Governance of water use in agriculture: the role of innovation and regime type in sustainable agricultural water management

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In partial fulfillment of the requirements
for the Degree of
Doctor of Philosophy

Friedman School of Nutrition Science and Policy
Tufts University
Boston, MA

May 2018

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This work is dedicated to my spouse, Jaime and to my family

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Abstract

Background
Anthropogenic impacts to water systems pose a serious threat to water security across the world. Agriculture, as the largest user and one of the primary polluters of water, plays a central role in water problems. The impending global water crisis cannot be resolved without making agricultural impacts to water more sustainable. Water problems are complex, and many are the result of governance failures. Overcoming them requires innovative solutions attained through good governance. This dissertation presents analysis at different scales, aspects, and contexts of agricultural water governance.

Methods
This dissertation uses a variety of methods, including technological innovation systems analysis, identifying the presence of Ostrom's eight institutional design principles for sustainable management of common pool resources, and applying the social-ecological systems framework. Chapter 2 identifies blocking mechanisms and opportunities for a sustainability transition involving water harvesting practices in Jordan's rainfed agricultural system. Chapter 3 analyzes the extent to which three different U.S. state-level groundwater governance regimes reflect Water Diplomacy principles for sustainable groundwater quantity management. Chapter 4 identifies conditions within Nebraska's groundwater governance regime that are likely achieve groundwater quality goals relative to nonpoint source nitrate pollution.

Results
The water harvesting innovation system in Jordan's rainfed agricultural system is negatively impacted by limited financial resources at the national level, and the reliance on donors, as well as by the lack of a common vision for achieving sustainable agriculture water use, and informal and formal institutional problems. In the U.S., findings indicate that groundwater governance regimes reflecting Water Diplomacy principles can lead to adaptive and collaborative approaches to sustainable groundwater abstraction. Findings from Nebraska show that a nested, polycentric groundwater governance regime granting significant authority to empowered and transparent local governance entities can create the enabling conditions for managing groundwater quantity and quality sustainably.

Implications
Chapter 2 reinforces findings on the utility of the technological innovation systems approach for studying different types of developing country innovation systems in the context of sustainability transitions. It finds that donors can contribute to directionality problems that favor one form of a technology over another. Another finding is that formal and informal institutions can have equal impact in developing country sustainability transitions. Chapter 3 makes an important contribution to the discipline of Water Diplomacy, expanding the concepts to the water governance context. Chapter 4 marks a contribution to the limited literature base on governance of agricultural nonpoint source pollution. Using Nebraska as a case study, it highlights generalizable institutional design principles for the governance of agricultural nonpoint source groundwater pollution.

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CHAPTER 1: Introduction

BACKGROUND AND SIGNIFICANCE

Global water use has been growing at a rate of more than twice the rate of population growth in the last century, to a point where water services are no longer reliable in many regions (FAO, 2012). The 2030 Water Resources Group (2009) estimates that by the year 2030, in a business as usual scenario, global water demand will outstrip current available supply by 40 percent. As described in the Stockholm Statement to the 2012 United Nations Rio+20 Summit, "[t]his would place water, energy and food security at risk, increase public health costs, constrain economic development, lead to social and geopolitical tensions and cause lasting environmental damage" (SIWI, 2011).

Agriculture is the economic sector that faces the most pressing challenges with regards to water. It is responsible for approximately 70 percent of global freshwater withdrawals and more than 90 percent of its consumptive use (FAO, 2012). Global demand for crop calories is projected to double, requiring an increase in global crop production of between 70 to 110 percent, from 2005-2050 (Tilman et al., 2011). To meet increasing food demands, water withdrawals for agriculture will need to increase by 70 to 90 percent, unless dramatic improvements in crop water productivity are achieved (de Fraiture et al., 2007). Agriculture is also one of the primary sources of water pollution globally, and in the U.S. is the main source of pollution in rivers and streams, the second main source in wetlands, the third in lakes, and a principal source of groundwater pollution (Exner et al., 2014; Mateo-Sagasta et al., 2017; USEPA, 2018).

From a global water quantity perspective, there is enough water on the planet to meet human needs; human civilization has not yet reached the planetary boundary for water (Rockström et al., 2009). The challenge is one of distribution. Precipitation often does not fall where or when demand is highest and much of it cannot be captured for human use, this is particularly the case in semi-arid and arid regions (FAO, 2012; Rogers, 2008).

Many water problems, however, are less a result of the resource base itself and can instead be attributed to governance failures at multiple levels (Pahl-Wostl, 2017). Groundwater, for example – which offers a more reliable source of water than precipitation, can buffer droughts, and has been essential in lifting millions out of poverty – is experiencing overexploitation and pollution across much of the world, problems associated with poor governance and management (Shah, 2014). Thus, overcoming water problems requires innovative solutions attained through good governance.

Water Governance

The United Nations (2006, p.47) defines water governance as , "the range of political, social, economic and administrative systems that are in place, which directly or indirectly affect the use, development and management of water resources and the delivery of water services at different levels of society." Water is governed within the context of a social-ecological system (SES). An SES is an ecological system connected to and impacted by one or more social systems; it is a subset of social systems in which interdependent human relationships are deeply intertwined with interactions involving biophysical and non-human biological units (Anderies et al., 2004). Water, is also governed in the context of a common-pool resource (CPR). Virtually all water-related resources – ranging from the use of surface water and groundwater to fisheries – exhibit the qualities of a CPR, meaning that the resource base is sufficiently large to make it difficult to exclude users, and each individual's use reduces benefits to other users who share the resource (Ostrom, 2000; Pahl-Wostl, 2015).

Water governance occurs through regimes. Governance regimes are defined as, "the wide range of rules, norms, traditions and other institutional arrangements (laws, policies) by which decision making is exercised, enforced and modified, over time, by different actors" (Narayanan and Venot 2009, p. 321). Governance regimes are complex networks influenced by diverse interests and power relationships, characterized by self-organization, emergence, and diverse leadership (Pahl-Wostl, 2015). Thus, governance isn't just the organizations that manage a resource; it is the people, culture, and collective experience involved in the path to sustainable decisions. Effective governance is as much about the context of the SES being governed as it is about the policy instruments developed to govern them. There are no institutional panaceas that guarantee effective governance (Ostrom, 2007). Policy instruments that work in one place may fail in another.

There are, however, observable conditions that are frequently present in SES governance regimes that achieve or are likely to achieve sustainable governance of CPRs and that are robust enough to adapt to new problems as they emerge (Ostrom, 2008, 1990). Regimes that exhibit these qualities offer valuable insight on how to develop effective governance to meet sustainability goals. Alternatively, regimes that are failing to achieve effective governance can offer equally valuable insight. A wide, and growing, body of literature provides a range of methods that can be used to identify the characteristics of SES governance regimes that increase the likelihood that they achieve sustainable CPR governance (e.g. Anderies and Janssen, 2013; Frey, 2017; McGinnis and Ostrom, 2014; Ostrom, 2009).

Approaches to evaluating governance of SESs are complimentary with those of another field of research that is focused on sustainable outcomes, the field of sustainability transitions.

Linking SES research and sustainability transitions

The SES perspective is one of a coupled human-environment system, where socio-economic and biophysical forces interact to influence a resource system (which in the context of this dissertation is water) (Foran et al., 2014). The focus of sustainability transitions is principally on socio-technical systems (i.e. sectors like energy supply, water supply or transportation) (Markard et al., 2012). According to Markard et al. (2012, p. 956), "sustainability transitions are long-term, multi-dimensional, and fundamental transformation processes through which established socio-technical systems shift to more sustainable modes of production and consumption." Chapter 2 discusses how different aspects of a governance regime can act as enabling and blocking mechanisms in sustainability transitions.

It could be argued that the socio-technical focus of sustainability transitions effectively nests the discipline within the context of an SES. While both SESs and sustainability transitions involve multilevel, multiphase, and cross-scale processes (Olsson et al., 2014; Ostrom, 2009), sustainability transitions largely leave out the ecological perspective but maintain much of the social systems focus present in SESs. Thus, the sustainability transitions discipline can of value when analyzing desired systemic properties in components of a larger SES. This approach is relevant in situations where a sector (e.g. agriculture), or a sub-system of a sector (e.g. a specific agricultural production system), of a larger SES is the focus of specific technical or management interventions focused on making that sector more sustainable. That is the approach taken in Chapter 2 of this dissertation.

RESEARCH OBJECTIVES

The dissertation is composed of three main objectives, each designed to look at different aspects and contexts of agricultural water governance. The first objective (Chapter 2), is international in scope and examines governance within the context of a developing country, Jordan, pursuing a transition to greater sustainability in agricultural water use. It focuses on the systemic problems and opportunities in an emerging technological innovation system to achieving widespread implementation of a suite of sustainable agricultural practices, known as water harvesting.

The second and third objectives are domestic in scope and are principally concerned with groundwater governance regimes at the U.S. state level. Objective 2 (Chapter 3), focuses on the role of governance regime type in achieving sustainability goals for groundwater quantity. Objective 3 (Chapter 4) examines the role of regime type in the adaptability of a governance system to respond to emerging groundwater quality problems caused by nonpoint source agricultural pollution.

Objective 1: (Chapter 2)
Identify key blocking mechanisms and opportunities for a sustainability transition involving the integration of water harvesting practices into the Jordanian rainfed agricultural system.

- *Sub-objective 1.1:* Provide actionable knowledge on the water harvesting innovation system to inform the transition of Jordanian agriculture towards more sustainable water usage
- *Sub-objective 1.2:* Contribute to the broader debate on sustainability transitions in developing countries, for which literature is still limited.

Objective 2: (Chapter 3)
Identify the extent to which three different U.S. state-level groundwater governance regimes possess the principles needed for Water Diplomacy solutions for the sustainable management of groundwater quantity.

- *Sub-objective 2.1:* Expand the concept of Water Diplomacy to encompass groundwater governance

- *Sub-objective 2.2:* Assess where and to what extent Water Diplomacy principles are in use for groundwater governance in the High Plains Aquifer region of the U.S.

Objective 3: (Chapter 4)
Identify conditions within Nebraska's Natural Resource District groundwater governance regime that are likely limit nonpoint source pollution of nitrates into groundwater and lead to the eventual reduction of nitrate concentrations to safe levels.

- *Sub-objective 3.1:* Identify the enabling conditions that have led to one groundwater quality program achieving a successful downward trend in groundwater nitrate concentrations
- *Sub-objective 3.2:* Identify the enabling conditions that allowed for self-organizing by Natural Resource Districts to form two collaborative groundwater quality programs, overcoming potential governance scale imbalances
- *Sub-objective 3.3:* Identify generalizable aspects of the Natural Resource District groundwater quality governance regime that can be applied elsewhere as multiple states develop and improve plans to address agricultural nonpoint source groundwater pollution.

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CHAPTER 2: Transitions in Water Harvesting Practices in Jordan's Rainfed Agricultural Systems: Systemic Problems and Blocking Mechanisms in an Emerging Technological Innovation System

Written in the style of *Environmental Science and Policy*
Published Online August 8, 2017 http://dx.doi.org/10.1016/j.envsci.2017.08.010

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ABSTRACT

This study identifies systemic problems and opportunities for transitions in water harvesting – a water conserving agricultural practice – in the context of a developing country pursuing greater agricultural sustainability. We utilize a combined and enriched functional-structural technological innovation system (TIS) analysis to identify systemic problems in the water harvesting TIS in rainfed agricultural production systems of Jordan. Results indicate Jordanian water harvesting TIS development is hindered by three principal blocking mechanisms: 1) inadequate financial resources to support innovation; 2) lack of a common vision across government ministries; 3) institutional problems that inhibit legitimizing the technology. These challenges are caused by interlocking systemic problems, which indicate the need for integrated policy approaches and interventions. Our analysis reinforces the concept that in developing countries, donor interventions should be centrally considered because they play a role in influencing priorities throughout the system and in supporting TIS development. Donors can counteract TIS development and contribute to directionality problems that favor one form of the technology over another, which gives insufficient protection for the water harvesting TIS until markets for technologies form. This would require more effective coordination between different donors' efforts to develop critical mass in TIS development. We also show that cultural institutions and interactions between formal and informal land tenure laws play a significant role in causing an erosion of trust in the government and counter efforts to promote and engage farming communities in water harvesting activities and innovation. This requires recognition that, in developing countries, informal institutions may have the same status as formal institutions.

