014), the counts of

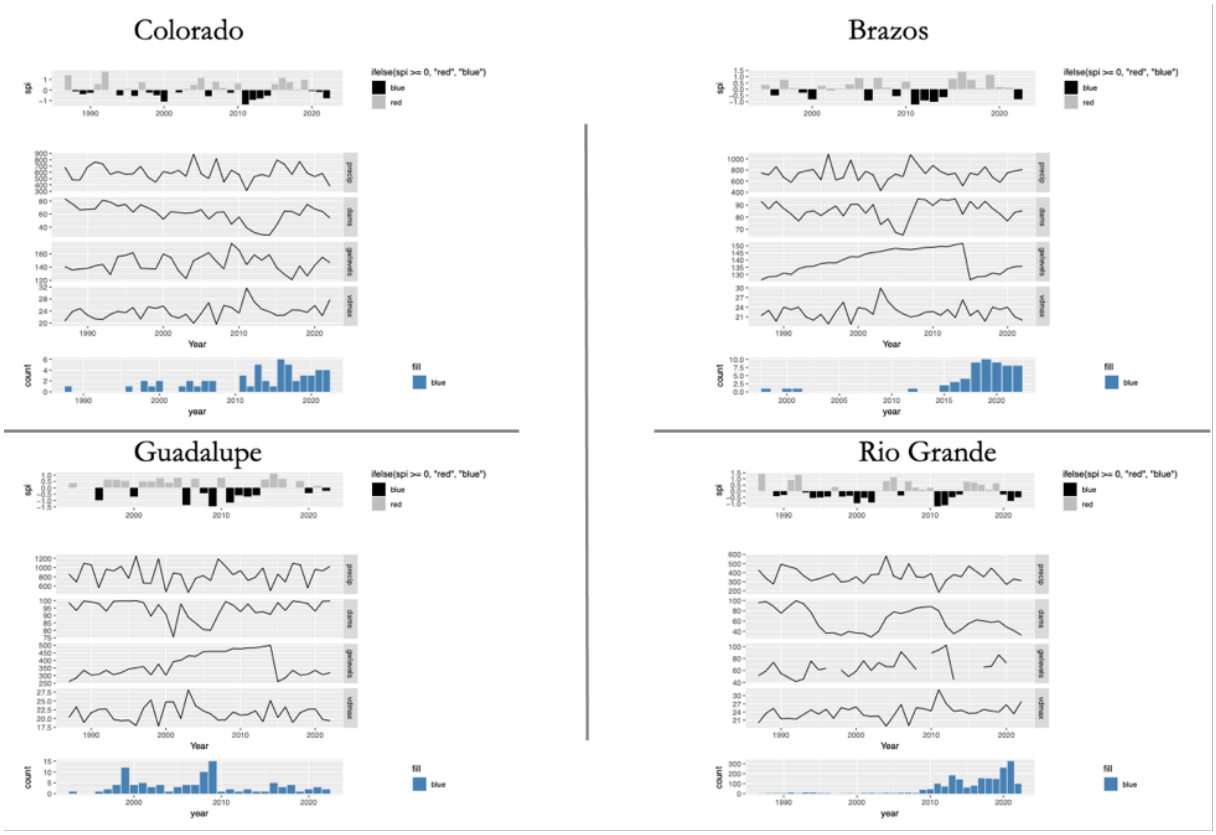

Figure 5.8: Trends in variables tested in regression models: precipitation, dams (reservoir storage), groundwater levels, and vpdmax with SPI (top) and count of transactions (bottom in blue) over the past 40 years for each basin

transactions exhibit four distinct patterns. The "dams" variable, representing the percent full of reservoir storage in each basin, varies considerably across basins, which are hypothesized to affect water availability and trading dynamics (Maas et al., 2017). An examination of this variable reveals that during the 2011-2014 drought, both the Colorado and Rio Grande basins experienced decreases in storage. In contrast, the Guadalupe and Brazos basins maintained storage levels above 80%, highlighting differences in reservoir management practices among the River Basin Agencies. Additionally, VPDmax, a metric for crop water stress, exhibits substantial variation across all basins, reflecting differences in crop types and water demand. Despite the similarity in specific metrics, such as vpdmax in Colorado and Rio Grande basins, the count of transactions over time demonstrates striking individuality at the basin level. This individuality reflects variations in water management practices, institutional arrangements, and

market conditions. Overall, basin-level analysis provides a more fine-grained understanding of the factors shaping water trading in Texas, highlighting the need for context-specific policies and interventions.

5.4.3 Developing regression models to test: are there certain biophysical or economic variables that are statistically correlated with water transactions?

Our objective was to identify biophysical and economic variables associated with water transactions. The choice of those variables was informed by recent literature of water transactions (Ghosh, 2019; Hansen et al., 2014; Isaaks & Colby, 2020; L. Jones & Colby, 2010). We created a panel dataset with 13 variables (see table 1 above) indexed by basin i=1,2,3,4 and year t=1987,...,2022. Ideally, we would like to have a large number of basins to rely on the asymptotic properties of panel data estimators and to control for unobserved, time-invariant basin-level characteristics, such as differences in baseline characteristics, that may be driving the relationship between the variables of interest. However, at present our t >N meaning the the number of time periods (t) or observations is greater than the number of data points (N). This presents important considerations for time series and panel data analysis. We therefore present a series of models including pooled OLS, linear fixed effects, and Poisson fixed and random effects. We show robust standard errors in our results table. In the pooled OLS, in addition to the variables of interest, we include basin dummies and a time variable (year of transaction) to control for differences between basins and trends. With these caveats in mind we would like to draw the attention of the reader to the general direction and trends of the regressions more than relying on the statistical power.

In a linear fixed effects regression, the dependent variable is treated as continuous (i.e., drawn from a continuous distribution such as the normal) whereas in Poisson, the dependent variable can be a count variable, in our case number of transactions. The Poisson fixed effect model was estimated using the quasi-maximum likelihood methods suggested by (Wooldridge, 2014)

with standard errors that are cluster-robust to some kinds of misspecifications. For our base model, we used the following formula:

$$\begin{aligned} count_{it} =& \beta_0 + \beta_1 precip_{it} + \beta_2 dams_{it} + \beta_3 spi_{it} + \beta_4 temp_{it} + \beta_5 gwlevels_{it} + \\ &+ \beta_6 rice_{it} + \beta_7 cotton_{it} + c_i + \mu_{it} \end{aligned}$$

where $count$ is the number of transactions (sales and/or leases)

When T is large and N is small, the case of this dataset, panel data regression results must be interpreted with caution if the variables are serially autocorrelated (Wooldridge, 2015). Inference can be established if the correlation between observations separated by time lags get smaller at a sufficiently fast rate (i.e. weak independence). An AR(1) model is weakly dependent provided $\mid \rho \mid$ is sufficiently smaller than one in the following regression:

$$count_t = c + \rho count_{t-1} + e_t$$

The count of transactions is persistent, with a $\hat{\rho} = 0.826$ but the first difference of count is weakly dependent ($\hat{\rho} = 0.304$, statistically significantly different than one). Therefore, in addition to the two Poisson fixed effects models, we included an Arellano-Bond fixed effect model where the lagged dependent variable is included as an explanatory variable, and a first difference regression model (e.g., $\Delta y_t = y_t - y_{t-1}, \Delta x_t = x_t - x_{t-1}$). These models have the advantage of turning an integrated time series process into a weakly dependent process.

We present our results by comparing a series of regression and interpreting how the results compare. The table below (figure 5.9) shows five different models. In Model 1 (Pooled OLS), groundwater levels emerges as the sole statistically significant predictor (p <0.05), exerting a negative effect on count of transactions suggesting that groundwater availability buffers against scarcity and reduces the need for water transactions. Moving to Model 2 (Poisson Fixed Effects), a broader picture emerges with ”dams,” ”spi,” ”temp,” ”gwlevels,” ”rice,” and ”cotton”

displaying statistical significance (p <0.05). Notably, ”gwlevels” continues to exhibit a significant negative impact on count, while ”rice” and ”cotton” demonstrate significant positive effects. In Model 3 (Poisson Fixed Effects with VPDmax), ”dams,” ”spi,” ”rice,” ”cotton,” and the introduction of ”vpdmax” are all statistically significant (p <0.05), with ”vpdmax” also revealing a noteworthy impact on the dependent variable. Model 4 (the Arellano-Bond regression) shows groundwater levels as statistically significant, also with a negative effect on the count of transaction (i.e., when groundwater levels decrease, transactions increase). Finally, Model 5 (First difference regression) is an example of an OLS where each variable is first differences and we see that both groundwater and cotton show statistical significance.

Table 1: Regression Results

	Model 1	Model 2	Model 3	Model 4	Model 5
dams	-0.2427227	-0.017954*	-0.0203011**	0.155334	-0.5966414
	(0.308773)	(-0.0030872)	(-0.0039256)	(-0.4558099)	(0.315082)
spi	2.23302	0.9237197**	1.091205**	2.201817	2.367568
	(6.267639)	(0.1828843)	(-0.2174568)	(-56.58189)	(4.269964)
temp	3.824372	0.3191371**		26.75927	0.6321877
	(3.024552)	(0.0293903)		(-36.68237)	(1.99092)
gwlevels	-0.3625469*	-0.0076271	-0.0057565	-.4421611**	-0.3040235**
	(0.0999469)	(-0.0041923)	(-0.0050955)	(-0.1504815)	(0.1058977)
rice	-0.1019773	0.0071033**	0.00566**	0.1618005	-0.0746133
	(0.0811568)	(-0.0002181)	(-0.0002386)	(-0.1117306)	(0.0666914)
cotton	0.0282754	0.0015912**	0.001464*	0.0163855	0.026705*
	(0.0143094)	. (0.0004034)	-0.0004431	(-0.020322)	(0.0114788)
PDSI					
vpdmax			0.1947045**		
			(-0.0153782)		
precip				0.0176747	-0.0044857
				(-0.1065016)	(0.0137246)
$*p < 0.05$, $**p < 0.01$					

Model 1: Pooled OLS with basin dummy and year as controls
Model 2: Poisson fixed effects
Model 3: Poisson fixed effects
Model 4: Arellano-Bond regression
Model 5: First difference regression

1

Figure 5.9: Four different regression models showing the relationships between count of transactions and various variables

The results of the biophysical factors align with theoretical expectations. For example, as

temperatures increase, or reservoir levels decline, water trading increases in response to a decreased (or less reliable) supply. In terms of commodity prices, rice and cotton have the highest statistical significance likely due to their high consumptive water demand. Producing cotton in many parts of Texas requires irrigation. Likewise, rice farmers rely on significant volumes of water to flood irrigate, and competition for water between cities and rice farmers downstream is a well-documented pattern. [2]

In summary, our econometric analysis sheds light on the dynamics of water market activity and some factors potentially influencing transactions. While we acknowledge the limitations posed by our relatively small sample size and the 't >N' challenge, we view these results with optimism in terms of a contribution to science and policy. Leveraging advanced methodologies to harness high-resolution data, our study provides an initial glimpse into potential drivers of water market transactions at the basin scale. We envision future research in this area to capitalize on our findings, offering a deeper understanding of the complexities of water market behavior. With the potential for larger datasets of transactions, we anticipate uncovering even more insights into the dynamics shaping water market activity which could inform policy.

5.5 Discussion

5.5.1 The effects of scale on econometric analyses of transactions data

Recent studies drawing on the Water Strategist dataset and employing econometric analyses focused at the state-level scale for calculating the independent variables in their models and each provided valuable insights on water markets in the Western United States (Ghosh, 2019; Hansen et al., 2014; Xu et al., 2019). For example, (Xu et al., 2019) focused on random forest regression models (RFR) to predict water prices, and (Ghosh, 2019) demonstrated a statistically

[2] https://stateimpact.npr.org/texas/2012/04/16/rice-farmers-used-more-than-three-times-as-much-water-as-austin-last-year

significant effect of drought intensity on the volume and price of water using an instrumental variable (IV) regression (Ghosh, 2019). Using a binary discrete choice model, (Hansen et al., 2014) were able to test hypothesis about their influence of economic, hydrologic, and institutional variables on the water market activity. These studies emphasized the need for future research to focus on basin-scale analysis, especially for biophysical variables.