Keywords: Water harvesting, technological innovation systems analysis, sustainability transitions, transformational failures, developing country

INTRODUCTION

Population pressure, land degradation, and recent reductions in rainfall have led to concerns over the sustainability of dryland agricultural systems, which are often based on unsustainable extraction of surface and groundwater for irrigation (Qadir et al., 2007). Irrigation in some areas has reached its limits and results in aquifer depletion and salinization of agricultural lands. There has been a renewed interest in the utilization of water harvesting as a way of achieving sustainability transitions in water management (Humpal et al., 2012; Karrou et al., 2011; Qadir et al., 2007) – a diverse topic that has received considerable interest in transitions literature (see Brown et al., 2013; Fam et al., 2014; Moore et al., 2014; Van der Brugge and Rotmans, 2007).

Use of water harvesting as a supplemental water source dates back thousands of years (Critchley and Siegert, 1991; Oweis et al., 2001). Water harvesting is the collection and concentration of rainfall runoff from catchments for use in agricultural production, landscape restoration, erosion control, drought mitigation, and for domestic purposes (Karrou et al., 2011; Oweis et al., 2001; Ziadat et al., 2012). This practice is well-suited to dryland agricultural systems, where annual rainfall may be insufficient to meet crop water demand and where rainfall is unevenly distributed across the growing season – often coming in intense events interspersed with periods of little to no rain (Oweis et al. 2001; Oweis and Hachum 2006; Qadir et al. 2007). Water harvesting addresses one of the biggest challenges in dryland agricultural systems: precipitation is at its lowest point during the most sensitive growth stages (flowering and grain filling) of cereal and legume crops (Oweis and Hachum, 2006). Harvested water can be stored in the soil root zone of plants or in small reservoirs or cisterns for supplemental irrigation or for watering animals (Oweis et al. 2001; Qadir et al. 2007; Critchley and Siegert 1991).

Here we study the development and diffusion of water harvesting practices in the Middle-Eastern country of Jordan, which suffers from over-exploitation of groundwater and resultant landscape degradation. Different types of water harvesting practices are suitable for different agricultural zones and scales of production in the Middle East, and can be grouped into two primary categories: micro-catchment and macro-catchment systems (Critchley and Siegert, 1991; Oweis et al., 2001). According to Oweis et al. (2001), micro-catchment systems are typically employed on individual farms and divert surface runoff from a small catchment area (ranging in size from a few square meters to 1000 m^2). Macro-catchment systems are characterized by having runoff water collected from a catchment area greater than 1000 m^2. Two commonly used macro-catchment systems in the region are *marabs*[1] and *hafirs*[2] (See S-1 in Supplementary Material).

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[1] A *Marab* is a natural formation at the end of a *wadi* (a valley or channel that is dry except for in the rainy season) where the water flow terminates. In a *Marab* system, a series of check dams or bunds are built to slow the flow of water. As one check dam fills to capacity, the water flows around the edges and down to the next dam. Behind each check dam or bund, water and sediment accumulate allowing for cultivation of crops, usually barley.

[2] In a *hafir* system, a water channel is built off of a *wadi* along with a diversion that allows a flow of water to fill up a holding pond or reservoir

The Jordanian government has identified the expansion of water harvesting as an important component in addressing the hydrological challenges in the agricultural sector (Ministry of Water and Irrigation, 2016). Multiple stakeholders, including government ministries, research centers, non-governmental organizations, and donors, are working to increase the improvement, adaptation, and integration of water harvesting within the agricultural system. Despite these efforts, rainwater harvesting practices are not widely implemented in Jordan (Ziadat et al., 2012). While several water harvesting projects exist, this sustainability transition in water management encounters significant challenges.

This paper focuses on the water management transition in Jordan, with a specific focus on water harvesting. This contributes to a developing body of work on sustainability transitions in developing countries, which has focused on: 1) different regions in the developing world where sustainability transitions take place, 2) the different types of transitions (i.e. sustainability issues addressed and technologies to replace incumbent technologies), and 3) the different systems analytical approaches used. Geographically, the focus has primarily been in Asia (e.g. Lachman, 2013) and Africa (e.g. Acheampong et al., 2016; Romijn and Caniëls, 2011) and minimally on Latin America (exceptions include Marques et al., 2010; Mejía-Dugand et al., 2013) and the Middle East (exceptions include Bichai et al., 2016; Moallemi et al., 2014; Vidican, 2015). The types of transitions studied have mainly been energy production, water management, and sustainable and urban development (e.g. Acheampong et al., 2016; Bai et al., 2009; Hamann and April, 2013; Meijerink and Huitema, 2010). Different frameworks from the family of transition approaches (Markard et al., 2012) have been used, such as multi-level perspective (MLP) and technological innovation system (TIS) analysis. TIS analyses in particular have increased in in recent years (e.g. Binz et al., 2014; Gosens et al., 2015; Murphy, 2015).

In developing countries, formal institutional, legal, and regulatory frameworks are generally weak and have less reliable enforcement mechanisms, and the institutional frameworks on which innovation systems are built tend to be more informal (Altenburg, 2009; Szogs et al., 2011). Limited national financial capital has a negative impact on developing economically productive and competitive markets and on education systems (Altenburg, 2009). Political instability can act as a barrier to innovation through negatively impacting the quality of scientific institutions, inhibiting collaboration between universities and private industry, reducing the availability of scientists and engineers, and by retarding pro-business reforms that encourage entrepreneurial activities (Allard et al., 2012). Donors providing development assistance partly fill financial and capability voids and impact developing country sustainability transitions in two primary ways: 1) by supporting niche level experiments, such as through projects demonstrating the feasibility of specific technologies; or 2) by directly intervening at the regime level, such as through projects that actively work to overthrow existing technological and/or policy regimes (Hansen and Nygaard, 2013; Marquardt, 2015). Donors can also potentially play the role of intermediaries (Szogs et al., 2011) or so-called ‘institutional entrepreneurs’ (Farla et al., 2012; Jolly et al., 2016) in emerging TIS, acting as catalysts for change by building linkages between users, consumers, and producers to stimulate entrepreneurial activities.

While the body of work on sustainability transitions in developing countries is growing, there is still a lack of knowledge on transitions in specific regions of the world and a need to analyze the different conditions that impact transitions in them, as well as how issues such as prominence of informal institutions, underdeveloped markets, lack of capacity, political instability, and reliance on donors work out in these different contexts (Bergek et al., 2015). The scarce literature on transitions specific to the Middle East has primarily focused on renewable energy (e.g. Moallemi et al. 2014; Vidican 2015; Vidican et al. 2012) and very little on water (an exception includes Bichai et al. 2016). In view of this literature gap, we present a study on a type of technology that has not been researched from a transition perspective – water harvesting – in an understudied region – the Middle East. In line with the trend of using the TIS approach for analyzing transitions in developing countries (e.g. Binz et al., 2014; Gosens et al., 2015; Murphy, 2015), we do a TIS analysis to identify key blocking mechanisms and opportunities for the integration of water harvesting practices into the Jordanian rainfed agricultural system, which we consider a sustainability transition. In doing this TIS analysis, the paper aims to realize two concrete goals: 1) specifically to provide actionable knowledge on the water harvesting innovation system to inform the transition of Jordanian agriculture towards more sustainable water usage; and 2) to contribute to the broader debate on sustainability transitions in developing countries (Berkhout et al., 2010; Markard et al., 2012; Rehman et al., 2010; Romijn et al., 2010; Hansen et al., *this issue*; Wieczorek and Romijn, *this issue*), for which literature is still limited.

The remainder of this paper is structured as follows. Section 2 presents the analytical framework. Section 3 describes the research methodology, which includes the case introduction and scope of analysis and the methods for identifying systemic problems and for data collection. Section 4 presents the analysis and blocking mechanisms hindering the development of the water harvesting TIS. The discussion and conclusion are found in section 5, which includes policy recommendations and the contributions of this paper to the broader literature base.

ANALYTICAL FRAMEWORK: COMBINING FUNCTIONAL-STRUCTURAL TIS ANALYSIS WITH THE COMPREHENSIVE TRANSFORMATIVE FAILURES FRAMEWORK

Bergek et al. (2008, p.408) define TIS as, “socio-technical systems focused on the development, diffusion and use of a particular technology (in terms of knowledge, product or both).” A TIS may be a sub-system of a sectoral system (in this case agriculture). TIS analysis can be used to analyze and assess the barriers and drivers of a niche as it grows and "institutionalizes" to further challenge the existing regime (Markard and Truffer, 2008).

Following earlier transitions studies in developing and developed countries (e.g. Andersen, 2015; Blum et al., 2015; Gosens et al., 2015), we utilize the TIS approach to analyze the dynamics of developments in water harvesting in Jordan to overcome the current regime, which is characterized by overuse of groundwater for irrigation and rangeland degradation caused by overgrazing. For doing so, a TIS should employ a set of seven functions. The seven functions as described in Hekkert et al. (2007) are (See S-2 in Supplementary Material for more detail):

1. Knowledge development
2. Knowledge diffusion through networks
3. Influence on the direction of the search
4. Entrepreneurial activities
5. Market formation
6. Creation of legitimacy
7. Resource mobilization

The execution of those functions is influenced by the presence and quality of four structural components, in which we follow the classification by Wieczorek and Hekkert (2012): *actors, institutions such as regulations, norms, and values), interactions in networks of actors,* and *infrastructure such as physical, knowledge, and financial infrastructure* (See S-3 in Supplementary Material for more detail).

The combined functional-structural TIS analysis first analyzes the functions of the system, followed by a second-tier examination of the performance of each of the functions through the lens of the four structural elements (see Wieczorek & Hekkert 2012). When a function does not perform well, this can be traced back to systemic failures or problems in one or more of the structural elements (Wieczorek and Hekkert, 2012) (See S-4 in Supplementary Material for full description of systemic problems). Often, these failures or problems have causal relationships that lead to blocking mechansisms (Turner et al., 2016). The blocking mechanisms are clusters of interrelated systemic problems (structural, transformational, and market), which can cause vicious cycles that negatively impact the functioning of the system (Klein-Woolthuis et al., 2005; Weber and Rohracher, 2012). These link to what Weber & Rohracher (2012) have called, transformational failures, which can be considered higher-level failures, to complement the existing structural problems specific to long-term transitions. We extend the current combined functional-structural TIS analysis to include these transformational failures. Different authors use the terms "failures" and "problems" synonymously; in line with Wieczorek and Hekkert (2012) we refer to them as systemic problems.

METHODS

This section first describes the case study area and the spatial, temporal, and technological scope of the research. We then discuss the methods used for identifying the systemic problems in the TIS and close with a description of the data collection methods.

Case introduction and scope of analysis

Country context – Jordan's rainfed agricultural system and water harvesting

Jordan's population of about 9.5 million people is expected to double by 2050 (Ministry of Water and Irrigation, 2016). Jordan is one of the most water scarce countries in the world. Its current annual renewable per capita water resources are less than 100 m^3 (Ministry of Water and Irrigation, 2016), placing it well below the water stress index threshold for absolute water scarcity of 500 m^3 per capita per year (Falkenmark et al., 1989). The water shortage in Jordan is expected to become more severe over the coming decades, making the transition to a comprehensive approach to water management imperative (Humpal et al., 2012).

Agriculture is the largest water user in Jordan, accounting for approximately 60% of withdrawals (Ministry of Water and Irrigation, 2016). Despite representing only about 3-4% of Gross Domestic Product (GDP), agriculture is the main source of income for about 15% of the population, employs about 6% of the workforce, supports export-oriented value chains, and supports a large number in jobs in parts of the country where alternative job creation is difficult (Ministry of Water and Irrigation, 2016; Salman et al., 2016). Water harvesting can play a significant role in addressing the hydrological pressures from agriculture by reducing the amount of groundwater pumped from dwindling aquifers in Jordan, and can improve water security for vulnerable farming and grazing communities in the parts of the country with the greatest variability in rainfall and climate (Salman et al., 2016).

The country is divided into three major agricultural zones, each with different cropping patterns and water resources: the Jordan Valley, the Highlands, and the Badia (See Map S-6 in Supplementary Materials). Agriculture in the Jordan Valley is characterized by the use of surface water and treated wastewater for irrigation of higher-value crops for domestic use and export (Talozi et al., 2015). Agricultural water use efficiency in the Jordan Valley is relatively high thanks to requirements by the Ministry of Water and Irrigation (MWI) /Jordan Valley Authority (JVA) that farmers use drip and micro sprinklers (Humpal et al., 2012).

The Highlands were traditionally a rainfed agricultural system, and rainfed production continues in the areas that receive sufficient rainfall. Beginning in the 1980s, irrigated agriculture using groundwater from the underlying aquifers began to play a more prominent role in the Highland agricultural system (Salameh, 2008). Irrigated olive production, which would be unprofitable without a regime of subsidies, accounts for roughly half of the Highlands water demand (Humpal et al., 2012). The 2002 Underground Water Control Bylaw (see Figure 1) (THKJ, 2002) put in place surcharges for groundwater abstraction and appears to have slowed the rate of decline. However, abstraction is still unsustainable, and groundwater levels in the Highlands are declining by at least 1m per year (Humpal et al., 2012).