With advancements in server-side processing capabilities, particularly through platforms like Google Earth Engine, quantifying biophysical variables at the basin scale has become more efficient and feasible. This has significantly reduced the time required for analysis, enabling us to detect trends in variables like SPI over time within individual basins. Given the vast geographic scale of Texas, this basin-scale approach is more appropriate for capturing localized changes and providing a more comprehensive understanding of the state's biophysical dynamics. Our findings generally align with the state-level findings, particularly in identifying statistical associations with transaction drivers. Future research can focus on quantifying the specific effects of variables on different types of transactions (lease vs. sales) and explore the relationship with price, such as the price of water transactions. We hypothesize that certain variables may exhibit consistent signals between the basin and statewide scales (e.g., PDSI), while others, such as VPDmax, may demonstrate varying strength of association.

The question of quantifying the effects of scale on market transactions holds significance, particularly considering the argument that federal and local laws have a greater impact than state laws in shaping water market activity (Getches, 2001). This argument was presented in (Hansen et al., 2014) as well and has particular resonance in the context of Texas. Notably, the Edwards Aquifer market's establishment was significantly influenced by the federal Endangered Species Act (ESA) (Votteler, 1998). Although the management of the Edwards Aquifer, and market, is driven primarily at the local level today, it stands as a unique case within Texas. The research presented in this article sheds light on the wide-ranging variation of water markets across the state, emphasizing the significant influence of state-level laws in facilitating their establishment, even though their current management is predominantly handled at the

local level.

5.5.2 Improving enabling conditions for sustainable water markets in the future

From a strictly economic perspective, sales and leases of water rights represent fundamentally distinct types of transactions that encompass various nuanced factors, including transaction costs, property rights, risk allocation, and market dynamics (Libecap, 2010). However, taking an interdisciplinary perspective, which has been the primary focus of the literature aiming to enhance the effectiveness of water markets for sustainable development, examining the count of transactions (including both sales and leases) enables meaningful intra-basin comparisons (Garrick et al., 2020; O'Donnell & Garrick, 2019). We feel this interdisciplinary can be especially helpful for improving policies and market designs at the state level.

This comprehensive statewide analysis reveals two key findings in the context of improving enabling conditions. First, the Texas legislature has established essential water institutions that have successfully facilitated the emergence and development of water markets. Second, water markets in Texas are effectively meeting multiple needs. Nonetheless, we contend that targeted interventions aimed at improving a broader and mutli-dimensional perspective on performance within these markets can yield significant improvements for future Texans and their environment (Garrick et al., 2023).

For example, market activity in the Rio Grande demonstrates the effectiveness of watermasters in enhancing the management of water rights and market activity. Regional watermaster programs can better serve needs of water users at the basin level by offering timely and comprehensive protection of water rights holders that is not available outside of watermaster areas. Another area that requires improvement pertains to environmental water transactions, which, although technically feasible, are currently hindered by high transactions costs. One specific aspect that presents a ripe opportunity for improvement is the interpretation of bed-and-banks authorization. The current interpretation is excessively narrow, preventing transactions that

could potentially benefit various water users. To address this, it is critical to broaden the interpretation of bed-and-banks authorization to allow for new authorizations dedicated to environmental flow protection. This should be possible without necessitating a physical diversion, as long as existing rights are safeguarded and no new appropriation is involved.

5.6 Conclusion

This study takes stock of water market activity in Texas, covering over 2,350 individual surface water transactions across 13 major basins between 1987 and 2022, reallocated over 4 million acre-feet of water at a total cost of $1.3 billion USD. Our research provides the first basin-scale analysis of water markets in the state, detailing their costs, volumes, and directions of transactions, including those towards the environment. We observe an increasing trend in water transactions across the state over the last decade. Focusing on four basins that constitute over 90% of transactions, we quantify high-resolution econometric and biophysical metrics to identify the factors driving this trend. Our regression models reveal that reservoir levels, SPI, temperature, groundwater levels, and commodity prices for rice and cotton are correlated with water transactions. From an academic standpoint, our research underscores the power of combining high-resolution remotely sensed data with econometric modeling to identify trends over time. Furthermore, our findings contribute to the ongoing discussion regarding the role of water markets in addressing global water scarcity. We demonstrate that state-level enabling conditions provide a critical opportunity to develop water markets tailored to the specific demands of different basins, thereby offering a promising avenue to meet the growing challenges of water scarcity. Our findings demonstrate that neighboring basins can tailor water markets to their specific needs if the necessary institutional capacity is in place. Moreover, the results indicate that Texas' investment in improving enabling conditions for water markets has had a demonstrable return. With incremental changes to existing legislation, transaction costs could decrease, incentivizing more trading and proving a valuable tool for managing scarcity and improving resiliency in the future.

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Chapter 6

Targets and Trade-offs: Designing Environmental Water Transactions to Navigate Compounding Competition in San Saba, Texas

Abstract

In river basins experiencing water scarcity, water demands for freshwater ecosystems and water users increasingly compete with one another. Environmental water transactions (EWT) offer a mechanism for resolving this competition via a voluntary agreement in which existing water users are paid to modify the time, place and/or volume of their water right to provide an environmental benefit. However, the disconnect between surface water and groundwater management creates barriers to implementation and scaling of EWTs. We study EWTs addressing water scarcity in Texas's San Saba River, focusing on targeting the location and timing to fulfill conservation objectives. We integrate recent hydrological studies to identify trends in groundwater-surface water interaction, prioritizing stream reaches for intervention and considering both geologic and anthropogenic drivers of scarcity. We analyze water rights and well data to estimate consumptive water demands during the irrigation season. We quantify the volumetric contribution of different portfolios of water rights paired with different types of EWT to assess their contributions to flow targets, including costs and benefits associated with each portfolio. Results demonstrate that the effectiveness of EWTs relies on coordinated spatial and temporal targeting within the context of hydrogeological settings and water users. We provide cost estimates for implementing four types of EWTs ranging from one season to perpetuity ($32,040 and $404,722 respectively) that can provide 3 cubic feet per second (cfs) to help meet subsistence flows in the height of irrigation season (June-Aug). These costs are contextualized within a broader water governance context that considers the benefits to producers and the environment and underscores the importance of future policy to integrate groundwater-surface water interaction.

6.1 Water scarcity in Texas

In water-scarce regions, water demands of food producers, urban centers, and the environment often compete for access to a limited supply of freshwater. This competition carries both economic and environmental implications, often placing rural and urban water users in conflict and frequently overlooking the essential requirements of environmental water (Flörke et

al., 2018; Richter, Andrews, et al., 2020). The state of Texas, in the southwestern United States faces the dueling challenge of increasingly variable water supplies and shifting demands which give rise to water scarcity (Nielsen-Gammon et al., 2020). Climate change in Texas alters water availability, threatens groundwater recharge, and will increase aridity and temperatures across the state (Banner et al., 2010; Loáiciga et al., 2000; Wurbs, 2017). Historically, and today, water demand for irrigation exceeded municipal demands in Texas. However, water demand for municipal uses is projected to exceed water demand for irrigation by 2060 (TWDB 2021) as Texas' population is projected to nearly double and reach 47.4 million by 2050 (Texas Demographic Center). This increase in population is predominantly concentrated in urban centers, which has important implications for water management including how urban water use efficiencies can help decouple water use from economic growth (Gleick, 2018; Richter, Benoit, et al., 2020).

Against this backdrop, Texas invests hundreds of millions of dollars each year in infrastructure to cope with water scarcity. Since 1957, Texas Water Development Board (TWDB) has spent $27.6 billion in financial assistance for water projects (Halbrook, 2019). In 2020, the state budgeted over $62 million dollars for the Water Infrastructure fund, compared to only 1 million dollars for the Agricultural Water Conservation Acct (Texas Water Development Board, 2019). Texas also relies heavily on groundwater production for irrigation and municipal use. In 2020, more than one-third of irrigation and livestock water supplies came from the Ogallala or Edwards-Trinity Aquifer (TWDB State Water Plan 2020). Future groundwater production zones include brackish aquifers which may provide an additional 182,000 acre-feet of water/year by 2070 (TWDB State Water Plan 2020). Desalination and treating wastewater currently contribute to approximately 4% of water supplies. However supply-side measures, including building reservoirs are increasingly costly, produce negative environmental externalities, and often do not provide their intended water security benefits (Baldassarre et al., 2018; Petheram & McMahon, 2019; Poff et al., 2007).

Despite significant investment to increase water supplies, Texas water users and the environment are still vulnerable to water shocks and droughts which impact all sectors of the economy,

especially the energy sector, agricultural producers, and municipal users (Nielsen-Gammon, 2012; Scanlon et al., 2013). The 2011 drought, for example, accounted for an estimated $5.2 billion USD in agricultural losses and threatened freshwater species across the state directly by dewatering streams and indirectly e.g., via toxic algae blooms (Combs, 2012; Mayes et al., 2019; VanLandeghem et al., 2013; Wilde & Urbanczyk, 2013). These shortcomings suggest the need to look towards water management strategies that focus on reducing water demand.

6.1.1 Challenges in conjunctive use: a mismatch between water governance and hydrogeology

The OECD has identified water scarcity as primarily a challenge of governance (Gurría, 2008). In Texas, this challenge is exacerbated by outdated water laws that were originally designed for a different climate and demographic (Gurría, 2008). Texas water law is especially complex due to its legacies of Spanish, Mexican, and English legal traditions, as well as its division of the water cycle into legal components which do not recognize hydrologic connectivity. For additional literature on Texas water law see (Gervais, 2015; Porter, 2012; Votteler, 1998). Texas water law technically recognizes four distinct classes of water, although in practice, there are two (1) surface water and (2) groundwater (Kaiser, 1996).

Texas recognizes both riparian and prior-appropriation doctrines for surface-water rights, despite their fundamental differences. The riparian doctrine, dating back over 200 years to Spanish settlement in San Antonio, grants water rights to landowners along water bodies. In the late 19th century, Texas adopted the appropriation doctrine. Land acquired from the state after 1895 no longer automatically carried riparian water rights. Instead, individuals had to follow statutory procedures to appropriate water rights from the state. However, existing riparian rights were consistently acknowledged by all appropriation statutes during this period. Between 1895 and 1913, a landowner could divert water from a stream by filing a sworn statement and map with their county clerk (Drummond, 2017; Otis, 2019). As a result, today most rivers in Texas are overallocated (Erdenesanaa, 2023).

Groundwater law on the other hand is based on the rule of capture. This strict common-law rule, often referred to as the 'English' rule, or 'rule of capture' was set by the Texas Supreme Court in the case of Houston and T. C. Ry. v. East (1904). According to this rule, the owner of the overlying land has relatively unrestricted rights to pump and use the water, regardless of its impact on neighboring landowners or more distant water users. The rule of capture has been a target of reform in Texas water law for its implications with personal property rights as well as an Achilles heel of groundwater markets (Drummond et al., 2004; Kaiser et al., 1994; Opiela, 2002). Due to the historical differentiation in legal treatment between surface water and groundwater under these two doctrines, the management of groundwater and surface water has traditionally been conducted as separate entities, despite the acknowledged hydrological interconnection between them.

It is well established in the field of hydrology that groundwater and surface water dynamically interact, influenced by hydrogeological factors, especially in certain areas of Texas (A. Smith et al., 2015; Cantor et al., 2018; Fleckenstein et al., 2010; Kalbus et al., 2006; Young et al., 2018). In hydrology, infiltration and percolation refer to two related but different processes describing the movement of water through soil. Infiltration refers to the water entering the soil from the surface, while percolation refers to the movement of that water through the soil, often to deeper layers (Sharp, 2008). Conversely, the movement of water from groundwater to surface water comprises spring flow and the contribution of baseflow to surface streams and lakes. In this context, baseflow refers to the seepage of groundwater into a stream. When dealing with a stream situated above an aquifer, water can either flow from the stream into the groundwater system, known as a 'losing stream,' or from the groundwater system into the stream, referred to as a 'gaining stream. As is observed in many Texas rivers, it is common to encounter stretches where the stream gains water in one section and loses it in another. A 2016 report published by the Texas Water Development Board (TWDB) quantified several metrics specifically related to groundwater-surface water interaction. For example, in an average year, approximately 9.3 million acre-feet of groundwater flow from major and minor aquifers to surface water, constituting around 30% of Texas' average surface water flow. Re-

gional and aquifer-specific variations in aquifer-surface water interactions exist, ranging from 14% to 72% of streamflow over aquifer outcrop areas originating from groundwater discharge. The most significant groundwater contributions to surface water are observed in East Texas, the Hill Country, and around major springs in West Texas. The Gulf Coast Aquifer leads in groundwater discharge to surface water, with an estimated annual contribution of 3.8 million acre-feet (Bech Bruun et al., 2016). This variation in terms of contribution depends on the specific interactions between the stream and the groundwater system. Understanding surface water-groundwater interaction is crucial for water management because changes in one resource often impact the other. Human activities can significantly influence this interaction (Caschetto et al., 2014; S. B. Foster & Allen, 2015). For instance, aquifer pumping from wells can lead to reduced spring flows and baseflows, affecting surface streamflow. In extreme cases, aquifer pumping can even reverse the natural flow, shifting water from the stream into the aquifer. Additionally, diverting streamflow before it infiltrates into an aquifer alters water levels and flow within the aquifer (Mace et al., 2007).

Amidst the backdrop of hydrological interaction between groundwater and surface water, and legal doctrines rooted in traditional water compartmentalization, the concept of conjunctive use has been a topic of interest within policy, academia, and practice for many years. Conjunctive water use is a water management strategy that involves the coordinated and integrated use of both surface water (such as rivers, lakes, and reservoirs) and groundwater (water stored underground in aquifers) to optimize water supplies and meet various demands. The literature on conjunctive water use points to various potential benefits of its implantation, including for irrigated agriculture, aquifer storage, and the environment (Bredehoeft & Young, 1983; Hernandez et al., 2014; Richter & Thomas, 2007). Unlocking this potential largely depends on effective governance. Given the distinct legal treatment of surface water and groundwater, this presents a significant hurdle in many regions of Texas, especially as it relates to providing water for the environment.

6.1.2 Providing water for the environment – a balancing act of science and strategy

There is demonstrable evidence that allocating water to the environment provides multiple benefits, including indirect benefits to people by maintaining the ecosystem services on which we depend (M. Acreman et al., 2017; Cowx & Portocarrero Aya, 2011). Although early efforts in environmental water legislation can be traced back to the UK Water Resources Act of 1963, and the Clean Water Act in the US in 1972, current sustainable development goals (SDGs) are more explicit in their calls for sustainable water withdrawals, as well as the protection and restoration of ecosystems (SDG 6) (Cooter, 2004; Petts, 1996; Sadoff et al., 2020). Environmental water targets are typically set either by (1) legislation, which specifies objectives for a river or (2) stakeholders and water users who define expectations for a river ecosystem and water uses (M. C. Acreman & Ferguson, 2010; M. Acreman et al., 2017). Setting environmental water targets underpinned by a strong conceptual understanding of the ecological effects and flow regime is critical for evaluating how environmental water can enhance ecological outcomes (Rolls & Bond, 2017).

One type of institutional arrangement for securing environmental water is through water markets, specifically through the use of environmental water transactions (EWTs) (Erfani et al., 2015; Garrick et al., 2011). EWTs are voluntary agreements in which existing water users are paid to modify the time, place, and/or volume of the water they use to provide an environmental benefit. Like water transactions between water users, EWTs can be short-term leases or permanent sales. However, empirical evidence in the Western US and Texas demonstrates that leases are far more common than sales, highlighting the impact of transaction costs and associated legal, cultural, and economic barriers on different types of EWTs (Garrick & Aylward, 2012; Scarborough & Lund, 2007). EWTs today build on decades of experimentation that originated in Oregon in the early 1990s (Neuman, 2004). What began as simple transactions involving water banks to purchase water rights from farmers and dedicate them instream has evolved into a sophisticated toolkit of transactions designed to provide multiple benefits to

multiple users (Burke et al., 2004; Hardner & Gullison, 2007; Kendy et al., 2018; Loomis et al., 2003). While Texas builds on a model tried across the Western US, including the development of a state water bank in 1993 and the water trust in 1997, several legal barriers challenge the implementation and efficacy of EWTs:

1. **Rule of Capture:** The adage 'whoever puts the biggest straw in the ground gets the most water' creates frictions between private property (e.g., groundwater in Texas), a common pool resource (CPR) like an aquifer, and how water could be traded in a market without a "cap."

2. **Non-Conjunctive Management:** The implicit assumption in the rule of capture contributes to poorly defined property rights and increased transaction costs associated with multiple agencies being responsible for different types of water (e.g., surface water vs. groundwater).

3. **No Specific Allocations for Environmental Water:** Texas does not consider the environment as a water user group in the context of water supply planning, which precludes water allocation from the state.

EWTs can occur within water markets lacking specific environmental water protections, such as Texas, or within dedicated environmental water markets with legal enabling conditions tailored for EWTs (Womble et al., 2022). Empirical evidence from the Colorado River Basin suggests that EWTs can decouple market activity from water law to temporarily transfer water rights to the environment (Womble et al., 2022).

6.1.3 The San Saba River – a natural laboratory for studying compounding competition

The San Saba River, a major tributary of the Colorado River faces multifaceted water scarcity challenges, making it an ideal natural laboratory for the study of Environmental Water Trans-

actions (EWTs). Situated at the transition zone between the Hill Country and the Rolling Plains, the San Saba exemplifies many of the challenges confronting rivers in the western United States and abroad. These challenges include competition among water users, conflicts between water users and environmental considerations, increasingly unpredictable precipitation patterns, and land fragmentation. From a governance perspective, the failure to recognize the environment as a water user adds complexity to the design of EWTs in the San Saba region. However, if EWTs can be designed and implemented in the San Saba despite these challenges, there is potential to scale their use in other basins facing similar types of scarcity, existing incentives, and governance challenges.

Figure 6.1 below illustrates the complexities of water use within the basin. In terms of surface water (lower map), water rights tend to cluster in both the upper and lower basins, fostering a local dialogue of competition between upstream and downstream users (Sadasivam, 2017, 2018). The adjudication of water rights in the San Saba occurred in the 1970s. The limited number of claims downstream of Menard County and upstream of the Brady Creek confluence suggests a historical absence of consistent surface water flows in this river stretch. In terms of groundwater use (upper map), wells are distributed throughout the basin, especially concentrated in the middle reach where water rights are absent.

From a hydrogeological standpoint, surface water and groundwater are intricately connected, although we lacked a comprehensive map quantifying this interaction at the basin scale. Therefore, Figure 6.2 below was created to elucidate how the San Saba River both contributes to and draws from groundwater in different reaches. In Figure 6.2, as the river flows from Menard County (left-hand side), the water level (indicated by the blue line) remains close to the surface (alluvium) for the initial 40 miles, suggesting that groundwater contributes to the river's flow. Further downstream, the river intersects the Hickory Uplift, a series of faults (between miles 60-100), where the water level indicates a losing reach—where the river recharges aquifers. This losing reach subsequently transitions to a gaining reach around mile 90, near the Penn Marble Falls formation.

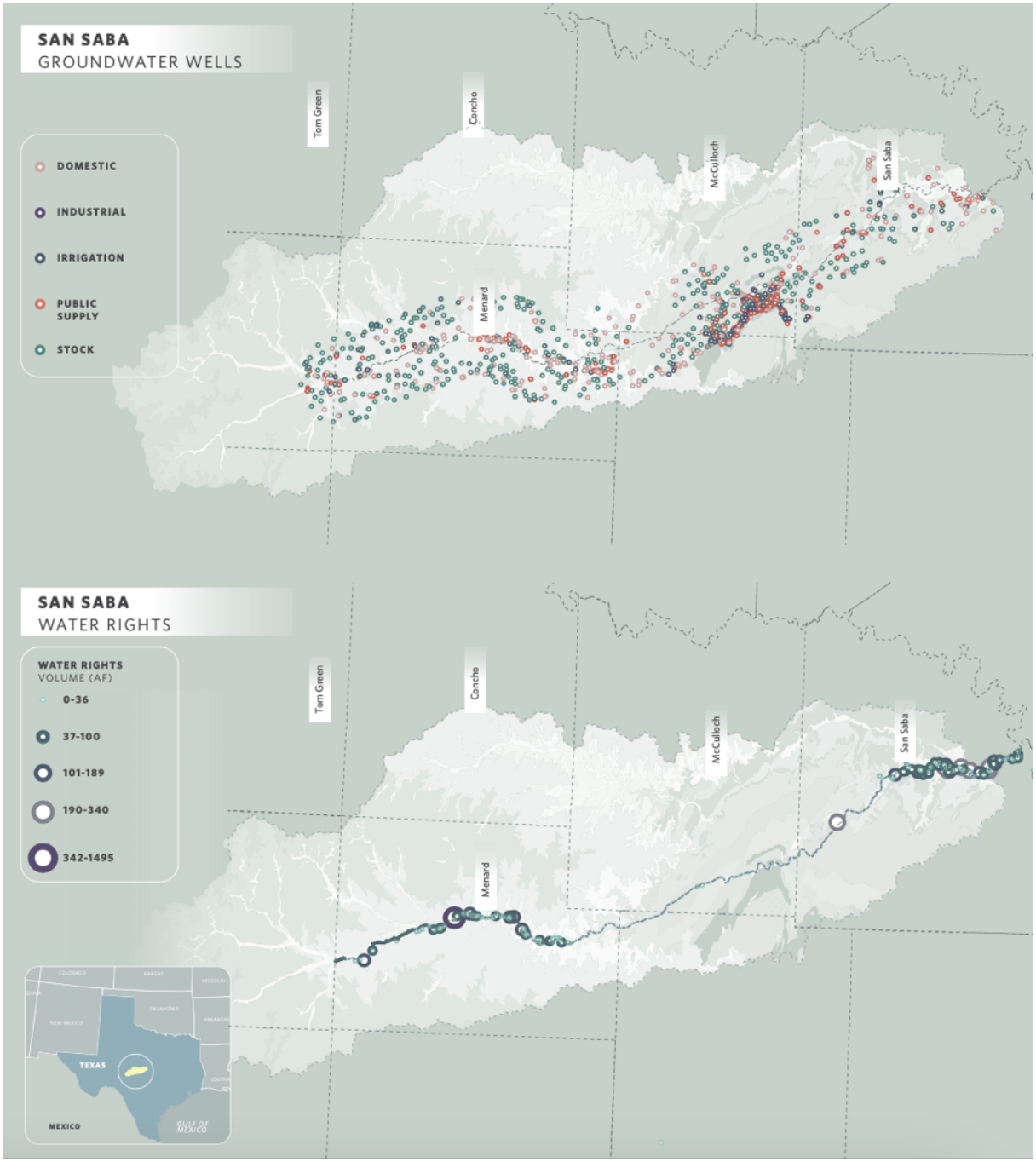

Figure 6.1: Two maps showing water-use on the San Saba via groundwater wells as omnipresent throughout the basins (above) differentiated by sector and surface water rights (symbolized by volume) which demonstrate the sharp divide in lower and upper basin water users.