The Badia region, comprising about 80% of Jordan's area, is the driest of the agricultural zones, receiving less than 200mm of rainfall annually (ICARDA, 2016a). It is characterized by sparsely vegetated rangeland that decreases in precipitation moving southward (Ministry of Agriculture, 2013). Some groundwater abstraction occurs in limited areas for irrigation of vegetables, fruit trees, and field crops (Ministry of

Agriculture, 2013; Talozi et al., 2015), but the majority of the Badia is characterized by livestock grazing (Interviews 12,21). The landscape has been severely degraded due to overgrazing and climate change (Akroush and Telleria, 2013; World Bank, 2012).

Boundaries and history of the case under study

The *geographical boundary* of the system under study is the region consisting of the Highlands and the Badia. We exclude the Jordan Valley from our analysis primarily because efforts to promote widespread water harvesting in agriculture have focused on the Highlands and Badia, but also because agriculture in the Jordan Valley is significantly different from the other two regions, as described above.

There are a number of factors that make the Highlands and Badia suitable for widespread water harvesting: both include traditionally rainfed agricultural systems where there is a history of water harvesting use and that are now suffering from rainfall shortages; both have highly variable agricultural production and are experiencing land degradation; and neither have a steady supply of surface water for irrigation, making them reliant on rapidly depleting groundwater (Abu-Sharar, 2006; Interview 13). Specific foci for water harvesting in the Badia are remediation of widespread land degradation caused by livestock overgrazing and production of fodder crops for livestock feed. Water harvesting practices can stabilize crop production, restore degraded land, and provide a source of supplemental irrigation (Karrou et al., 2011; Oweis et al., 2001).

The *technological boundary* of the system is water harvesting for agricultural production and ecological restoration, and excludes domestic and urban use. Water harvesting exists within a broader agricultural system and its innovation is impacted by laws, strategies, and projects that are focused more broadly on agricultural water conservation. As a result, some interview responses included discussion of this broader context. We include this broader context only where it impacts and enriches the understanding of the water harvesting TIS functions.

The *temporal boundary* of the system focuses on the modern era of agricultural production in Jordan, ranging from 1960 to 2016, when data were collected for this research. The thrust of our analysis is water harvesting innovation in the last 24 years after water harvesting research began in the region in approximately 1992 to where the system was in 2016, but to sketch the overall context a timeline is given of the 1960-2016 period. This includes key events that have impacted current drivers and barriers in the water harvesting innovation system, including the build-up of an irrigation-oriented regime since the 1960s.

Figure 1 shows these key events. Four multi-year periods (indicated in brackets on the timeline) show transitional eras that affected the usage of water harvesting today. The introduction of diesel powered groundwater pumps in the 1960s and a boom in irrigated agriculture fueled by the introduction of modern irrigation and cropping techniques in the 1970s and 1980s were largely responsible for the displacement of water harvesting practices in the traditionally rainfed production systems (Demilecamps, 2010). The mid-

1990s marked the start of research on the applicability of water harvesting practices to modern agriculture (Oweis and Taimeh, 1996; Interview 2). Beginning around 1960, the government began a program to settle pastoralist, nomadic Bedouin tribes in the Highlands by convincing them to adopt groundwater-irrigated agriculture (Demilecamps, 2010). Relevant organizational, project, and geopolitical landmarks are also indicated in Figure 1, as are strategy documents and laws that identify water harvesting as an important element to achieving sustainability or that were intended to reduce the impact of groundwater abstraction.

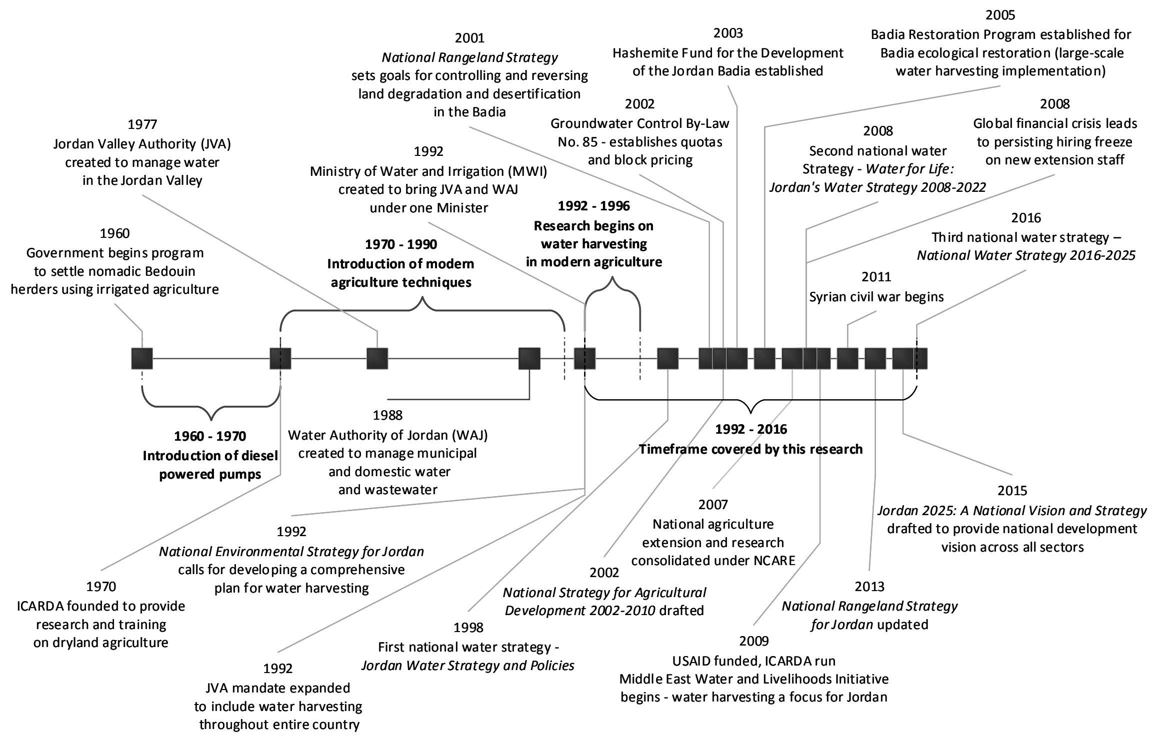

Figure 1: Key events in recent history impacting the water harvesting innovation system (compiled from interviews and *Badia Restoration Program, 2016; Demilecamps, 2010; Humpal et al., 2012; ICARDA, 2016b; MercyCorps, 2016; Ministry of Agriculture, 2013; Ministry of Municipal, 1991; Ministry of Water and Irrigation, 2016; Oweis and Taimeh, 1996; World Bank, 2012)*

Methods for identification of systemic problems

Following Turner et al. (2016) and Wesseling and Van der Vooren (2016), this analysis is carried out for all of the functions (see S-2 in Supplemental Information) in the system as well as for the systemic problems (See S-4 in Supplemental Information) that contribute to the weaknesses. The sequence in which the different functions appear in the literature varies by publication, and because they are mutually reinforcing they are sometimes combined (Hekkert et al., 2007; Turner et al., 2016). In our analysis, we combine the *knowledge development* and *knowledge diffusion through networks* functions together into one function called, *knowledge development and diffusion* because they are tightly interconnected in the Jordanian water harvesting TIS. Evidence of this interconnectivity is discussed in section 4.1.1.

The results of the functional-structural analysis for identifying systemic problems in the Jordanian water harvesting TIS is summarized in Table 1 and described in greater detail in sections 4.1.1-4.1.6. The conditions impacting each system function are described in the sections below, and the systemic problems impacting them are indicated in brackets (i.e. […]).

Table 1: Functional-structural analysis identifying systemic problems in the water harvesting TIS

System Function	**Systemic Problems Hindering Function**	**Description of links between systemic problems**
Knowledge development and diffusion	- Capabilities - Demand articulation - Network - Formal institutional - Knowledge infrastructure - Information asymmetry - Reflexivity	Financial capabilities problems hinder the capacity of the national extension system[3], negatively impacting end-user engagement in innovation and causing demand articulation problems and information asymmetry. Capabilities problems negatively impact the development of a knowledge network and infrastructure, and increase reliance on donors. When donor funded projects end, there are no policies in place to ensure project continuity, representing formal institutional and reflexivity problems.
Influence on the direction of the search	- Capabilities - Directionality - Policy coordination	Financial capabilities problems leave the country reliant on donors to manage refugees. Donor and government focus on engineering-oriented water harvesting at the expense of on-farm micro-catchment systems represents a directionality problem. Lack of a common vision and policy coordination problems between government organizations negatively impacts complementary policies and hinders agricultural extension's engagement in the TIS.
Entrepreneurial activities	- Capabilities - Demand articulation - Directionality - Formal institutional - Physical infrastructure - Information asymmetry - Reflexivity	Entrepreneurial activities are mostly limited to donor projects, and resources to encourage private sector carry-over after project completion are not in place, representing directionality, capabilities, and reflexivity problems. Low value production systems in the Badia provide little motivation for farmer investment and demand for private sector goods and services, representing information asymmetry and demand articulation problems. Infrastructure problems pose challenges for marketing and distribution of higher value goods. Formal institutional problems (i.e. subsidies) reduce demand by farmers for water harvesting.
Market formation	- Directionality - Formal institutional - Informal institutional - Physical infrastructure - Financial infrastructure - Information asymmetry	Incumbent groundwater subsidy regimes influenced by formal and informal institutional problems favor existing production practices and discourage formation of a market for water harvesting. Continuation of these subsidies represents a directionality problem. Lack of financial infrastructure for providing loans and credit for water harvesting hinders the formation of a market. Physical and financial infrastructure are insufficient to develop a market for higher-value crops that could be produced using water harvesting.
Creation of legitimacy	- Capabilities - Informal institutional - Formal institutional - Physical infrastructure - Knowledge infrastructure - Financial infrastructure - Reflexivity	Incumbent groundwater subsidy regimes influenced by formal and informal institutional problems favor the existing production regime and negatively impact the legitimacy of water harvesting. The informal institutional problem of *wasta* negatively impacts farmer engagement in the innovation process. Land tenure laws and culture perpetuate the existing production regimes, representing formal and informal institutional problems. Capabilities, financial infrastructure, knowledge infrastructure, and reflexivity problems lead to insufficient maintenance of water harvesting systems and impact legitimacy. Insufficient maintenance negatively impacts the physical infrastructure of larger water harvesting systems.

[3] Agricultural extension is a common name for dedicated advisory services aimed at farmers

Resource mobilization	- Capabilities - Directionality - Formal institutional - Physical infrastructure	A directionality problem does not prioritize campaigns to build water scarcity awareness in agricultural communities, and financial capabilities problems would make any such campaign dependent on donor funds. Directionality and formal institutional problems impact the development of financial infrastructure for providing credit, loans, and a subsidy regime for developing the water harvesting TIS. Infrastructure problems manifesting in the lack of a suitable physical infrastructure for distributing higher-value crops are primarily driven by capabilities problems to build and maintain them.

Data collection methods

Our study was based on semi-structured interviews (primary data), complemented with a literature review (secondary data), a method common in TIS analyses (Bergek et al., 2008; Blum et al., 2015; Wesseling and Van der Vooren, 2016; Wieczorek et al., 2015). Semi-structured interviews allow for flexibility, so the interviewer can focus on interesting comments and on aspects of the topic on which interviewees have more expertise (Bruges and Smith, 2009; Turner et al., 2016). Interview questions were designed to cover two aspects of the analytical framework: *functions*, to show how well the innovation system is working (Bergek et al., 2008; Hekkert et al., 2007; Wieczorek and Hekkert, 2012) and the *structural components* that can cause blocking mechanisms in the innovation system (Wieczorek and Hekkert, 2012) (See S-5 in Supplementary Material for interview questions). The question format consisted of 22 overarching questions with probing follow-up questions designed to elicit in-depth responses, from which both aspects of the analytical framework could be assessed. The interviews systematically covered all functions for each respondent.

We conducted a pilot study in Jordan in spring 2015 to refine the scope of the research and interview questions and to develop a list of interviewees. For this pilot, we selected twelve potential interview participants who are experts on water harvesting and agricultural water conservation in Jordan. Using snowball sampling, we identified a list of potential interviewees and scheduled interviews for May of 2016. Twenty-four interviews were conducted with a diverse set of subject matter experts representing: Jordanian government ministries and national research centers (10), non-governmental research centers and universities (6), international donors (4), non-governmental organizations (NGOs) (2), and the private sector (2). All relevant stakeholder groups were included to develop a clear picture of the functions and structure of the TIS, and the sample of interviewees represented local, national, and international stakeholders (Blum et al., 2015). Nineteen of the interview respondents were Jordanian nationals, representing each of the stakeholder groups. The identity of each respondent is protected by randomly rearranging the order of their interviews and assigning an anonymous interview number (e.g. Interview 1).