In this context, our article focuses on a hierarchical set of questions designed to disentangle the mismatch between the governance and hydrology of the San Saba, and use that information

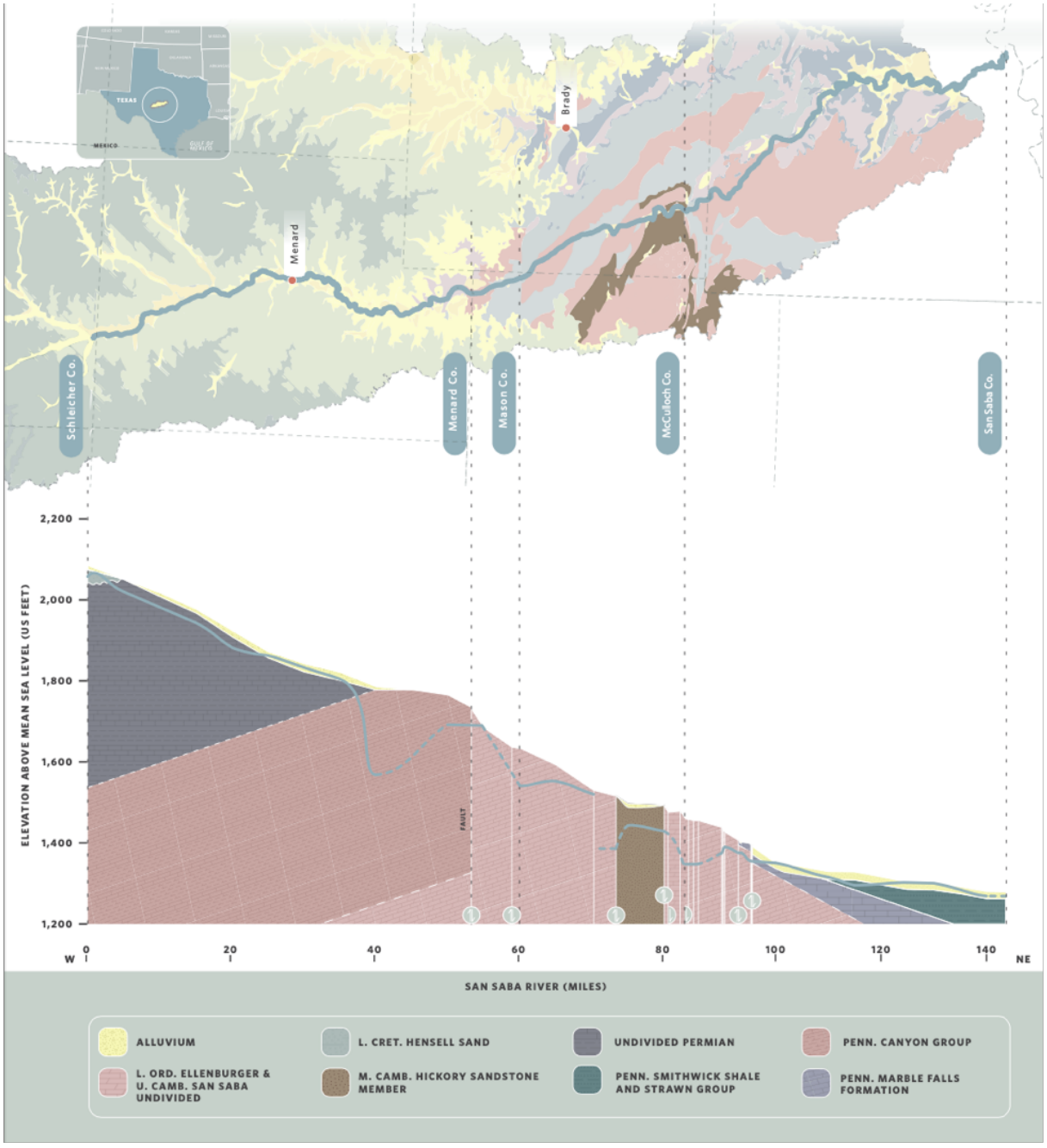

Figure 6.2: Two maps showing the hydrogeologic context of the San Saba. We aligned a geological map of the San Saba River Basin superimposed on a cross section of the San Saba River from its headwaters to the confluence of the Colorado showing the influence of geology on water levels (in blue in the cross section).

to spatially target EWT portfolios:

1. Which sections of river require intervention during times of scarcity to maintain flow targets? (i.e., priority reaches)

2. In these priority reaches, what are the spatial and temporal influences of natural (geologic) and anthropogenic (water use) drivers of scarcity?

3. What volumetric contribution can different portfolios of water rights paired with different types of EWT contribute to flow targets? And what are the costs and benefits associated with each portfolio?

Insights from our work on the San Saba can offer valuable contributions at multiple scales: at the basin scale, mapping the hydrogeology can provide a foundational understanding for local residents; at the state level, analyzing how to design EWTs to align with existing (non-environmental) water markets can unlock opportunities for EWTs in additional river basins; and as a case study from Texas, it can contribute to the broader scholarship on EWTs, particularly in a state where such examples are relatively scarce. Additionally, our work offers a methodological contribution through the prioritization framework we have developed.

6.2 Methods

6.2.1 Gain-loss studies identify spatial and temporal dynamics of groundwater-surface water interaction

To identify priority reaches, we relied on a gain-loss study that took place between 2018-2021 in the section of the San Saba in Menard County. Gain-loss studies are an example of a physically based model and are used to quantify interactions between groundwater and surface water within a system (Harte & Kiah, 2009; Slade Jr et al., 2002). Measurements of streamflow are taken at various locations in the main channel. The channel gain or channel loss is computed for each sub-reach between measurements by comparing the inflows and outflows plus flow gain or flow loss in the sub-reach. We employed a gain-loss study because (a) we

needed to identify reaches in the river that were losing and gaining to ensure we could meet the conservation objective; (b) the results allow us to unpack the anthropogenic and hydrogeological influences on the system; and (c) because there is a growing interest in the state of Texas to understand groundwater/surface water interaction considering the legal and governance implications (A. Smith et al., 2015; L. K. Foster et al., 2021). For the San Saba, a gain-loss study was performed in June 2018 where streamflow was measured at 14 locations in Menard and McCulloch Counties to identify (a) where groundwater contributes to streamflow and (b) where water use may be reducing streamflow. The locations of the study were based on a previous study in July 1933 (found in (Slade Jr et al., 2002)) and focused on the reach between the head water springs and Paleozoic outcrop. This reach is where most irrigation takes place and is composed of complex interactions with underlying aquifers. The flow measurements were collected by TNC, Texas Parks and Wildlife Department, and WSP USA. All measurements were made with a Sontek FlowTracker following USGS protocols and measured twice at each location. June 2018 corresponded with very dry conditions immediately before a period of heavy rainfall in fall of 2018. Low flow periods provide an advantage for gain-loss studies because interactions between the river and the bedrock geology are more observable.

6.2.2 Monitoring wells uncover interactions between groundwater and surface water based on sources of water and geographic location

To understand the interactions between streamflow, precipitation, and groundwater levels, we relied on gauges from well data. Six In-Situ Model 400 Level-TROLL transducers were installed in local alluvium and Edwards-Trinity groundwater wells on June 28th and July 27th, 2018. These transducers record semi-hourly water level changes. On July 20th, 2018, two Model 100 Rugged-Troll transducers were installed at Fort McKavett Springs and Clear Creek, two locations previously measured by the U.S. Geological Survey. The long-term goal with monitoring both surface water and groundwater levels are to identify gains and losses in both irrigation, and non-irrigation seasons to (a) understand how the system responds to pumping

and (b) identify specific EWTs strategies that respond to the system and protect habitat.

6.2.3 Developing an estimate of mass water balance for the area of interest helps quantify consumptive water demand

To estimate the consumptive use of water in Menard County, we developed a model to estimate the volume of consumptive groundwater and surface water used during the irrigation season.

For surface water demand, we used a water availability model (WAM) run 8 scenario and selected water rights in Menard County (n=83) (Wurbs et al., 2005). Run 8 of the model is current conditions and simulates recent demands. Therefore, we assume that volumes from users were consumptively used during this time period and do not account for return flows. We took the sum of the volumes from the WAM model for the months of March to October to represent the irrigation season. The volume of water, which we call the surface water demand irrigation season, is equal to 7,484 AF of water, which is 31.18 AF/day or 15.72 cubic feet per second (cfs) for 8 months.

For the groundwater demand of the model, we filtered groundwater wells inside Menard County. We then used data from the Texas Water Development Board (TWDB) which calculated the consumptive water demand of groundwater wells. We mapped the demand curve of the surface water demand irrigation season to the groundwater wells to provide an estimate of consumptive demand during the irrigation season. The volume of water, which we call groundwater demand irrigation season, is equal to 440 AF of water, which is 1.83 AF/day or 1 cubic feet per second (cfs) for 8 months.

Future research should focus on calculating water demand at the field level, which would provide a more nuanced, high-resolution picture of consumptive water demand across the basin including the dynamics of infiltration and return flows. Combining ground truthing, with well production volumes, and crop types could significantly improve estimations. Additionally, differentiating between the sources of groundwater – alluvial, and different aquifers

(e.g. Edwards, and Hickory) carry important management implications. While alluvial and Edwards well likely interact with surface water flows, the much deeper Hickory aquifer is for the most part hydrologically disconnected from the river. Therefore, in terms of integrated management scenarios, the ability to switch groundwater sources in times of scarcity could provide improved scenarios for river conservation.

6.3 Results

6.3.1 1. Which sections of river require intervention during times of scarcity to maintain flow targets? (i.e., priority reaches)

Based on previous fieldwork, stream gauge analysis, and our gain-loss study we identified an area a few miles upstream of the town of Menard and the county line of Menard/ McCulloch where (a) baseflows can drop below a subsistence flow of 4 cfs, (b) there are existing habitat for freshwater mussels (Goldsmith et al., 2022; Randklev et al., 2018), and (c) there are numerous water rights which could be used for EWTs. Choosing this area as a priority reach means that our conservation objective is to maintain freshwater habitat in this reach, as well as extend areas of refugia in times of drought. We are aware of the 40-mile stretch of the San Saba River downstream of this priority reach which landowners have noted have run dry for 10 of the last 16 years (Friends of the San Saba 2015). However, there are economic and volumetric limits to employing EWTs to rewater this reach. Dewatering the priority reach not only impacts riparian habitat negatively but also brings economic hardship to landowners who rely on the river for domestic and livestock purposes. The timing of these dewatering events is also critical. The times of most scarcity coincide with the height of the irrigation season (late July and August) which overlap with the highest temperatures and highest crop stress. The graphic below (Figure 6.3) shows the geographic location of the priority reach and a hydrograph showing monthly discharge for 30 years at Menard:

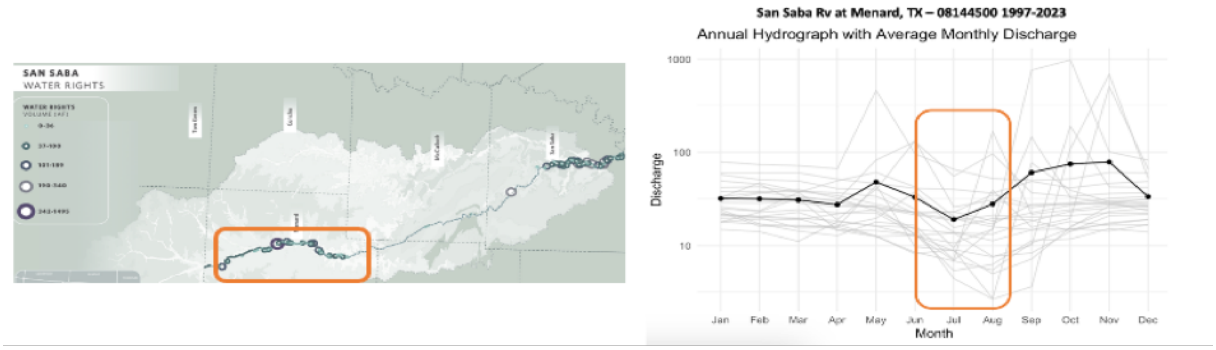

Figure 6.3: A graphical display of the priority reach surrounded by numerous water rights, and the hydrograph showing the timing of the lowest flows historically, July and August (right hand side)

6.3.2 2. In these priority reaches, what are the spatial and temporal influences of natural (geologic) and anthropogenic (water use) drivers of scarcity?

Results from the gain loss studies (Figure 6.4 below) identify reaches where surface water contributes to aquifers, and where groundwater contributes to river discharge. Analyzing the results of the 2018 gain-loss study and those of the 1933 study allow us to interpret the results in the context of pre-development conditions (with no significant groundwater pumping) and assume that loses in the reach in 1933 are primarily attributed to recharge (Slade Jr et al., 2002). Streamflow during the 1933 study was generally twice as much as the 2018 study. Flow at Menard in 1933 was 19 cfs, compared to 9.5 cfs in 2018. Likewise, flows at Fort McKavett were 21.1 cfs in 1918 and 5.4 cfs in 2019. Rainfall totals were similar for both time periods suggesting that reduced flow at the Schleicher-Menard County line can be partially attributed to increased groundwater pumping in the headwater since 1933. Agreement between the 1933 and 2018 study shows a 10 cfs loss in eastern Menard County which occurs below the downstream confluence of the Menard irrigation canal and river at Ten Mile Crossing. Measured channel loss between Menard irrigation canal inflow and outflow varied between the 1933 and 2018 studies. There is loss in the system due to the hydrogeologic circumstances, but the difference between the loss in 1933 vs. 2018 (holding precipitation close to constant between the two

studies) shows a loss of 0.05 cfs in 1933 and 4.2 cfs in 2018 between Menard and Fivemile crossing.

The graphic below (Figure 6.4) illustrates the spatial and temporal variability of gaining and losing reaches based on data from three different gain-loss studies conducted in 2018, 2019, and 2021.

Figure 6.4 above depicts changes in the San Saba River under varying climatic, groundwater levels, and irrigation conditions between March 2018 and June 2021. In March 2018, representing average pre-irrigation season conditions, no significant losing stretches were observed in the study area. However, by June 2018, during a typical dry condition for the watershed in the irrigation season, we observed losses in the upper headwaters and in a reach with irrigation just upstream of the highly faulted Ellenburger group.

In August 2019, after a recharge event, we noted significantly fewer losses, even during the irrigation season. Fast forward to June 2021, with higher groundwater levels, which represented normal irrigation season conditions, and we found that the gaining stretch in the headwaters was longer than in June 2018. Notably, the gaining stretch in the headwaters resembled that of March 2018, but the area downstream of Menard, which was gaining in June 2021, had turned into a losing stretch, along with a small section upstream of Menard.

These four graphics collectively demonstrate how different stretches of the San Saba can shift between gaining and losing depending on climatic conditions and the presence or absence of irrigation. When comparing March 2018 and June 2021, we can discern an anthropogenic influence during the irrigation season, particularly in the extent and number of losing sections. Notably, the section most susceptible to low flows in various conditions, including dry years and dry-year irrigation, lies downstream of Menard toward the county line between Menard and McCulloch counties.

Upon overlaying these gain-loss maps with transects, we observe the influence of two key hydrological attributes: springs and geologic formations. For instance, the uppermost section

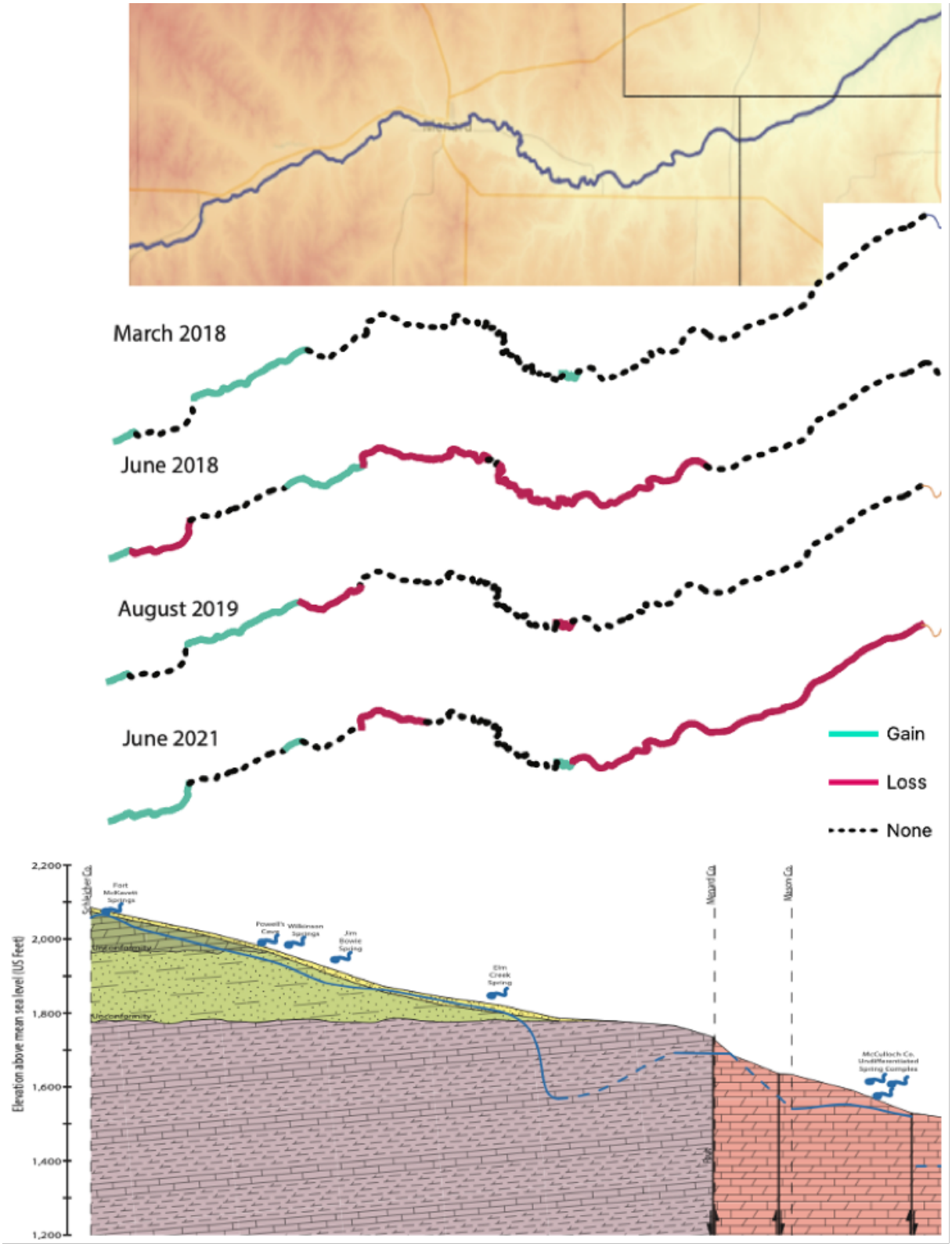

Figure 6.4: (March 2018) Normal conditions during non-irrigation season (top); (June 2018) Dry conditions during irrigation season (second); (August 2019) wetter conditions during irrigation season (third); (June 2021) normal conditions during irrigation season (bottom)

of our graphics, associated with the Hensell Sand group near the alluvium and in proximity to Fort McKavett Springs, consistently exhibits gaining characteristics. Conversely, approximately 15 miles upstream of the Menard/Mason County line, water levels dip into the Penn Canyon Group before encountering a series of faults near the county line. This stretch coincides with losing conditions, especially during periods of high-water demand, such as in June 2018 and 2021.

To further illustrate the connectivity between groundwater and surface water, please refer to Figure 6.5 below. The figure shows wells located in relatively close proximity that draw water from hydrologically disconnected sources. The results of the well data were generated using the Ecohydrology package in R (Fuka et al., 2014). All the results are presented for the same time period, indicated on the lower x-axis, with the San Saba streamflow (in cubic feet per second, cfs) displayed on the y-axis. The upper x-axis represents rainfall in inches. Well levels, depicted in blue, are presented in feet, corresponding to the depth of the wells below the ground surface.

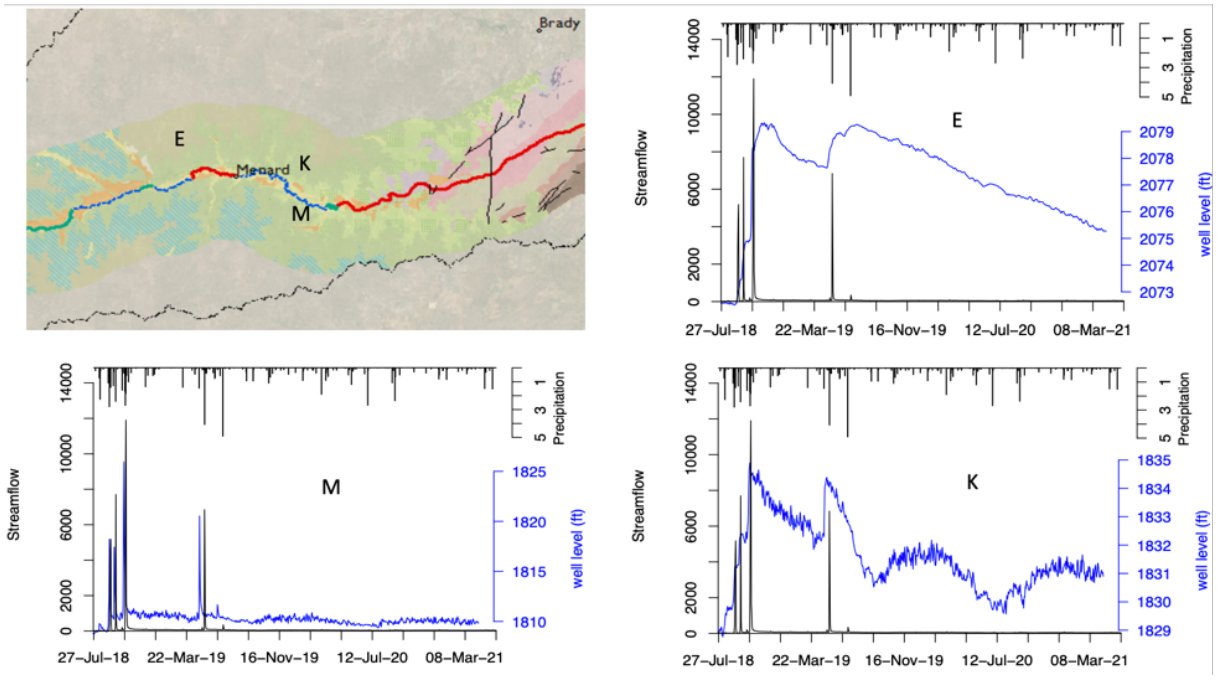

Figure 6.5: Three different groundwater wells demonstrating different signatures in the San Saba Basin

These graphics serve as valuable tools for visualizing distinct hydrogeological characteristics and how various wells along the same river respond differently to precipitation events. For instance, we observe that both alluvial wells, represented as K and M, exhibit fluctuations in response to changes in streamflow discharge and precipitation. The signature of well K is so closely aligned with streamflow that we interpret it as actively pumping river water. Conversely, the signature of well M, while also drawing water from the alluvial layer, suggests a more pronounced storage component within the alluvium.

In contrast, well E appears to draw water from the Edwards-Trinity aquifer, making it less dependent on both precipitation and streamflow. Precipitation in the region closely correlates with spring discharge, as supported by all three wells in Figure 7. Although the response times of springs may vary, it's worth noting that spring discharge in the basin has exhibited a decreasing trend over the past 30 years (refer to the spring discharge trendline in the appendix), indicating changes in overall water supply, likely influenced by precipitation patterns.

6.3.3 What volumetric contribution can different portfolios of water rights paired with different types of EWT contribute to flow targets? And what are the costs and benefits associated with each portfolio?