Each interview was conducted either in-person or over internet telephony and took 45 to 90 minutes. The interviews were recorded and transcribed for analysis using the NVivo for Mac software package (Version 11.3.2; QSR International, 2016)[4]. Interview

[4] http://www.qsrinternational.com/nvivo-product

responses were coded based on the functions and systemic problems discussed in Section 2 of this paper.

Secondary data sources were consulted to supplement interviews and, where possible, to verify certain claims by interviewees. Secondary data include reports from international donors, research centers, and NGOs (e.g. Humpal et al., 2012; ICARDA, 2016a; Karrou et al., 2011; Salman et al., 2016), national policy documents (e.g. Government of Jordan, 2015; Ministry of Agriculture, 2013; Ministry of Water and Irrigation, 2016), and peer reviewed studies on water harvesting in Jordan (e.g. Akroush et al., 2017; Akroush and Telleria, 2013; Ziadat et al., 2012). However, the peer reviewed literature specific to water harvesting in Jordan turned out to be of limited utility due to the narrow scope of the papers on either farmer adoption of the practices in specific pilot-study communities (Akroush et al., 2017; Akroush and Telleria, 2013) or on assessing the biophysical suitability of rainwater harvesting (Ziadat et al., 2012), but did provide additional insights.

RESULTS AND ANALYSIS

This section first discusses the functional-structural analysis to identify barriers to innovation within the TIS and to highlight potential opportunities within the innovation system. The section closes with an analysis of the structural conditions of systemic problems and how these create blocking mechanisms.

Functional-structural analysis

Knowledge development and diffusion

Knowledge development and diffusion is primarily affected by two systems conditions: 1) the involvement of donors in building capacity for water harvesting innovation; and 2) capabilities problems within the public extension system (i.e. agricultural advisory services).

Multiple interviewees indicated donor involvement plays a positive role. The Middle East Water and Livelihoods Initiative (WLI) (see Figure 1), a regional project funded by the United States Agency for International Development (USAID) and implemented through the International Center for Agricultural Research in the Dry Areas (ICARDA), was mentioned as playing such a role. In Jordan, ICARDA works with the National Center for Agriculture Research and Extension (NCARE) building capacity there and engaging with farmers to innovate water harvesting practices.

In a well-functioning extension system, a knowledge network utilizes feedback mechanisms to innovate a technology or set of practices – end-user experience is relayed to research and research knowledge to end-users through extension, which builds legitimacy and demand for the technology (Rivera and Sulaiman, 2009). Most donor-funded water harvesting projects have these feedback mechanisms in place, but donors must allocate limited resources throughout the country across multiple priority areas (Interview 6). When a donor project reaches the end of its funding cycle, support for knowledge development and diffusion activities either ends or is significantly diminished, leading to problems of continuity [formal institutional, reflexivity problems] (Interview 6). Additionally, only a small number of donors are focused on water harvesting (and even then not as a top priority), and each donor project only engages with a small subset of government partners and has a relatively small number of demonstration projects [network problem]. As a result, the community of actors focused on water harvesting is rather small and somewhat insular when compared to other priority areas (e.g. refugee response and urban water management), impacting engagement with farmers to build widespread awareness of the water crisis and benefits of water harvesting (Interviews 2,7,8,13,19).

The primary public organization responsible for water harvesting research and extension activities is NCARE, which is a semi-autonomous organization with its own Director General under the authority of the Ministry of Agriculture (MoA). Despite the positive collaborative activities discussed above, eight interviewees spoke of severe capacity challenges within NCARE [capabilities problem]. There are currently only 70 extension officers for the entire country, with little technical specialization and advanced training, and without the financial resources to attend additional training abroad (Interviews 9,11,15,22). The understaffed extension system is an outcome of the 2007-2008 global financial crisis, which led to a hiring freeze on new extension officers that remains in place (See Figure 1) (Interview 2). In many countries, universities also play a role in connecting research and extension. However, only two universities, the University of Jordan and the Jordan University of Science and Technology, have any substantive research on water harvesting, and they are limited by a lack of financial resources [capabilities, knowledge infrastructure problems] (Interview 12).

The capabilities, institutional, network, knowledge infrastructure, and reflexivity problems in the system lead to interaction with only a small subset of farmers. As a result, their demand for water harvesting and their goals for its utilization are not known, and their involvement in the innovation system is limited.

Influence on the direction of the search

Influence on the direction of the search refers to the development of a common vision for the innovation system and orientation of other functions towards that vision (Turner et al., 2016). There are three key elements that significantly affect this function: 1) the current influx of refugees from Syria and Iraq have impacted development planning at the national level and contribute to Jordan's dependency on international donors; 2) the priorities of international donor organizations play an important role in defining the agenda for development across the whole country, and priorities differ between donors; and 3) a lack of policy coordination and a common vision for agricultural water management between key ministries has negatively impacted water harvesting innovation.

There are more than 1.4 million refugees in Jordan, with over 650,000 having come from Syria since 2011 (Ministry of Water and Irrigation, 2016; UNHCR, 2016). Responding to the refugee crisis has seriously strained Jordan's water and financial resources, making it more reliant on donor aid [capabilities problem] and has contributed to the prioritization of resources for short-term crisis response over mobilization towards long-term development goals [directionality problem] (Interviews 2,3,15).

Donor aid influences the direction of the search in both positive and negative ways. On the positive side, donors have priorities for how aid money is spent and conditions that the government must meet to receive it. As a result, donor priorities often become the priorities of the different government ministries that receive aid money (Interviews 3,6,7,9,13,15,19). Water harvesting was initially prioritized almost exclusively by donors, and most of the activities are still donor-driven in some form (Interviews 3,9). By prioritizing water harvesting, donors have begun to influence the direction of the search towards the practices within different ministries, even while the government struggles to respond to the refugee crisis.

On the negative side, donors have contributed to the focus on engineering-oriented or industrial-scale water harvesting technologies at the expense of simpler, on-farm micro-catchment systems. Research has shown the benefits and applicability of both types of water harvesting (Oweis and Hachum, 2006). Interviewees noted that the focus on *only* the engineering/industrial water harvesting types, rather than on *both* those and the on-farm micro-catchment types, leaves out of the system a set of important water harvesting practices that could be highly beneficial in achieving greater agricultural sustainability [directionality problem] (Interviews 17,18,20). There is anecdotal evidence that these farm-level micro-catchment systems are widely used, but there have been no studies on the extent of their use, how the innovation system for these systems functions, and what the demand among farmers is for them (Interviews 2,17,18,20).

One reason for the lack of focus on these systems is the lack of resources to study them [capabilities problem] (Interviews 17,20). However, the preference towards the engineering/industrial water harvesting technologies is also partially due to the requirement for donors to produce measurable indicators of success at the end of the project cycle (Interviews 11,17,18,20). The construction of *marabs* or *hafirs* is more quantifiable over the timeframe of a project than changes in behavior and individual values (Interview 18). While the donor project cycle contributes to directionality problems, conditions endemic to the different Jordanian government organizations involved with water harvesting play a more significant role.

Many respondents indicated that there is no common vision for water conservation in agriculture, ecological restoration of degraded lands, or innovation of water harvesting practices across relevant government organizations (Interviews 2,3,6,9,10,12,13,17,18, 20,22,23). There is also very little collaboration on water harvesting projects between the MWI, MoA, and NCARE [policy coordination problem] (Interviews 6,13,22). Each ministry has its own vision for agricultural water management, and their strategies are developed without extensive policy coordination with other ministries [directionality, network, policy coordination problems] (Interview 2). It was also noted that these ministries do not readily share centralized databases, so information on groundwater levels, runoff, and irrigation water volumes, for instance, can deviate between ministries by as much as 10% (Interview 20).

Entrepreneurial activities

The unique nature of water harvesting from the technical perspective and the agricultural systems of the of the Badia and drier parts of the Highlands impact opportunities for entrepreneurial activities in ways that traditional TIS studies do not normally see. Within these contexts, it is important to identify who the potential entrepreneurs in the TIS are.

Water harvesting differs from the types of technologies frequently analyzed in TIS studies because it is a suite of practices and low-tech solutions based on agricultural practices that pre-date modern agriculture, rather than a technology in the traditional sense. Thus, water harvesting can be considered a “retro-innovation”, as it combines a set of ancient practices with modern ones and configures them to meet current and future needs (Stuiver, 2006; Marques et al., 2010). In this case, the land preparation techniques for the different water harvesting modes have been known for a long time, but now they can be prepared with modern and sometimes specialized machinery.

Private sector entrepreneurial activities are challenged by the fact that, given its characteristic as a retro-innovation, water harvesting presents less of an opportunity for a tangible marketable product than do other higher-tech agricultural technologies, such as precision irrigation. The introduction of precision irrigation in the Jordan Valley provides an example of how private sector-driven change has traditionally occurred in the Jordanian agricultural sector. Entrepreneurs were engaged in the expansion of precision irrigation in the Valley because it is a technology used in the production of higher value crops, and one for which goods and replacement parts can be sold and for which private extension services can be marketed. The government mandate required its usage, and its linkage with higher-value crops meant that farmers could see a return on their investment and that entrepreneurs had a market for goods and services (Interview 6). These types of linkages are less obvious for water harvesting at first glance, and engaging entrepreneurs in this TIS requires a different approach, which will be discussed later in this section.

Entrepreneurial activity also links to the type of agriculture done in systems served by water harvesting. The production systems of the Badia and the drier areas of the Highlands suffer from low yields and produce low-value crops, or are rangeland grazing systems that produce fodder crops for livestock (Interviews 2,6,18). The low market value of the crop production system outputs and the nomadic nature of herding provide little motivation for farmers to invest in their production system, reducing demand for goods and services from the private sector [information asymmetry, demand articulation problem] (Interviews 2,6,13). Multiple interviewees spoke of production of higher-value crops as a precondition to any increase in private sector activity in the areas where crops are grown. In order for higher-value crops to have access to a market, both the marketing and transportation infrastructures would have to be improved [physical infrastructure problem] (Interviews 3,7). In the grazing agricultural systems, the motivation behind widespread water harvesting implementation is restoration of overgrazed, degraded land

and production of fodder crops in order to reduce grazing pressures (i.e. public or common good goals rather than private good goals).

To summarize, in light of these conditions, the opportunities for entrepreneurial activities in the Jordanian water harvesting TIS look different than what we commonly see in the TIS literature. Most interviewees thus did not have insight as to who the potential entrepreneurs are. However, two (Interviews 2,13) identified the following opportunities for entrepreneurial activities: 1) there is an opportunity for advisory and construction services for water harvesting systems, and due to the vast land area suitable for water harvesting and the maintenance requirements on some systems, there is the potential for repeat business for a company providing these services; 2) water harvesting could be integrated into production chains that produce higher-value crops or value added products; 3) there is an opportunity for establishing domestic production of specialized equipment used in certain types of water harvesting systems and marketing this equipment to entrepreneurs who can construct water harvesting systems across multiple farms; and 4) rangeland restoration using water harvesting in the Badia could be linked to international carbon accounting programs as a source of income from water harvesting activities.

Despite these potential opportunities, entrepreneurial activity is largely non-existent in the water harvesting TIS (Interviews 2,3,9). This is because the enabling environment is weak, with too many impediments and not enough incentives to investment for the private sector. The challenges facing private sector entrepreneurship in the Highlands and Badia are closely related to the *Knowledge Development and Diffusion* and *Creation of Legitimacy* functions and manifest in the current production systems, lack of financing mechanisms for loans for building water harvesting systems, subsidy regimes, and technology preference in existing projects. Interviewees offered differing opinions on whether these barriers could be overcome and whether private sector involvement in the water harvesting TIS could mirror that of precision irrigation in the Jordan Valley.

The persistence of the groundwater abstraction subsidy regime reduces the demand by farmers for water harvesting construction and private extension services [formal institutional problem] (Interviews 13,19). This is because where groundwater is available, it is a consistent source of water. Water harvesting can be impacted by rainfall variability, leading to uncertainty about how much water the technology will provide year over year (Interview 12). This causes uncertainty about whether it is financially prudent to invest in water harvesting and thereby impacts the formation of a market in which entrepreneurs can make money [information asymmetries].

Additionally, as noted in section 4.1.2, water harvesting activities have been dominated by the construction of engineering-oriented macro-catchment systems and by industrial scale installation of micro-catchment systems using a specialized plow [directionality problem]. This poses a challenge for a private-sector driven water harvesting market because macro-catchment systems like *hafirs* and *marabs* can impact watersheds in ways that could reduce access to water for others in the same watershed (Interviews 20,21). There is entrepreneurial opportunity in making the specialized plow commercially viable, but private sector involvement in the construction of these systems would require government oversight and/or permitting, which would put additional strain on the financial capabilities of government organizations.