Based on the conservation objectives and scope of this study, our interventions focus on dry-year conditions during the irrigation season in the priority reach. There is opportunity for future research to quantify the costs and benefits of employing nature-based solutions (NbS), crop optimization, and other market-based incentives during non-irrigation season. However, for the purposes of prioritization, the scope for this study focused on the time of most need, which is a dry-year irrigation season where the compounding factors of less than average precipitation and more than average water-use drive water scarcity in the river. We also note that in the San Saba, like many other rivers with groundwater-surface water interaction, we must consider EWTs which work to decrease water use on both surface and groundwater

sources.

Based on target flow calculations from the Great Plains (GP) Environmental Flow Information Toolkit (EFIT) Hydrology Dashboard, which are based on Indicators of Hydrologic Alteration (IHA) and Hydrology-Based Environmental Flow Regime (HEFR), our target low baseflow in the summer (June-Aug) is 5.4 cfs. Therefore, we focused on designing three portfolios using EWTs which can each provide 356 AF to the priority reach in July. 356 AF provides 3 cfs for 2 months and assumes that the EWTs would be deployed when discharge reaches 3 cfs.

Of the 224 water rights on the San Saba, 178 have a reliability over 90% (WAM3) and of those with high reliability, 37 are downstream from Menard, which is where we prefer to focus intervention. Of the 37 water rights which meet our criteria, only one has a volume over 356 AF, the minimum value is 9AF with a median and mean value of 45 and 77 AF respectively.

We estimated the financial costs associated with leasing, and purchasing different water rights by using a database on water transactions (see Chapter 5) with 59 transactions in the Colorado, Llano, and San Saba basins in the last 30 years. We further calibrated our costs based on knowledge of five EWTs in the San Saba and neighboring Llano Basin. Based on the most recent EWTs the median price for leases for EWTs was $50/AF and the median price for sales was $1,137/AF. However, we know these numbers vary significantly depending on supply and demand of water in addition to other factors associated with the water right, including seniority. We use the median price because water this transaction data is skewed and non-normally distributed. For the purposes of this model, we use a price of $70 USD per AF which represents a competitive market price for high seniority and high reliability water rights. Table 1 below shows the tradeoff associated with different types of EWTs to provide the same volumetric contribution 356 AF.

While Figure 6.6 provides a simplified overview of complex transactions, it is important to note that each transaction entails extensive trade-off and cost-benefit analyses by both parties involved. For instance, if a producer opts for a forbearance agreement while during a multi-

Type of EWT	Costs	On farm considerations	
Dry-year options	3-year term agreement if no dry-year event costs = $10,680; if 1 dry-year event, costs = $32,040	Economic security in the event of a dry year. Reduced maintenance costs for fields out of production. Soil health advantages for resting field.	Risk associated with starting and potentially abandoning a crop
Forbearanc e agreement	3-year term agreement totaling **$74,760** for $70/AF per year	Economic security for a season. Reduced maintenance costs for fields out of production. Soil health advantages for resting fields.	Missed economic opportunity in the event of a wet year or high crop demand.
Water Rights purchase	A one-time cost of **$404,722** ($1,137/AF)	Immediate Capital: Selling water rights can provide an immediate infusion of capital, which can be valuable for funding the source switch to hickory/more reliable water sources, paying off debts, or making investments in other areas.	Permanent loss of water rights and potential long-term consequences for water availability
Water rights lease	A yearly cost of **$24,920** ($70/AF)	Flexibility: Leasing allows water rights holders to retain ownership while temporarily transferring usage rights to others.	Managing leases, ensuring compliance, and negotiating terms can be administratively burdensome, particularly for small water rights holders.

Figure 6.6: An example of financial tradeoffs and on farm consideration of different EWTs

year crop rotation, additional costs for weed control must be considered. Similarly, a producer contemplating source switching, such as tapping into the deep Hickory Aquifer with wells reaching depths of 2,000 ft., must factor in fixed costs of drilling and variable costs of powering the pump. These factors must be weighed against the economic gains from selling water rights, which may be less reliable and less readily available than water from a Hickory well, all while considering the associated trade-offs, particularly in terms of water quality.

Dry-year lease options pose intricate trade-off considerations for both producers and NGOs. In a three-year dry-year lease, the NGO initiates the agreement with an upfront payment,

typically at a reserve price of $10 per acre-foot (AF). If river flows fall below a predetermined threshold, say 8 cubic feet per second (cfs), the NGO pays $70/AF, which can incentivize producers by exceeding their irrigation opportunity costs during dry years. In any of the EWTs there are significant administrative challenges and transaction costs can impede environmental benefits. For instance, creating EWTs during dry years is impractical due to the need for contract completion well in advance of option activation. One reason forbearance agreements are appealing to NGOs is their lower administrative and transaction costs, even if the financial cost is higher in terms of $/AF. One significant incentive for the producer is that EWTs offer a level of resilience that is challenging to find a substitute for in the current market. Finally, there exist new frontiers for scholars in the field of EWTs to explore. These include developing structural strategies that offer long-term incentives, such as over a 20-year period. Such incentives should be substantial enough to not only cover irrigation opportunity costs but also address capital expenditures related to source switching, exemplified by the case of the San Saba with its deep Hickory well.

6.4 Discussion

Upstream and downstream water users in San Saba agree that water scarcity is a threat to their livelihoods, although they may not agree on who is to blame (Hamilton, 2013; Sadasivam, 2018). Amidst increasing competition, conservation organizations are grappling with how to commit water to the environment in times of scarcity. A multidisciplinary perspective reveals that solutions to water scarcity in the San Saba must navigate an irreconcilable rift between the hydrology and governance of the groundwater/surface water relationship. On one hand, the hydrogeology of the basin does not discriminate groundwater from surface water. Depending on climatic conditions and water use, gaining and losing stretches in the river work together to balance aquifer levels and streamflow. On the other hand, water users who rely on water to grow food lack the governance and institutional capacities to manage water use conjunctively. This disagreement between hydrologic communication and water governance

limits options for managing water by challenging the typical common pool resource (CPR) or private property strategies for scarcity.

Studying the San Saba contributes to advancing EWT science and strategy. While future policy changes could enhance outcomes for both producers and the environment, there is an immediate need for effective tools that operate within current institutional conditions to address existing environmental water needs. The results of the hydrological studies (results Figures 6.4 and 6.5) inform a spatial targeting method which helps spatially target EWTs and compare the tradeoffs for addressing water scarcity. The following sections focus on the final considerations of applying spatially targeted EWTs by drawing on the literature of spatial action mapping (Tallis et al., 2021).

6.4.1 Actions

There is an increasing amount of attention placed on quantifying actions, analyzing relationships amongst actors, and measuring impacts of conservation initiatives (Alexander et al., 2016; Ferraro & Pattanayak, 2006; Maron et al., 2013). In the case of EWTs in the San Saba River of Texas, we limited our focus to a short list of EWTs which have a record of implementation. This decision was pragmatic as the objective of our study was to contribute to the science of spatial targeting of EWTs. However, considering changes in demographics and potential political shifts in Texas, future work should consider additional EWTs that could be implemented under different local and state water policies (Huerta & Cuartas, 2021). This includes but is not limited to changes in groundwater policy, either by bolstering groundwater conservation district's institutional capacity or a shift in legal recognition of conjunctive use (Johnson et al., 2011; Pulido-Velazquez et al., 2016). Analysis on EWTs could also be improved by comparing potential impacts to counterfactuals or business-as-usual (BAU) scenarios to better depict what could happen absent a given EWT intervention (Ferraro, 2009; Maxwell et al., 2020). Future research could also explore sustainable funding strategies, potentially involving Federal and State governments. Such strategies could facilitate the renewal of contracts

with producers without being constrained by the limitations often associated with traditional grant cycles.

6.4.2 Actors

For this study, we implicitly focused on three types of actors which carried their own assumptions:

1. **Producers** who use water as an economic input for their business (farming)
2. **Water districts** who play role in organizing trades at the basin level, but who lack sufficient funding to provide adequate monitoring and conflict resolution
3. **NGOs** who fund different transactions with the aim to contribute to pre-defined conservation objectives without expectation of financial returns

Additional analysis of actors, including understanding the influences of power dynamics is strongly recommended and for improving equity and conservation outcomes (Dietsch et al., 2021; Lau, 2020). From an economic perspective, there are also opportunities to analyze how transaction costs affect actors' perceptions of engaging with EWTs and the incentive structures themselves (Garrick & Aylward, 2012; Womble & Hanemann, 2020). Related, quantifying unintended consequences of EWTs (both social and environmental) at a basin level remains a rich area of opportunity for water resource management (Kendy et al., 2018; Rey et al., 2019).

6.4.3 Impacts

Although EWTs have played a role in securing water for the environment in specific locations, under certain conditions they have struggled to scale (Ayres et al., 2018; Garrick et al., 2020; Pilz et al., 2017). EWT's future success could be improved by incentive design which can respond to seasonal fluctuations in supply and demand, while providing a minimum threshold of private and public benefits. For example, in years where minimum flow metrics are met (i.e., public

benefit satisfied), "conserved" water which has already been allocated to the EWT but no longer needed, could be reallocated on a spot market for downstream users to increase private benefits. In this article, we focused on spatially targeting EWTs during the irrigation season which represents the greatest threat to environmental flows. However, sustainable pathways for addressing water scarcity need to also focus on actions during times of decreased scarcity so that communities invest and maintain the institutional capacity necessary for facilitating transactions under shocks or conflict.

For example, designing a EWT for properties who source water from alluvial wells like well M (figure 6.5), and are located on a reach that loses streamflow during the irrigation season, may benefit from focusing on reducing consumptive use, and on a permanent basis, e.g., water acquisition or direct intervention. Alternatively, properties located in the headwaters where the reach transitions from losing to gaining depending on the climate condition may be better served by a EWT that focuses on temporary agreements, e.g., dry-year lease, or forbearance. These results demonstrate how an EWT focused on changing water withdrawals should pay particular attention to the (a) location and (b) volume of their intervention relative to a losing reach. An EWT implemented upstream of a losing reach with insufficient volume (or seasonal baseflow) to pass through the reach may inadvertently be recharging an aquifer. An additional limitation of EWTs is that fulfilling system-level outcomes requires investments in coordination and group level interventions (e.g., minimum flow legislation or mitigation banks). Changes in water-use behavior (e.g., improved monitoring to irrigate more efficiently without increasing acreage) on farms near the river, should be considered with caution so as not to increase consumption (Grafton & Wheeler, 2018; Jensen, 2007). Recent evidence suggests resources focused on researching and testing feasibility and performance of transition pathways for transformational institutional change have a better ROI for water savings than technology for water use efficiency (Pérez-Blanco et al., 2021). In line with this recommendation, we also note that decisions on targeting specific reaches or properties should balance the short vs. long term trade-offs of on farm technologies vs. institutional transformations in the context of sustainable pathways.

6.5 Conclusion

In river basins experiencing water scarcity, competition for freshwater extends to include environmental needs. Environmental Water Transactions (EWTs) present a means to alleviate this competition through voluntary agreements, compensating existing water users for adjusting the timing, location, and volume of their water rights to benefit the environment. Despite sporadic success, scaling EWTs faces significant hurdles in design and implementation. A prominent challenge lies in designing EWTs for areas lacking conjunctive management of surface and groundwater interactions. The San Saba River offers a valuable opportunity to advance EWT science and strategy, given its complex scarcity drivers: geological and anthropogenic factors, coupled with a deficit in governance to ensure environmental flows. Our contribution is twofold. Methodologically, we employ a triangulation approach across various hydrological studies to quantify the spatial and temporal dynamics of surface-groundwater interaction. This includes creating a longitudinal transect that incorporates water levels and geological data, conducting gain-loss studies over distinct timeframes, and monitoring well gauges, all of which illuminate the intricate relationships between surface and groundwater. Additionally, we estimate the consumptive demands of both surface and groundwater users during the irrigation season. We also offer cost estimates for four EWT types, spanning from single-season lease transactions to perpetual water rights purchase, with costs ranging from $24,920 to $404,722, respectively. These EWTs have the potential to contribute 3 cubic feet per second (cfs) to support subsistence flows during the peak irrigation season (June-August). Our findings underscore that EWTs, akin to other tools addressing water scarcity, come with inherent limitations, costs, and benefits. We demonstrate that spatial targeting of EWTs can effectively address several limitations, navigate associated costs, and optimize benefits for both producers and the environment.