While there is currently limited entrepreneurial activity in the water harvesting TIS among the private sector, donors could be considered partial or quasi-entrepreneurs. According to Hekkert and Negro (2009, p.586), "[t]he role of the entrepreneur is to turn the potential of new knowledge development, networks and markets into concrete action to generate and take advantage of business opportunities." Donor activities do play an integral role in directing knowledge generated from water harvesting research through networks to generate projects that provide employment and services (an example of this would be the USAID funded, ICARDA implemented WLI project). However, donor activities do not participate in a market for water harvesting goods and services, as this is generally outside of the scope of traditional international donor mandates.

Donors are engaged in a nascent effort to encourage entrepreneurial activity in the private sector. Many donor-funded projects require engagement with the private sector, so some projects have utilized private contractors for construction of water harvesting structures or have partnered with local consulting firms to assist in project management (Interviews 2,15,17,20). However, water harvesting activities currently remain almost completely project based, and the resources to encourage private sector carry-over after the completion of projects are not in place [reflexivity, directionality problems] (Interview 19).

Although currently unrelated to water harvesting, there are multiple projects being funded by international and domestic donors (e.g. the USAID Hydroponic Green Farming Initiative[5] and the Hashemite Fund for the Development of the Jordan Badia[6]) that are developing production systems and markets for higher value-crops through the introduction of hydroponic systems, developing nurseries to produce indigenous shrub species for restoration of the Badia, and building value added chains for milk processing. Projects like these have the potential to integrate water harvesting systems as sources of water. Integration of water harvesting into these projects is currently not in place, but one interviewee (2) spoke of this a being a potential opportunity for entrepreneurial activities.

Market formation

We noted in section 4.1.3 that information asymmetries on year over year water availability impact entrepreneurial activities for water harvesting. They also play a role in the development of a market for them. While variability in the amount of water that water harvesting provides does not inherently make it an undesirable technology, it does make it undesirable under current groundwater subsidies. In the driest parts of Jordan, water harvesting may not provide a reliable source of year-round water, but it can extend the time in which a farmer does not need to irrigate with groundwater by 3-9 months (Interviews 2,5). If the cost of irrigation water were not so artificially low, an investment

[5] https://www.usaid.gov/jordan/fact-sheets/usaid-hydroponic-green-farming-initiative-hgfi
[6] http://www.badiafund.gov.jo/en

in water harvesting could potentially be more desirable (see section 4.1.5 for more detail on subsidies). In effect, the incumbent subsidy regime is sustaining current production practices and discouraging the formation of a market for water harvesting [informal and formal institutional problems].

There is also no financial infrastructure for providing loans or credit for financing water harvesting activities to farmers and communities or for investment by the private sector [financial infrastructure, directionality problems] (Akroush et al., 2017; Interviews 1,4, 7,15,18,22). Nor are there any subsidy or cost share regimes in place to provide for the development of a market for water harvesting construction, maintenance, extension, and innovation (Interviews 1,7). Finally, as noted in section 4.1.3, the existing physical infrastructure in the Badia is not sufficient for a distribution system for higher-value crops, should there be a production system shift in that direction [physical infrastructure problem]. While the lack of financial infrastructure for providing loans and subsidies primarily represents directionality and formal institutional problems, the limitations within the physical infrastructure for distribution of higher-value crops (should a market for them be developed) is largely driven by the lack of financial capabilities to build and maintain this infrastructure across a large, sparsely populated area (Interviews 3,7).

Creation of legitimacy

For a technology or set of practices to develop effectively, legitimacy for it must be built to overthrow the current technological regime or to become part of it (Hekkert et al., 2007). In the case of the Jordanian water harvesting TIS, the following conditions block the creation of legitimacy: 1) subsidies on the cost of groundwater used for irrigation; 2) *wasta* (an Arabic word that translates loosely to ‘connections’, ‘clout’, or ‘influence’); 3) land tenure laws and customs; and 4) lack of carry-over from donor-funded projects.

The cost of groundwater for irrigation is driven by both the cultural aspects of water in Islam, under which the price of water should not exceed that of cost recovery [informal institutional problem] (Faruqui, 2001; Interviews 11,13,19), and by policies that subsidize the cost of energy for groundwater abstraction that lead to a unit price for water to farmers well below cost recovery [formal institutional problem] (Interviews 11,13,19). Analysis done by the 2030 Water Resources Group (2011) found that the average price Highland farmers pay for water from all sources is about JD 0.02/m^3 (1 JD=approx. 1.4 USD), while the true cost of bulk supply is JD 0.15, amounting to an approximate subsidy of JD 0.13/m^3 (Humpal et al., 2012). The Groundwater Control By-Law No. 85, passed in 2002 and amended in 2004 (See Figure 1) (THKJ, 2004, 2002) established a quota of 150,000 m^3/year, with the amount up to the quota being free and increasing block rate tariffs for amounts beyond that (Venot and Molle, 2008). The block rate tariffs were supposed to increase in the year 2008, but rates were not changed and have remained at the same rate as they were in 2002 (Humpal et al., 2012). Additionally, malfunctioning meters at rates as high as 40% are a recurring problem [physical infrastructure problem] (Venot and Molle, 2008).

Wasta was cited by 17 interviewees as being responsible for an erosion of trust in government, counteracting government efforts to promote water harvesting [informal institutional problem]. While cultural equivalents of *wasta* exist in many countries, its role in impacting legitimacy was so frequently cited that it deserves attention. Through *wasta*, powerful farmers in the Highlands have personal connections to upper levels of government (or in some cases are members of the government). This influence has been used to maintain the current system of subsidies for groundwater abstraction and olive production (Interviews 9,11,19). *Wasta* was also noted for its role in helping some individuals obtain influential jobs in government (Interview 22).

In the Highlands, land tenure and subsidized olive production are closely linked [informal and formal institutional problems]. This situation has its roots in policies from the 1960s to settle the nomadic Bedouin tribes (See Figure 1) (Interview 2). These policies included land ownership rules stipulating that sustained development of public land for over 15 years conferred ownership rights, and olive trees became the means through which sustained development was demonstrated (in fact, it is not clear whether this right is conferred more by tradition or by rule of law) (Humpal et al., 2012; Interview 2). Thus, land development confers ownership, olive production demonstrates development, and olive production is possible because of subsidized groundwater, which externalizes the true costs of production and acts as an economic deterrent to farming communities investing in water harvesting (Interviews 9,11,19). This type of land development has made a comparatively small number of Highland farmers wealthy and influential (Interview 2).

Multiple interviewees (Interviews 2,11,16,19,21) noted some promising initiatives that are working to build trust in government. In 2013, the Minister of Water and Irrigation began a campaign to cap illegal wells in the Highlands (Ministry of Water and Irrigation, 2016). This campaign has penalties for drilling illegal wells that include jail time and has even targeted political elites and tribal leaders engaged in illegal pumping. Two projects funded by USAID, the Non-Revenue Water project and the Improving Water Sector Management and Governance project, have partnered with the government of Jordan to increase capacity for monitoring and maintenance of well meters.

Land tenure in the Badia is also a legally grey area [informal and formal institutional problems]. Officially, much of the land is owned by the government, but from a cultural-historical point of view, many of the tribes in the Badia view it as their land, because they were using the land before the country of Jordan was established (Interview 21). Engagement with leaders of tribes that graze on traditionally communal land is important to build legitimacy for water harvesting landscape restoration projects (Interviews 17,21). Representatives from MoA and the Badia Restoration Program (BRP) acknowledged the importance of community engagement in the early phases of a project, but other interviewees (2,14) indicated that the necessary level of engagement is still insufficient (both from the government and donors), and that lack of trust in government hinders this engagement. Interviewees (1,2,9,13) noted that the projects run by ICARDA in the Badia effectively engaged local communities but failed to sufficiently coordinate with Bedouin groups who nomadically graze the areas. So at some of the project sites, while the local villages had buy-in, the Bedouin did not see the benefit of the program and grazed the shrubs that were being established.

Finally, legitimacy is negatively impacted when water harvesting activities fail to continue after the duration of a project [reflexivity problem]. Multiple interviewees noted that while some projects have effective end-user engagement during the project cycle, there are no effective policies in place to hand over projects once the cycle ends [formal institutional problem]. There are also insufficient follow-up studies after the completion of projects to see what kind of carryover they have over time, primarily due to limited financial resources [capabilities problem] (Interview 23). Most water harvesting systems require regular maintenance to function properly, and experience on some projects has shown that this maintenance has not been properly kept up after the after completion of the project. Three interviewees (2,18,20) noted that while the communities involved in the projects highly value the water harvesting systems, they did not have sufficient financial resources or training on the skills necessary to maintain them, which has links to the *knowledge development and diffusion* functions. This was especially the case with the larger, engineered water harvesting structures, such as *hafirs* and *marabs*.

Resource mobilization

While resource mobilization in the water harvesting TIS remains limited, there are some examples of a nascent activities in this direction. Examples of this by the Jordanian government include the BRP and the Hashemite Fund for Development of the Jordan Badia (HFDJB) (See Figure 1). Under the umbrella of the Ministry of Environment, and in collaboration with ICARDA, the BRP is researching, developing, and implementing industrial-scale water harvesting projects for ecological restoration in the Badia using a specialized plow (ICARDA, 2016a). The HFDJB is financing the construction of two *hafir* water harvesting systems in the Badia, which is being implemented by NCARE (HFDJB, 2016). Another example of resource mobilization is the campaign by MWI to cap illegal wells discussed in section 4.1.5.

Donors play the principal role in resource mobilization for water harvesting. The most direct example of this is the partnership developed with USAID, ICARDA, and NCARE in the WLI project. In the WLI, ICARDA has used USAID funding to conduct research and extension on water harvesting at benchmark sites in the Badia. They are implementing these activities in partnership with NCARE, working to build human capacity at the Center and overcome some of the capabilities problems discussed in section 4.1.1 (Interviews 7,13). These donor supported activities provide a mechanism through which field trials and feedback from farming communities can be used to innovate and improve water harvesting practices. It is unclear what the carry-over from this project will be once all activities are complete.

With funding from USAID, MWI launched a campaign in the cities to build awareness of the water shortage among domestic water users, but no resources have been mobilized for a similar campaign in the agricultural communities of the Highlands and Badia [directionality, capabilities problems] (Interviews 2,15). Not extending this awareness campaign to agricultural communities represents a directionality problem because it is not addressing water conservation in the economic sector that is responsible for most of the water use. It also represents a capabilities problem for the government, because without donor support, such a campaign will not be possible.

The examples above demonstrate what could be defined as the early phases of resource mobilization in the water harvesting TIS. However, absent from resource mobilization activities (as discussed in sections 4.1.3 and 4.1.4) are financing and credit mechanisms to promote entrepreneurial activity and market formation.

Blocking mechanisms hindering development of the water harvesting TIS

The functional-structural analysis for the Jordanian water harvesting TIS has facilitated a study on how interaction between the different structural components leads to realization of the functions and what problems occur in this regard. Collectively, these interactions form the blocking mechanisms for achieving the goal of the TIS (i.e. the establishment of water harvesting practices in Jordan). Three key structural conditions are responsible for triggering a chain of problems that reverberate throughout the system, and the feedback between these problems causes so-called "vicious cycles" (Hekkert et al., 2007). These are: 1) financial capabilities problems impact multiple TIS functions and increase reliance on donors; 2) lack of a common vision for water harvesting and for the agricultural system impacts every other function in the system; and 3) informal and formal institutional problems (e.g. *wasta* and land tenure) impede creation of legitimacy for water harvesting. Figure 2 shows the whole water harvesting TIS. Along the top are the three key structural conditions that trigger the chain of systemic problems. Each of these is discussed in sections 4.2.1-4.2.3.

Overcoming these structural conditions will require novel institutional arrangements, policy change, and infrastructural changes in the agricultural and water sector, which connects to the politics involved with the water management transition in Jordan. As Meadowcroft (2011, p.71) points out, "Politics is the constant companion of socio-technical transitions, serving alternatively (and often simultaneously) as context, arena, obstacle, enabler, arbiter, and manager of repercussions." We acknowledge the importance of politics in overcoming the existing water management regime, but also point out that as with most countries, the dynamics of the political system in Jordan are complex. Due to this complexity, full understanding the governance dynamics would require more investigation, which was beyond the scope of our TIS analysis. However, this research has shown some elements of politics that will be briefly discussed in sections 4.2.1-4.2.3.