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Chapter 7

Synthesis and Conclusion

In the preceding chapters, I explored the core topics corresponding to the three primary research questions established in this thesis. This concluding chapter offers a comprehensive synthesis, summarizing the key findings for each research question. It encompasses an overview of the central conceptual, methodological, and empirical contributions I have made throughout this study. Additionally, it highlights how these findings impact decision-making processes. Furthermore, I critically examine the primary limitations I encountered and propose avenues for future research. Finally, I conclude with some closing remarks that encapsulate the essence of this work.

7.1 Thesis summary and main findings

The aim of this doctoral research was to identify pathways for how market-based incentives can address different types of water scarcity and contribute to sustainable water management. To systematically address this objective, three interrelated research questions were identified and meticulously explored across the three substantive chapters (Chapters 4, 5, and 6) of this thesis. Each of these chapters played an indispensable role, with their collective insights essential for fully addressing the thesis's overarching research aim.

7.1.1 Research Question 1

Research Question 1 formed the initial focal point of this inquiry, concentrating on a comprehensive assessment of the potential of market-based incentives at a global scale. This question revolved around two critical inquiries: What are the primary factors driving water scarcity? And which incentives and investments, both in the short and long term, hold the potential to effectively mitigate these drivers? To tackle this question, a novel typology of water scarcity was developed, grounded in the specific demands for water and their temporal dynamics. This typology served as the foundation for the creation of a global map, employing sub-basins as the fundamental unit of analysis. This map not only made a conceptual contribution to the field of water scarcity research but also provided a methodological contribution by developing a spatially explicit connection between the underlying causes of scarcity and prospective incentive-based solutions. Results of the map demonstrate that water demand within agriculture contributes to scarcity in 94% of the basins experiencing scarcity, concentrated in the central USA, Spain, and India. Urbanization has led to competition between cities and agriculture in 1,596 of 3,057 subbasins (52%).

Moreover, this innovative approach introduced a robust analytical framework, bridging the domains of hydrology, economics, and governance. It built upon existing hydro-economic models and harmonized the sub-fields of popular incentives for addressing water scarcity, water markets and water conservation technologies. This interdisciplinary exploration delved into various institutional mechanisms, particularly incentive-based water reallocation, and advanced technologies such as investments in water conservation technologies. By scrutinizing how these approaches could effectively address distinct forms of water scarcity, this chapter yielded valuable insights with substantial methodological implications. In particular, it underscored the potential to significantly enhance economic efficiency and marginal productivity in water use through a meticulous understanding of scarcity dynamics.

7.1.2 Research Question 2

Research Question 2 focuses on analyzing the performance of water markets in Texas over the past three decades. It seeks to answer key questions: Where have formal water transactions occurred in the last 30 years? Who are the participants in these water markets in terms of volumes and costs? And can we identify the drivers behind water market activity in this region?

To tackle this multifaceted research question, I compiled an extensive and original dataset comprising over 2,350 water transactions. This dataset covers the period from 1987 to 2020, spanning 13 major basins within Texas. The total volume of water reallocated through these transactions amounted to approximately 4 million acre-feet (AF), with a combined cost of $1.3 billion USD. This dataset represents a unique empirical contribution to the field of water markets, serving as the most extensive statewide transactions database to date.

Through spatial analysis and descriptive statistics, this research accomplishes the pioneering task of presenting the first comprehensive statewide analysis of water market trends. The variation of transactions within this dataset underscores that water market activity in Texas extends beyond regions like the Rio Grande or Edwards Aquifer. This finding holds significant implications for academic research on water market suitability and institutional conditions enabling their activity. This chapter explores the variation of transactional activities, quantifying the reallocation of water volumes among users, including environmentally-oriented allocations. Environmental allocations alone amount to 266,000 AF, with an average transaction size of 16,000 AF. These descriptive statistics enrich the literature on water market activity in the United States, including the sub-discipline of environmental water transactions, setting the stage for Chapter 6. The data on statewide transactions reveal a growing frequency of water trading (both sales and leases) across Texas. To explore correlations between changes in water supply and demand and transaction activity at the basin scale, I developed a Poisson fixed effects regression model. This model aims to test whether specific variables related to water supply (e.g., reservoir levels) or demand (e.g., population growth) are statistically cor-

related with increases in water transactions. The results highlight that reservoir levels, SPI, temperature, groundwater levels, and commodity prices for rice and cotton are significant predictors of water transactions.

These empirical findings not only provide an expansive overview of water markets in Texas but also make substantial contributions to the academic literature. By presenting the first extensive inventory of water markets across the vast expanse of Texas, this research broadens the horizons of knowledge in this field. Furthermore, the application of econometric models founded on high-resolution basin-scale data and remote sensing techniques represents a noteworthy methodological contribution. To the best of my knowledge, this study stands as the first instance of an econometric analysis for water markets utilizing the capabilities of Google Earth Engine, thus breaking new ground in the methodological approach to studying water markets.

7.1.3 Research Question 3

Research Question 3 builds on the following two chapters to focus on the design of environmental water transactions (EWTs) within a basin marked by competing anthropogenic and hydrogeologic factors, resulting in water scarcity that can lead to dry river sections. To address this complex challenge, a hierarchical set of questions guides this study:

1. Which sections of river require intervention during times of scarcity to maintain flow targets? (i.e., priority reaches)

2. In these priority reaches, what are the spatial and temporal influences of natural (geologic) and anthropogenic (water use) drivers of scarcity?

3. What volumetric contribution can different portfolios of water rights paired with different types of EWT contribute to flow targets? And what are the costs and benefits associated with each portfolio?

This chapter seamlessly integrates recent hydrological research to identify patterns in groundwater-surface water interactions, prioritize intervention areas in stream reaches, and account for both geological and anthropogenic drivers of scarcity. This methodological contribution extends the existing literature on groundwater-surface water interactions, traditionally found within geological studies, into the domains of water resources management and water scarcity scholarship.

By analyzing water rights and well data, I estimate consumptive water demands during the irrigation season which guide flow targets for intervention. I quantify the volumetric contributions of diverse water rights portfolios paired with various EWT types, evaluating their effectiveness in achieving flow targets while considering associated costs and benefits. The results emphasize that the success of EWTs relies on coordinated spatial and temporal targeting, taking into account hydrogeological contexts and water user dynamics. These outcomes enrich the literature on EWTs by integrating surface/groundwater interactions while providing a comparative assessment of costs across different portfolios.

Furthermore, this study yields a substantial contribution to Texas water governance by highlighting the disconnect in governance approaches between groundwater and surface water, despite their hydrological interconnectedness. This disconnect carries far-reaching policy implications, particularly in light of escalating competition for freshwater resources and the challenges posed by climate change.

7.2 Research Contributions

Beyond answering the three research questions, this thesis also makes a number of conceptual, methodological, and empirical contributions to the fields of water resources management, water scarcity, water markets, and environmental water transactions.

7.2.1 Conceptual Contribution: Linking drivers of water scarcity to incentives across scales

The comprehensive exploration of water scarcity in Chapter 2 and the subsequent three substantive chapters collectively underscore two crucial insights: (a) water scarcity is fundamentally a product of the intricate interplay between supply and demand dynamics, and (b) beneath the surface, the issue of water scarcity reveals itself as an intricate and often ”wicked” problem in the realm of water governance.

While the literature on water scarcity, historically rooted in hydrology, and that on incentives, predominantly grounded in economics, have both significantly evolved in the past two decades, they have largely progressed independently. This division allowed scholars specializing in governance and institutions to scrutinize the distinctive characteristics of water governance that hindered the realization of the potential benefits associated with water markets, including those related to environmental conservation.

Although recent scholarship has taken strides in amalgamating diverse disciplines to analyze the root causes of water scarcity and potential remedies, a formidable challenge persists in the effective implementation and scalability of water markets to contribute to achieving sustainable water management. As elucidated in each of the substantive chapters, scaling water markets confronts numerous obstacles, including the influences of local hydrological, economic, and institutional contexts, rendering the direct transference of one water market model from one region to another impractical. This challenge of scale is exemplified by the observation that the roster of countries with empirical evidence of water markets has remained relatively unchanged for more than two decades.

Within this context, the most significant conceptual contribution of this thesis resides in elucidating the existence of various types of water scarcity, distinct classes of incentives, and diverse cost-benefit profiles associated with each. It underscores the critical importance of adopting a spatially targeted design that prioritizes the specific type of scarcity, the nature

of the incentive, the geographic context of intervention, and the meticulous quantification of associated costs and benefits. This process necessitates a nuanced, but not perfect, understanding of the hydrological, economic, and institutional characteristics linked to the scale of intervention. For instance, in the case of a spot market facilitating transactions among irrigators within a river basin, it is imperative to align the hydrological, economic, and institutional facets with the needs and characteristics of that particular community of irrigators. Similarly, if the objective revolves around a statewide incentive scheme to promote groundwater transactions, the policy design must authentically reflect the valuation of water resources as perceived by the trading parties, which may or may not coincide with aquifer boundaries.

Indeed, the task of aligning models, stakeholder values, and navigating the intricate landscape of costs and benefits is undeniably challenging. However, it is imperative to compare this challenge to the alternative: (a) the escalating and substantial negative impacts stemming from water scarcity, and (b) the stark reality of limited successful replication when attempting to transplant a specific water market model into a divergent geographic context. In light of these considerations, it becomes evident that the complexity of designing and implementing water markets pales in comparison to the repercussions of unmitigated water scarcity. Furthermore, when measured against alternative approaches, it becomes apparent that incentives, like water markets, hold unparalleled potential to provide scalable solutions. Hence, for water markets to earn their place as a tool in the arsenal against water scarcity, careful design and implementation are not merely advisable but indispensable. If their design takes into account the considerations outlined in the frameworks of this thesis, their scalability can be achieved through spatially targeted prioritization aligned with local conditions rather than attempting a one-size-fits-all replication.

7.2.2 Methodological Contributions: Integrating models across disciplines in a multi-scale approach

Understanding water scarcity within the complex framework of a social-hydrological system necessitates a holistic interdisciplinary approach. This need for interdisciplinary synergy is equally relevant when it comes to analyzing potential solutions for mitigating water scarcity. Over the last two decades, scholarly efforts have propelled the development of spatially explicit hydro-economic models, and the increasing accessibility of low-cost high-resolution remote sensing data promises substantial growth in this field in the forthcoming years, holding significant implications for water resource management. However, a critical challenge faced by these models lies in the incorporation of governance metrics across various scales. Often, different regulatory frameworks are applied to distinct geographical regions within a hydrologic unit (e.g.,single basin or aquifer) presenting both methodological and conceptual hurdles for hydro-economic modeling.

Each of the three substantive chapters in this thesis offers methodological contributions on their own but the most significant comes from harnessing the synergy of each set of models to address scale-specific research inquiries. From a conceptual standpoint, this approach also has the potential to reshape our perspective on modeling complex problems by advocating for a portfolio of models rather than the construction of an all-encompassing model. At the global scale, Chapter 4 introduces a methodological contribution by establishing spatially explicit links between basins and a typology of water scarcity. This innovative perspective connects the dots between drivers and global-scale solutions, paving the way for future applications in water resources management, particularly concerning the challenges posed by climate change.

At the state or provincial scales, Chapter 5 provides a methodological contribution by meticulously constructing a geospatial database of transactions and subsequently organizing multiple variables from various sources (state databases, remote sensing data, etc.) for utilization in an econometric model. This contribution hinges on the potent capabilities of econometric models to uncover drivers, which, while obtainable through GIS, may face challenges when subjected

to typical geospatial statistical analysis due to the complexities associated with normalizing variables across basins or aquifers.