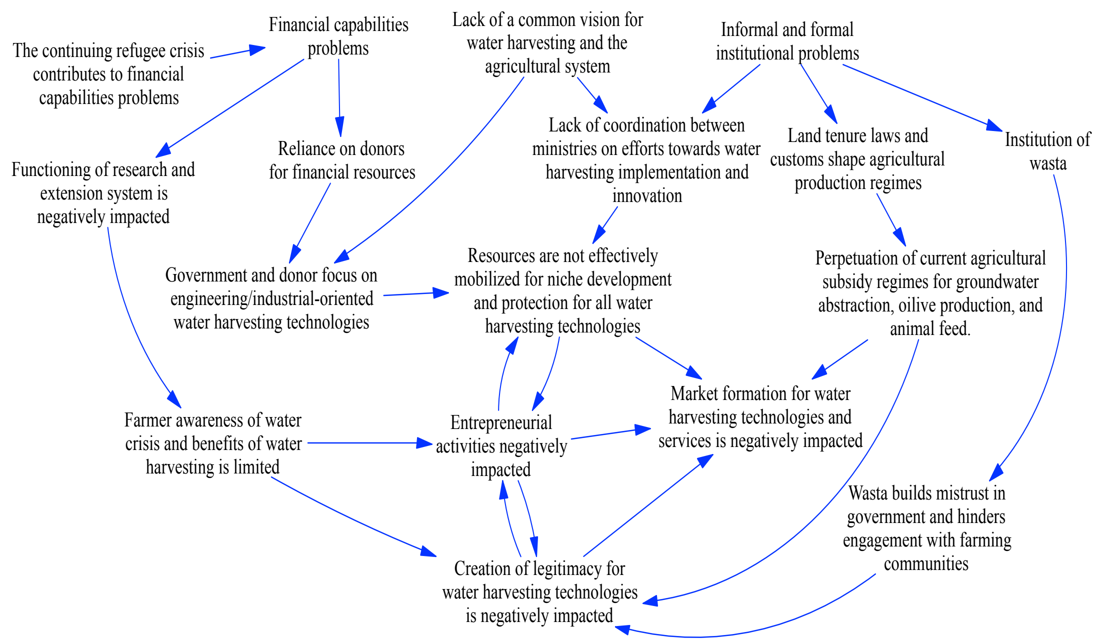

Figure 2: Interconnected causal mechanisms forming blocking mechanisms within the water harvesting TIS

Financial capabilities problems impact every TIS function and increase reliance on donors

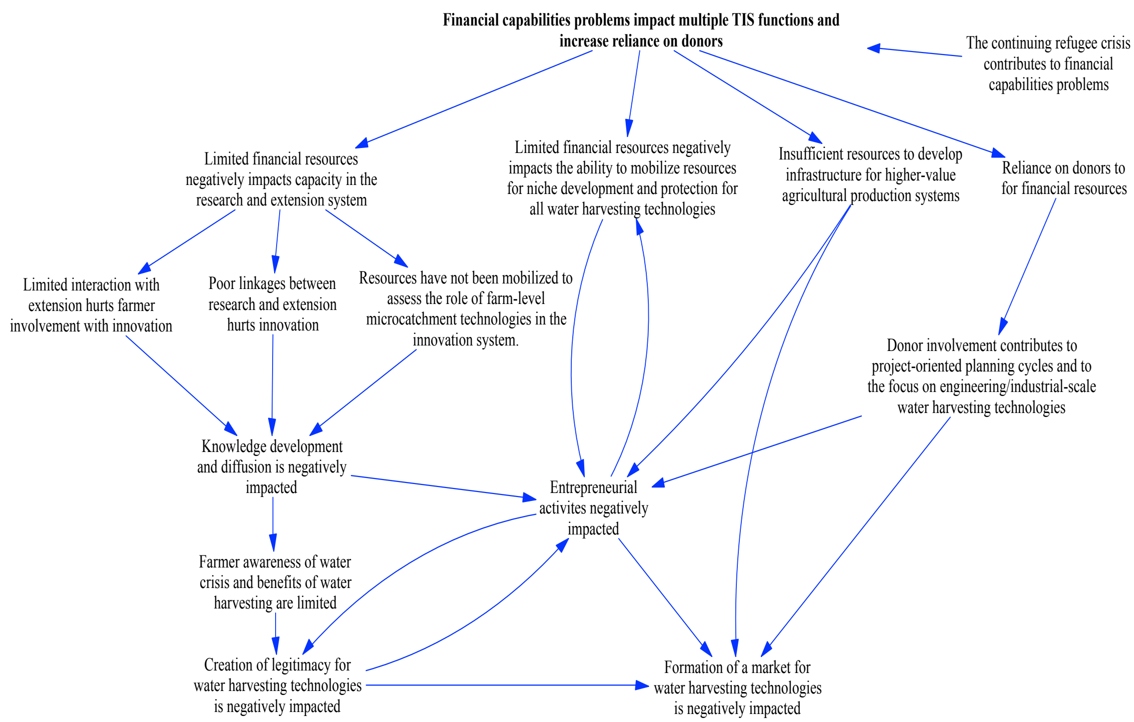

Figure 3: Financial capabilities problems form a core element in a series of causal mechanisms that negatively impact every function in the system.

Jordan is a developing country with limited financial and natural resources. This structural problem has impacts throughout the entire TIS and acts as a catalyst for a series of causal mechanisms that negatively impact, either directly or indirectly, every system function. The financial capabilities problems that Jordan faces make it reliant on donors for a significant share of budgetary needs. This challenge has been further compounded by a large influx of refugees from regional conflict.

The financial capabilities problems directly impact the ability of the national government to support knowledge development and diffusion through capacity challenges in the public extension system at NCARE, and through having insufficient resources to support greater involvement in these functions in the university system. This indirectly impacts the creation of legitimacy for water harvesting practices by limiting farming communities' awareness of the water shortage crisis and of the benefits of water harvesting. The impacts to the legitimacy function further impacts the development of a market for water harvesting and the involvement of entrepreneurs in the TIS.

The examples of Jordanian-driven efforts to expand water harvesting discussed in section 4.1.6 demonstrate that there are influential domestic actors who could play a role in changing the incumbent agricultural and water regime, but that the scale of their efforts to expand water harvesting are impeded by a lack of financial resources. Financial capabilities problems also inhibit the government's ability to mobilize resources, in the form of financing and credit, for development of a market for water harvesting practices and services and the entrepreneurial activities that would function in that market (Interviews 1,4,15,18,22).

We see a feedback loop between creation of legitimacy and entrepreneurial activities, where a lack of legitimacy hinders entrepreneurial activity in the TIS, and low entrepreneurial activity hinders advocacy for water harvesting by entrepreneurs. Another feedback loop exists between the mobilization of resources and entrepreneurial activities, where without sufficient protection for the water harvesting TIS and financial infrastructure, entrepreneurial activity will be hindered, which in turn limits advocacy by entrepreneurs. The feedback loops in the TIS can also be viewed as interactions between the functions that create vicious cycles that slow down progress in the innovation system (Hekkert and Negro, 2009). Hekkert et al. (2007) indicate that the influence in the direction of the search function is often a trigger that can shift vicious cycles to virtuous ones. The role of this function in the TIS is discussed more in section 4.2.2.

The reliance on donors indirectly impacts influence on the direction of the search, resource mobilization, and creation of legitimacy functions in both positive and negative ways. Donors represent strong political actors whose activities can directly influence the priorities of the national ministries. They contribute to creating the conditions that can both overthrow the incumbent technological regime or maintain it. Some donor projects have helped to build capacity at NCARE, which has had a positive role in the knowledge development and diffusion functions and thus on the creation of legitimacy function. However, as discussed in section 4.1.2, reliance on donors also negatively impacts the direction of the search through the focus on engineering-oriented water harvesting practices and through the discontinuation of water harvesting activities upon completion of donor funding cycles. This then has a negative impact on resource mobilization and through this function, on entrepreneurial activities and market formation.

Lack of a common vision for water harvesting and the agricultural system impacts every other function in the system.

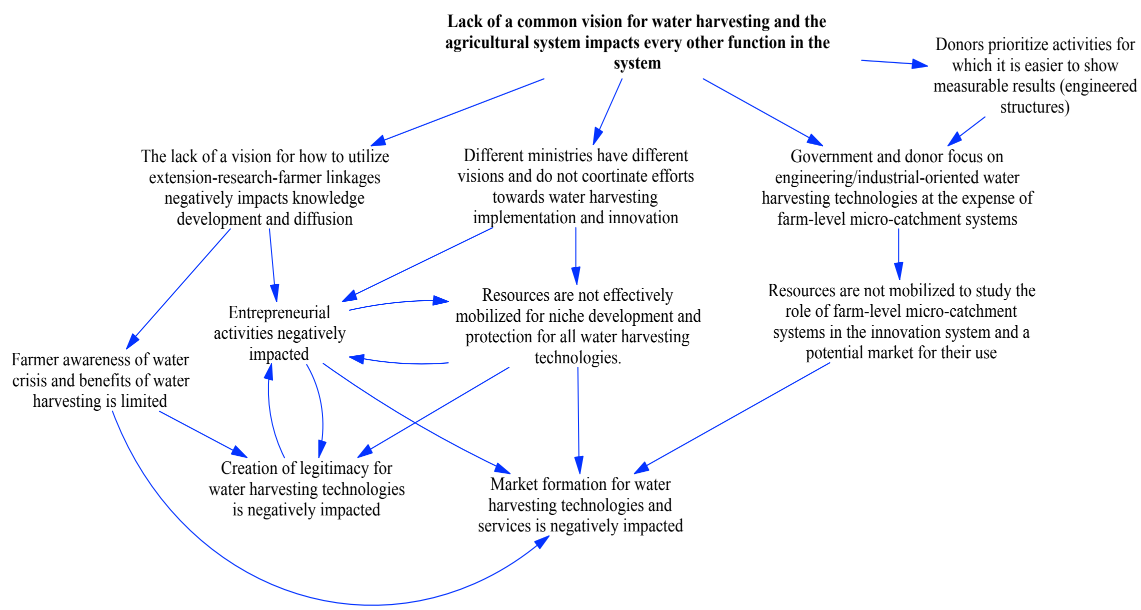

Figure 4: Lack of a common vision forms a core element in a series of causal mechanisms that negatively impact every function in the system

In the case of the water harvesting TIS, the lack of a common vision has reverberations that affect every TIS function to varying degrees. As noted in section 4.2.1, there are influential actors who could play a role in changing the incumbent regime to promote water harvesting innovation. Their efforts are not only impeded by financial capabilities problems, as indicated above, but also by the lack of a common vision among them for water harvesting innovation.

Lack of a common vision, which represents the underperforming of the influence in the direction of the search function, is partially responsible for the existing policy coordination problems, for the current water subsidies aimed at groundwater extraction, and for the lack of focus on on-farm micro-catchment water harvesting systems. This negatively impacts the creation of legitimacy, entrepreneurial activities, market formation, and resource mobilization functions in ways that were discussed throughout section 4.1. It impacts knowledge development and diffusion through the deprioritizing of extension at NCARE, which in itself impacts creation of legitimacy through not improving farmer awareness of the water crisis and of the benefits of water harvesting. We see the same feedback loops between entrepreneurial activities and creation of legitimacy and mobilization of resources for development and protection of the TIS as discussed in section 4.2.1.

Informal and formal institutional problems impede creation of legitimacy for water harvesting

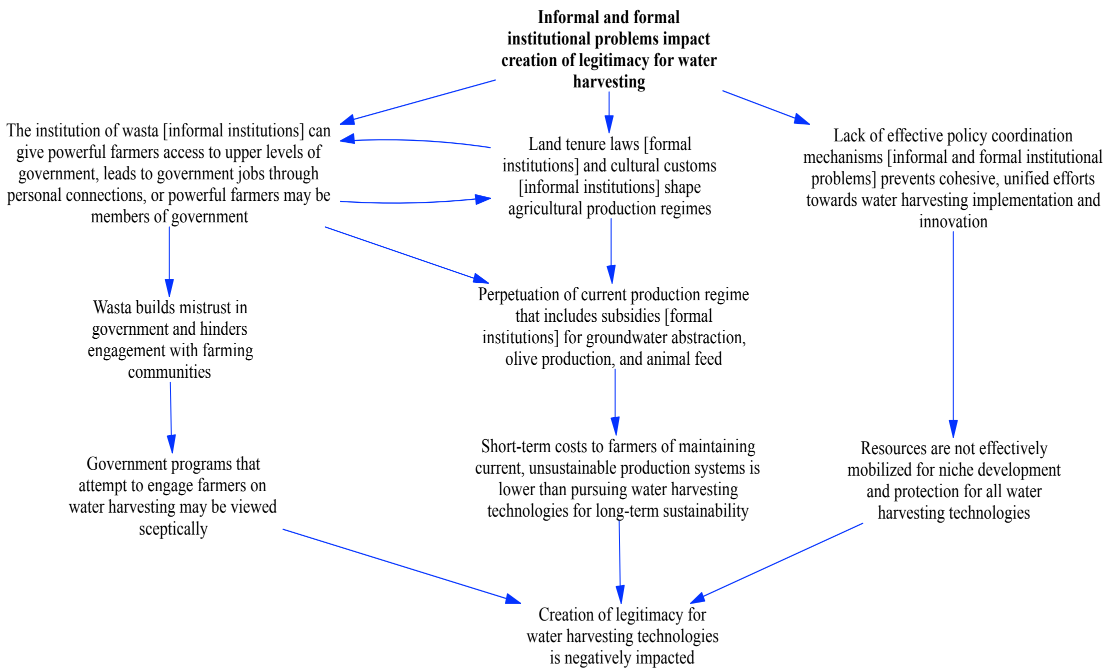

Figure 5: Both informal and formal institutional problems negatively impact legitimacy for water harvesting technologies

As discussed in section 4.1.5, aspects of both formal and informal institutions block the creation of legitimacy function in the water harvesting TIS. The policies (formal institutions) that subsidize the abstraction of groundwater and animal feed perpetuate an agricultural system in which the short-term costs to farmers of maintaining unsustainable groundwater irrigation practices and livestock overstocking are low enough to act as disincentives to pursuing water harvesting technologies. The mixture of official policies and cultural (informal) institutions around land tenure also contribute to the blocking of this function. Particularly, the cultural institution of *wasta* plays a role in perpetuating the continuation of the subsidy regimes and in mistrust of government, which indirectly impact legitimacy for water harvesting practices. *Wasta* and land tenure institutions form a feedback loop: the land tenure institutions allow a select group of farmers to become wealthy, which increases their power and influence, giving them greater influence in shaping the agricultural production regimes.

That the current subsidy regime remains in place is due to both informal and formal institutional reasons. Almost every interviewee, and notably those employed by the government, acknowledged that subsidies negatively impact water harvesting innovation and that ultimately, they have to be reduced or ended. However, while *wasta* plays a key role in keeping the subsidies in place, they also remain in place because their rapid termination could cause social unrest, which is linked to cultural norms around the price of water.

DISCUSSION AND CONCLUSION

This paper had two goals: 1) to provide actionable knowledge on the water harvesting innovation system to inform the transition of Jordanian agriculture towards more sustainable water usage, and 2) to contribute to the growing literature using TIS analysis in identifying systemic problems and opportunities in developing countries undergoing sustainability transitions and adding empirical knowledge on the specificities of these transitions from a particular context that has not yet been studied. To conclude the paper, we will now provide some policy recommendations (section 5.1), and reflect on the contributions of this paper to the broader literature on TIS and sustainability transitions in developing countries, including raising some topics for further research (section 5.2).

Policy recommendations

Regarding the first goal of our paper, we identified two policy priority areas towards which efforts should be directed to overcome the current challenges facing the innovation and implementation of water harvesting practices. These are: 1) improving coordination across ministries and donors to develop a holistic vision for water conservation in agriculture and for how water harvesting innovation and utilization fits into that vision; and 2) supporting TIS development for water harvesting practices, including resource mobilization for the formation of a market for them and for the involvement of entrepreneurs in that market. Our analysis highlights that donors are currently fundamental to developing the water harvesting TIS, and thus should play a central role in efforts to achieve these policy priority areas.

With regard to priority area 1, efforts to increase policy coordination across ministries can be seen in the existence of the National Water Advisory Council and the Highland Water Forum, which were created to coordinate water sector strategy and funding and to find collective solutions to groundwater management, respectively (Humpal et al., 2012). However, as of 2014, the National Water Advisory Council had only met once (OECD, 2014), and while the Highland Water Forum has played a role in the campaign to cap illegal wells, its activities are limited to the Highlands (Humpal et al., 2012). Additional policy action must thus occur to achieve policy priority area 1, in which donors can play key roles in the following ways: 1) by acting as intermediaries who build linkages between currently disconnected actors and by playing the role of institutional entrepreneurs acting as change agents (in line with ideas of Hansen and Nygaard, 2013 and Szogs et al., 2011); 2) as financial capabilities problems are identified throughout the water harvesting TIS, by providing a stable source of funding and increasing advocacy for water harvesting practices; and 3) by playing an integral role in supporting and helping to develop policy mixes for sustainability transitions.

Donors could play a central role in inducing and enacting niche protection and technological regime destabilization policies (following Marquardt, 2015) as institutional entrepreneurs (Jolly et al., 2016; Meijerink and Huitema, 2010), influencing and collaborating with domestic policy makers to support the development of an inclusive innovation system (Andersen and Johnson, 2015). However, this would require the will and ability to navigate the complex political dynamics in Jordan as well as coordinated efforts among donors to have sufficient political clout. As donors currently contribute to directionality problems, coordination between donors (following Lawson, 2013) and donors and government ministries (following Mockshell and Birner, 2015) should be improved.

There is a ministry whose role is to coordinate funding between donors and relevant ministries, the Ministry of Planning and International Cooperation (MoPIC). MoPIC could be the government actor that plays the principal coordinating role of integrating policies and visions across all ministries that work with water harvesting. MoPIC has already demonstrated its ability to play this role with funding from the United Nations High Commission for Refugees. This management structure, which could be applied to water harvesting, consists of MoPIC and the international donor at the top, under which are a series of working groups. Within each working group is a lead donor agency, a lead ministry, and a lead NGO. These working groups then work with local stakeholders. We advocate for a similar structure to be followed for water harvesting.

With regards priority area 2, in line with the policy actions identified by Kivimaa and Kern (2016) who focus on both supporting niche developments (i.e. supporting TIS build-up) and 'regime-destabilization' measures (i.e. making continuation of irrigation less attractive), we recommend the following actions for development and protection of the water harvesting TIS: 1) development of a subsidy regime for farmers that supports construction of water harvesting systems and the training necessary to effectively utilize and maintain them; 2) in partnership with the government and private banks, establishment of a low-interest loan regime for water harvesting; and 3) strengthening of the research and extension system by providing funds for training extension officers, increasing linkages between research and extension, and increasing the number of demonstration projects for the diffusion of knowledge on water harvesting practices. After feedback from multiple interviewees, we also advocate for exploring the potential for complementary pairing of water harvesting with other water conserving, higher-value crop production systems, such as the hydroponic systems that are currently in the early phases of support by USAID.

Besides these niche support policies, to develop the water harvesting TIS and form a market for water harvesting goods and services, one of the most important steps is policy support for destabilizing the incumbent dominant regime technologies (Kivimaa and Kern, 2016) – which implies the reduction or elimination of subsidies for groundwater abstraction and animal feed. As noted above, ending these subsidies will prove difficult for social reasons, and for this reason we advocate for a gradual reduction of them over time. It is imperative that instability not be an unintended result of changing the existing water management regime in a country surrounded by regional instability.

As indicated in section 4.2, the dynamics of the politics in the water transition in Jordan are complex as these involve multiple formal and informal as well as regional, national and international level institutions, so deeper knowledge of these political dynamics is needed to inform implementation of these policy recommendations.

Contributions of our study to the broader literature on TIS and sustainability transitions in developing countries

Regarding the second goal of our paper, we support the assertion by Tigabu et al., (2015) that the TIS approach is sufficiently generalizable to study different types of developing country innovation systems. In our analysis, we identified three key structural conditions that are responsible for triggering a chain of problems that reverberate throughout the system and form blocking mechanisms. Identification of these structural conditions adds to the existing literature on the TIS approach in the developing country context. In particular, these are the influence on the TIS by donors and informal institutions or customary law (e.g. *wasta*).

Like Gosens et al., (2015) and Binz et al., (2012), we found that the Jordanian water harvesting TIS is in fact a sub-system of an international TIS. In this case, it is connected to the international level through donor interventions, connecting to ideas on transnational linkages in sustainability transitions (Hansen and Nygaard, 2013; Wieczorek et al., 2015), which prove to be very important in the context of developing countries (Gosens et al., 2015). We showed that an important implication, therefore, is that different from many developed country TIS analyses, donor interventions should be centrally considered, as they play a role in influencing the direction of the search and in contributing resources towards the knowledge development and diffusion functions. In line with Hansen and Nygaard (2013) and Marquardt (2015), we found that development aid can support TIS development by providing resources for projects that demonstrate the technological, ecological, and economic viability of a technology. However, in the case of the water harvesting TIS in Jordan, we found that this impact has thus far been limited, primarily due to the lack of a concerted, coordinated effort with a common vision to develop the water harvesting TIS. A broader theoretical implication that nuances earlier findings on donor support of TIS development is that donors can contribute to directionality problems that favor one form of the technology over another, and that by not building sufficient capacity to ensure continued innovation activities upon project completion, can provide insufficient protection of the TIS until markets for technologies form.

We found that w*asta* plays a significant role in causing an erosion of trust in the government and works counter to its efforts to promote and engage farming communities in water harvesting activities and innovation. In conjunction with a mixture of both informal and formal land tenure laws, *wasta* contributes to the perpetuation of subsidy regimes that are central to maintaining the status quo production regime. Further, the land tenure institutions sometimes help to reinforce *wasta* through their enriching of a select number of individuals.

From our study emerges that formal and informal institutions go hand in hand in a country like Jordan; for example, the lack of clarity on which aspects of land tenure institutions are formal and which are informal is a condition that is highly influential. This confirms earlier work on regimes and innovation system contexts in developing countries, where informality and instability are common (e.g. Arocena and Sutz, 2000; Verbong et al., 2010; Wirth et al., 2013). Related to this, our analysis also touched upon the issue of politics, and revealed some political issues (e.g. the role of *wasta* in the political system and power dynamics within and between different ministries). However, to go deeper into the informal and formal politics would require a more dedicated analysis (following Avelino and Rotmans, 2009; Avelino and Wittmayer, 2015; Kern, 2015).

A concept that has emerged from this research that warrants additional research is the role of retro-innovation in sustainability transitions. Retro-innovation involves the adaptation of traditional practices into a modern innovation system (Stuiver, 2006), as is the case with water harvesting. This topic has received little attention in the developing country transitions literature, with Marques et al.'s (2010) paper on novelty production of medicinal plants in Brazil being the only example we have found. Additional research on retro-innovation and the role of locally-driven development and adaptation in the process warrants additional attention in transitions and innovation systems studies, as it is a means to counteract by often simple interventions the negative side effects of modern technologies (such as irrigation technologies in this case). This may also be linked to the biophysical aspects of innovation processes (Andersen and Wicken, 2016) and to current debates on “Jugaad” or “Frugal” innovation as a way to achieve inclusive innovation incorporating smallholder farmers in developing countries (Radjou et al., 2012).

Finally, we advocate for further research on how to adapt the structural-functional analysis as outlined by Wieczorek and Hekkert (2012) for use as an applied pre-project/program assessment tool (in a similar vein as Schut et al., 2015 have done for structural analysis, Alkemade et al., 2007 have done for functional analysis, and Andersen and Andersen, 2014 have done for innovation system foresight). In assessing the Jordanian water harvesting TIS, we have found that the clear picture of the innovation system that develops from this analysis could be useful for developing a thorough understanding of the system into which a new project or program occurs. This analysis could help in developing projects and programs at their inception to make them more in-line with a common vision and to reduce redundancy and waste by better understanding how the new activities fit in to the broader context of activities by other actors and institutional conditions.

ACKNOWLEDGEMENTS

This work was supported by the National Science Foundation under Grant #0966093, Integrative Graduate Education and Research Traineeship (IGERT) Program on Water Diplomacy at Tufts University, the Tufts University Institute for the Environment Fellowship, and the Tufts University Water: Systems, Science & Society Fellowship. We wish to thank all interviewees for their participation in this study. Special thanks go out to Dr. Scott Christiansen, Dr. Jim Hill, and Kris Dodge.

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CHAPTER 3: Water Diplomacy at the Macro Scale: Agricultural Groundwater Governance in the High Plains Aquifer Region of the United States

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Written in the style required for book chapter submission
Submitted for book chapter in: "Water Diplomacy: An Interdisciplinary Experiment in Problem-Driven Research and Practice"

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ABSTRACT

The High Plains Aquifer, which underlies parts of eight U.S. states, is one of the largest groundwater systems in the world. Water from the aquifer is vitally important to both the agriculture-based economies and rural communities in this region and to areas around the world that rely on agricultural goods produced there. Groundwater withdrawn from the aquifer generates more than $7 billion in crop production annually and supports about 20% of the corn, cotton, cattle, and wheat produced in the U.S. each year. Yet, an alarming decline in groundwater levels in some parts of the aquifer puts at risk the long term economic and ecological viability across most of the High Plains Aquifer region. Different states in the region have pursued varying paths to governing the use of water from the aquifer, with varying degrees of success towards sustainability. The nascent field of Water Diplomacy provides a useful lens through which to evaluate the governance institutions that different states have put in place to achieve sustainable use of High Plains Aquifer water. The High Plains Aquifer presents a useful case to further the conversation on Water Diplomacy as a discipline and its application to water governance situations. Here we look at the states of Kansas, Nebraska, and Texas to identify the extent to which U.S. state-level governance institutions possess the principles needed for Water Diplomacy solutions in the context of groundwater governance. To achieve this, we draw upon the work of Elinor Ostrom and apply her eight design principles for governing sustainable common-pool resources.