At the finest scale, Chapter 6 makes a significant methodological contribution by harmonizing hydrological data from various sources to unpack the intricate hydrological interplay between surface and groundwater, all within the framework of a regulatory landscape that traditionally governs these water sources separately. The model employed in this chapter goes further to illustrate the hydrological interactions between surface water and groundwater at different temporal and spatial points along the San Saba River which has not been done to date. Furthermore, this model takes into account the economic aspects by incorporating the costs associated with different types of environmental water transactions and analyzes them in the context of costs and benefits for both producers and the environment. This holistic approach to modeling hydrological data within the context of competition for freshwater withdrawals, encompassing both surface water and groundwater, represents a timely contribution to the literature on water governance. It is especially relevant in regions characterized by extensive hydrological connectivity between groundwater and surface water, where the coexistence of disparate management practices calls for precisely the kind of integration provided by this model to facilitate efficient conjunctive water use.

7.2.3 Empirical Contributions:

The empirical contributions of this thesis primarily originate from Chapters 5 and 6, both of which focus on Texas. One significant empirical contribution is the creation of an original database that encompasses transactions spanning the state over the past three decades. This database played a pivotal role in shaping the subsequent analyses and insights presented in the thesis. Importantly, its value extends beyond the thesis itself. Developing region-specific transaction databases can be a challenging endeavor, but the ROI in terms of analysis and insight are substantial. Traditionally, one of the major impediments to studying (formal) water markets was the lack of access to transaction data, which hindered comprehensive analysis.

Without transaction data, it is extremely difficult to incorporate quantitative data analysis on volumes, costs, and user, all fundamental variables for market design.

It is worth acknowledging that, despite amassing over 2,000 transactions, there are limitations when conducting econometric analyses, particularly when dealing with basins with fewer transactions. Consequently, alternative methodologies may be required for analysis in basins with lower transaction volumes. Nevertheless, the organization of transaction data represents a crucial step toward advancing the design of water markets. It is my aspiration that this database will serve as an inspiration for fellow scholars and practitioners to expand the Texas Water Transactions database and create additional transaction databases in different geographic regions. There is a substantial opportunity for the development of a global transaction database, facilitating the mapping of trends across and within various geographic areas.

Another noteworthy empirical contribution is the quantification and illustration of groundwater-surface water interaction in the context of the San Saba River. As explained in Chapter 6, the competition between upstream and downstream users has generated discord within a community that shares the same river. The gain-loss studies, coupled with the longitudinal profile, have the potential to function as objective visual aids, fostering constructive dialogues regarding water use and allocation within the community. These visuals can be potent tools for conflict resolution as they illustrate where and when specific segments of the river contribute to groundwater and vice versa. Such insights hold profound implications for the self-organization and management of what essentially constitutes a single common pool resource. These visuals also excel in conveying complexity, transcending academic journals by making the information accessible to individuals with varying levels of formal education but a deeply rooted sense of place. In essence, these visuals paint, for the first time, a comprehensive picture of a complex system upon which its long-term sustainability hinges.

7.2.4 Implications for Decision Making

One of the most significant implications for decision making that comes from this thesis is the focus on prioritization. This theme reverberates throughout all three substantive chapters, each facet of prioritization playing a pivotal role in the realm of decision-making.

For instance, Chapter 4 underscores the importance of a prioritization approach, particularly in terms of aligning specific incentives with particular types of water scarcity. This method of prioritization holds significant potential in policymaking by assisting decision-makers in narrowing their focus within the domains of research, investment, and implementation, ensuring that the first critical tier of matching scarcity types with incentives is effectively met. Chapter 5 also provides a notable illustration of prioritization. If policymakers aspire to enhance the enabling conditions that foster increased water transactions, a comprehensive transactions database, replete with information on costs and volumes, provides valuable (nearly non-substitutable) data for decision makers to analyze. With a collection of transaction data spanning various basins, policymakers gain the capacity to prioritize interventions based on specific criteria that factor in pertinent socio-economic considerations at different decision making scales (e.g. irrigation district, groundwater management district, state level, etc.). Furthermore, by constructing econometric models to test hypotheses regarding the driving forces behind transactions, decision-makers can strategically design market mechanisms to leverage particular biophysical or socio-economic factors influenced by these transactions. These examples exemplify systematic policy analysis. The alternative, from a policy making decision is trial and error which can be costly and ineffective.

Chapter 6 offers a localized perspective on prioritization. For decision-makers interested in piloting or scaling projects involving environmental water transactions (EWTs), employing a methodology akin to Chapter 6 can quantify the costs and benefits of various spatially targeted interventions. Such precise spatial prioritization proves valuable to decision-makers navigating the utilization of incentives within existing governance structures, facilitating a comprehensive understanding of the costs juxtaposed with their public and private benefits.

By spatially prioritizing actions and comparing them to alternative scenarios (refer to spatial action mapping in Chapter 6), decision-makers can chart a cost-effective path that spans the project lifecycle from inception to scaling.

A second overarching counsel for decision-makers revolves around the idea that water markets must be tailored to fit specific contexts. This notion is echoed across all three substantive chapters, replete with examples spanning various scales. The underlying premise posits that just as water scarcity is a product of intricate interactions between supplies and demands, water markets are equally intricate due to the multifaceted nature of water's values. Hence, to ensure that a water market aligns with the geographical parameters and objectives, investing in market design is deemed essential, often necessitating accompanying data, financial resources, and governance structures. While this may entail high upfront costs, it is crucial to weigh them against the alternative, considering the expenses incurred when modifying a water market post-launch. Recent experiences in Australia serve as a stark reminder of these costs, impacting various user groups, including environmental considerations.

Lastly, Texas decision-makers should consider investing in research to explore conjunctive water use governance. This concept transcends the borders of Texas and holds appeal for water-scarce regions where groundwater and surface water interaction is extensive. As elucidated in Chapter 6, Texas' prevailing water laws treat surface water and groundwater disparately, despite their hydrological interconnectedness, incurring substantial costs for most water users. While those with the financial means may continue drilling new groundwater wells in the short term, long-term management necessitates a water governance framework that aligns with hydrological realities. Even if groundwater modeling remains imperfect, accounting for conjunctive water management represents a "low-hanging fruit" in policymaking, promising substantial returns over the medium and long term. This is chiefly because, without conjunctive use management, groundwater and surface water users find themselves in competition over a shared resource governed by disparate rules and protections. These asymmetries in legal protections and rights do not offer an incentive to change water use behavior in a way

that reflects the common pool resource on which they all depend. These discrepancies do not encourage shifts in water usage behavior toward more interdependent practices, which are essential for incentivizing sustainable water management in the long run.

7.2.5 Limitations and Future Research

Chapter 3 provided a comprehensive exploration of several limitations, encompassing both conceptual and methodological constraints. However, certain limitations extend across all three substantive chapters and warrant further discussion. One pervasive limitation relates to the inherent disparities between modeled data and empirical data. All three substantive chapters relied on modeled data in their methodologies to garner insights and inform the research. It is important to note that historically, hydrologic data has been modeled, owing to the difficulty in monitoring so many parameters. The study's design acknowledges the potential for future improvements in the resolution and precision of these models. Should advancements occur in model accuracy, they could be integrated into the research framework, enhancing its robustness and efficacy. Future work using remote sensing to monitor and model hydrological data holds promise to this end.

Another significant limitation pertains to the delineation of boundaries within a multi-scaled analysis like this thesis. Chapters 4, 5, and 6 each operated within distinct scales – global, state, and basin, respectively. While this approach yields valuable insights and timely contributions to the literature expounded upon in Chapter 1, it is imperative to recognize that these political boundaries (as seen in Chapters 4 and 5) may not necessarily align appropriately with other hydrological scales, such as aquifers and river basins. Consequently, from a methodological perspective, the integration of spatial analysis techniques is requisite to bridge data from one type of polygon to another (e.g., aquifer to state). Nevertheless, this process may not always reflect the underlying social-hydrological relationships accurately. This issue is a recurring topic in cartographic literature, exemplified by the United States' maps, wherein state boundaries in the Eastern United States historically followed natural geographical features like mountain

ranges and rivers, whereas in the Western United States, straight-line state boundaries deviate from physical geography.

Furthermore, representing the price and costs of water transactions poses a formidable challenge. Entire dissertations are dedicated to dissecting various facets of this intricate predicament, encompassing transaction costs, transportation costs, non-traditional valuations of water, and more. Consequently, in an interdisciplinary thesis like this, I was compelled to confine the spectrum of values that water could assume, acknowledging that these may not comprehensively capture the diversity of water users within a specific geographic context. A salient example lies in the price data within the transactions database detailed in Chapter 5. While most transactions included prices or price per acre-foot, closer scrutiny and analysis unveiled discrepancies – at times, transaction costs were incorporated, and lease terms featured uneven payments over the duration of the lease. Regrettably, this led to the exclusion of price data from the analysis. From an econometric standpoint, price is typically regarded as an ideal exogenous variable. However, in the pursuit of research integrity and adherence to the highest standards, it was imperative to exercise caution and refrain from utilizing unreliable price data. Future work on transactions databases should be careful to curate reliable price data, which although difficult to do, offers tremendous potential for academic contribution as well as decision-making.

7.2.6 Concluding Remarks

This research journey's destination was to identify viable pathways for market-based incentives to effectively address different types of water scarcity by reducing water demand and achieving a sustainable water balance. The journey necessitated a multifaceted, mixed-methods approach, standing on the shoulders of conservation practitioners and drawing from the reservoirs of scholarship within hydrology, economics, and governance. Along this journey, numerous challenges emerged, presenting both conceptual and methodological hurdles that called for interdisciplinary methodologies to augment the depth of our understanding.

In tackling an intricate issue like water scarcity, it is only fitting that we employ a multifaceted solution set. One of the chief merits of an interdisciplinary thesis lies in its ability to offer contributions across all the fields it encompasses. In this instance, hydrologists may glean fresh perspectives on water scarcity, considering its intricate ties to institutional dynamics, while economists may discern the friction between modeling water as both a commodity and a fundamental human right.

Furthermore, the multi-scaled nature of this thesis bears fruit in the sense that it yields valuable contributions when viewed holistically, yet each substantive chapter also imparts distinctive insights in isolation. It underscores the importance of adopting an interdisciplinary, multi-scalar approach when striving for sustainable water management through water markets. With this in mind, I hope that this thesis can serve as a guiding compass for future endeavors in this challenging and critical domain.

Chapter 8

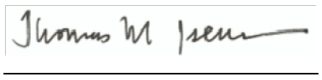
Appendix

8.1 Authorship Statements

As co-authors of the manuscript: *Mapping Incentives for Sustainable Water Use: Global Potential, Local Pathways*

We certify that Charles Wight completed the majority of the work for this article, which forms Chapter 4 of his DPhil Thesis:

Tom Iseman, The Nature Conservancy

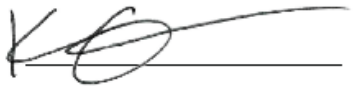


Dr. Dustin Garrick, University of Waterloo

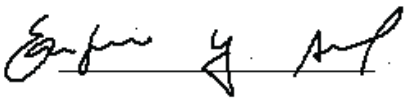
As co-authors of the manuscript: *Texas Water Markets: Taking stock of their trends, drivers, and future potential*

We certify that Charles Wight completed the majority of the work for this article, which forms Chapter 5 of his DPhil Thesis:

Kyle Garmany, TNC Texas



Dr. Eugenio Arima, University of Texas at Austin

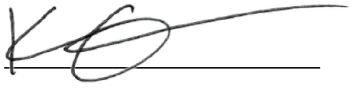


Dr. Dustin Garrick, University of Waterloo

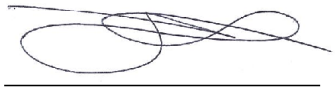
As co-authors of the manuscript: *Targets and Trade-offs: Designing Environmental Water transactions to navigate compounding competition in San Saba, Texas*

We certify that Charles Wight completed the majority of the work for this article, which forms Chapter 6 of his DPhil Thesis:

Kyle Garmany, The Nature Conservancy, Texas



Ryan Smith, The Nature Conservancy, Texas



Dr. Dustin Garrick, University of Waterloo