INTRODUCTION

The High Plains Aquifer (HPA), also known as the Ogallala Aquifer,[1] is one of the largest aquifer systems in the world, underlying more than 450,000 km^2 (174,050 mi^2) of eight U.S. states, from South Dakota to Texas (Figure 1)(Sophocleous, 2011). Crop sales from lands irrigated from the HPA generated more than $7 billion in 2007 (Gollehon and Winston, 2013). The aquifer supports approximately 20 percent of the corn, wheat, cotton, and cattle production in the United States and provides drinking water for over 80 percent of the people who live within its boundaries (Dennehy et al., 2002; Sophocleous, 2011; USDA-NRCS, 2016). It is the most intensively used aquifer in the country, accounting for about 30 percent of total withdrawals from all aquifers for irrigation (Sophocleous, 2011; USDA-NRCS, 2013).

Across most of the HPA region, declining groundwater quantity is a significant problem. Natural recharge of the aquifer from precipitation is low, and current groundwater abstraction exceeds the rate of recharge in many areas (Peck, 2007; USDA-NRCS, 2013). Recoverable water in storage in the aquifer declined 9% from before the widespread development of irrigation began in the 1950s to 2015 (McGuire, 2017). However, this figure, while alarming, represents an average decline in groundwater levels across an immense land area and masks significant variability. For example, while stored groundwater has declined by 29% in the HPA region of Texas, it has only declined between 0.5% and 1% in Nebraska (Bleed and Babbitt, 2015; Stanton et al., 2011).

There are a variety of reasons for this geographic variability, such as differences in precipitation patterns and underlying hydrogeology, which impact percolation of surface water to the aquifer. In addition, different agricultural practices and production systems and, perhaps most importantly, differences in governance institutions and policies that regulate how groundwater is used, are causes of variability. The states in the HPA region have pursued different approaches to groundwater governance with varying degrees of success towards sustainability.

This paper has two primary objectives: 1) to expand the concept of Water Diplomacy to encompass groundwater governance, and 2) to assess where and to what extent Water Diplomacy principles are in use for groundwater governance in the HPA region of the U.S.

Here, we look at the states of Kansas, Nebraska, and Texas because they collectively overlay 74.5% of the area of the HPA (Table 1), are all highly productive agricultural states, and because their different regulatory systems offer a useful case study for identifying the extent to which U.S. state-level governance institutions possess the principles needed for Water Diplomacy solutions in the context of groundwater governance.

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[1] Note that the terms “High Plains Aquifer” and “Ogallala Aquifer” are often used interchangeably in the literature (USGS, 2014; Verchick, 1999). The Ogallala Formation is the principle geologic unit of the High Plains Aquifer, which has led to the popular use of the term “Ogallala Aquifer” as a synonym (Sophocleous, 2011). We use the technical term “High Plains Aquifer” throughout this paper.

The paper first discusses the concept of Water Diplomacy and its application to the governance of groundwater, generally understood to represent a common-pool resource (CPR). This is followed by a description of governance of CPRs and an introduction to Elinor Ostrom's design principles for governing sustainable resources (Ostrom, 1990). We then provide a brief background on groundwater governance in the United States, followed by a discussion of groundwater governance institutions in each of the three states on which this study is based: Kansas, Nebraska, and Texas. We close with an analysis of the extent to which these three state-level institutions might be said to capture significant aspects of the principles of Water Diplomacy, and finally a discussion on the factors that influence these variations.

Table 1: High Plains Aquifer area, distribution, irrigated area, and water level by state (modified and updated from Sophocleous, 2011)

	Kansas	Nebraska	Texas	Total
HPA area in state[1] (km^2) (Total extent of HPA 450,788 km^2)	78,995	164,853	91,815	335,663
% of total HPA area in state	17.5	36.6	20.4	74.5
% of HPA water underlying state	10.0	65.0	12.0	87.0
Hectares irrigated using HPA water in 2013[2]	987,433	2,901,596	1,432,587	5,321,616
Change in water level from predevelopment to 2015 (m)[3]*	-8.0	-0.3	-12.5	N/A

* Area Weighted Average
(Gutentag et al., 1984[1]; Gollehon and Winston, 2013[2]; McGuire, 2017[3])

Figure 1: High Plains Aquifer Boundary
Source: USGS
https://water.usgs.gov/ogw/aquiferbasics/ext_hpaq.html

WATER DIPLOMACY IN THE CONTEXT OF GROUNDWATER GOVERNANCE

Water Diplomacy (WD) is a novel framework within the developing field of interdisciplinary water management. Broadly speaking, WD is a process engaged in by state or non-state actors to address, resolve, or avoid conflicts over access to water and water-related issues. It can also represent a skill set possessed by an individual or group of individuals (e.g. negotiators or mediators) exercised in dealing with conflicts over water on behalf of state or non-state actors. As an emerging interdisciplinary field, the definition, the disciplinary foci, and the tools it utilizes are still evolving, and an increasing body of literature is in the process of refining what constitutes WD (e.g. Islam and Madani, 2017; Islam and Susskind, 2013; Susskind and Islam, 2012; van Rees and Reed, 2015).

In their effort to advance the concept and practice of WD, Islam and Susskind (2013) identified six key principles that are thought to represent necessary conditions for achieving successful negotiated water results. These are:

1) Appropriate stakeholders and stakeholder interactions are identified and adequately represented.
2) Stakeholders engage in joint fact-finding to develop a shared understanding of their resource system and how key variables impact the system.
3) Relevant parties need to create value for stakeholders through "mutual gains," non-zero sum, policy solutions.
4) Informal problem-solving processes are linked to formal decision-making processes and authorities at a higher governance levels (i.e. at the national level or individual state level in federalist systems).
5) Policy solutions are developed within the context of collaborative adaptive management.
6) Management of water systems is improved through capacity building and societal learning among individuals, organizations, and networks.

WD as described by Islam and Susskind (2013) has been applied primarily to cross-national transboundary water negotiations involving national policymakers (e.g. Berndtsson et al., 2017; Brady et al., 2015; Choudhury, 2017), or to situations where a history of conflict over water is already present (e.g. Moazezi et al., 2017), or both (e.g. Huntjens, 2017). Largely absent from the literature (an exception being Koebele, 2015) is WD analysis that looks at water governance institutions at the sub-national level (e.g. water governance at the inter-state or individual state levels in the United States). This area of analysis is important and merits additional investigation. However, WD manifests differently at this level, and thus requires different tools for analysis. This paper represents one of the first forays into expanding WD analysis to the water governance context.

We argue that WD must be viewed through two different lenses, the micro level and the macro level. The micro level primarily encompasses water negotiations in which the focus is on utilizing trained negotiators, or on training people to be negotiators, in the six key principles central to the WD Framework described by Islam and Susskind (2013). The macro level of WD is more nebulous in that it attempts to take a higher-level look across complex water conflicts or governance situations to identify key factors that lead to robust governance institutions that produce sustainable water management outcomes. While the micro and macro levels of WD may seem independent of each other, the fact is that the policies, laws, histories, and values reflected at the macro level play a very important part in influencing whether and to what extent the six key principles are achievable in specific WD situations.

At its core, WD is a process or series of processes focused on finding mutual gains solutions to water challenges through adaptive, collective management. At the groundwater governance level, it is the governance institutions that set the stage for these processes. In other words, at this level, it is the structure of institutions that govern groundwater in complex social-ecological systems (SESs) that determines the extent to which the principles needed for WD solutions are present. An SES is an ecological system connected to and impacted by one or more social systems; it is a subset of social systems in which interdependent human relationships are deeply intertwined with interactions involving biophysical and non-human biological units (Anderies et al., 2004).

Research pioneered by Elinor Ostrom (e.g. Ostrom, 2009, 2008, 2000, 1990) examined the processes that lead resource users to develop and sustain robust institutions to effectively manage CPRs in complex SESs. Groundwater is typically thought of as a CPR, meaning that it is a shared resource that is sufficiently large to make it difficult to exclude users, and each individual's use reduces benefits to other users who share the resource (Ostrom, 2000). Ostrom (2008, 1990) identified certain conditions that seem to be present in robust CPR governance institutions. She also provided a road map for assessing the extent to which these conditions are present. Her research offers a way to connect the processes of CPR governance to the outcomes of adaptive, collective management. In the context of this research, the CPR is groundwater, and the desired outcome rests at the core of WD - sustainable groundwater governance. Thus, we argue that within the context of groundwater governance, WD can be considered a subset of Ostrom's work. In this paper, we apply Ostrom's institutional design principles to U.S. state-level groundwater governance institutions in three states in the HPA region to assess the extent to which these states possess the conditions that lead to WD outcomes. In short, the HPA represents a substantial common-pool resource whose governance is largely conducted by individual states and their institutions, and this governance in turn affects the extent to which sustainable water resource outcomes are achievable.

GROUNDWATER AND OSTROM'S EIGHT DESIGN PRINCIPLES FOR GOVERNING SUSTAINABLE COMMON-POOL RESOURCES

Like other CPRs, such as fisheries and forests, groundwater's lack of exclusivity and the subtractability of benefits to users who share it make governing its use difficult and overharvesting likely, leading to the eventual destruction of the aquifer from which the water is withdrawn (Ostrom, 2008). Managing groundwater sustainably is further complicated by the long timescales of natural groundwater processes and the time-lag of impacts associated with groundwater use, which are often inconsistent with policy timeframes established for managing groundwater (Gleeson et al., 2012; Ross and Martinez-Santos, 2010). Like Bleed and Babbitt (2015), we define a sustainable groundwater governance system as one that can sustain for current and future generations the benefits that society requires and desires from the water resource. To do this, the governance institution itself must be robust enough to be maintained, and the institution must be able to adapt to future challenges and condition in the resource (Bleed and Babbitt, 2015).

There is no panacea for groundwater governance, and institutional arrangements are dependent on a number of factors including political processes, culture, historic paths to institutional change, and the scale of the resource system being governed (Meinzen-Dick, 2007). While one approach may succeed in one place and fail in another, Ostrom (1990) identified eight institutional design principles that are frequently present in robust governance systems that sustainably manage CPRs. These principles are (Bleed and Babbitt, 2015; Ostrom, 2008, 2000, 1990):

1. Clearly defined boundaries: Both the individuals who have rights to withdraw resources from the resource system and the boundaries of that resource system are clearly defined.
2. Proportional equivalence between benefits and costs: Rules specifying the allocation of the resources are well-matched to local conditions (e.g. soils, climate, crops being grown, labor, etc.) and must be considered fair and legitimate by users.
3. Collective choice arrangements: Most of the stakeholders affected by harvesting and protection rules are included in the group that can make and modify these rules.
4. Monitoring: Individuals and organizations that monitor biophysical conditions and user behavior are at least partially accountable to users and/or are users themselves.
5. Graduated sanctions: Users who violate the rules are likely to receive sanctions that reflect the seriousness and context of the violation.
6. Conflict-resolution mechanisms: Users and their officials have rapid access to low-cost, local avenues to resolve conflict between users and officials or among users.
7. Minimal recognition of rights to organize: Users have the right to organize their own institutions and long-term tenure rights, and these rights are not challenged by external governmental authorities.
8. Nested enterprises: Governance activities are organized in nested enterprises in which appropriation, monitoring, enforcement, conflict resolution, and other governance activities are organized in multiple layers.

GROUNDWATER GOVERNANCE IN THE UNITED STATES

Groundwater law in the United States is primarily created and administered at the state level, with some federal influence in situations where groundwater use intersects with federal laws (e.g. the Endangered Species Act) (Peck, 2015). As a result, groundwater governance varies considerably between states. Groundwater governance is built around two fundamental principles: property rights and rules for allocation of groundwater.

Property rights structure determines who owns and controls the resource and influences what types of regulations can be used to manage it. A water right is a right to divert water for a period of time, from a specific source, to be used on a specific parcel of land (Peck, 2015). States often consider the “public interest” or the “public welfare” when determining whether to grant a water right or to change existing water rights (Getches, 2009; Peck, 2015). Water rights as property rights differ by state; some states consider them to be private property and others do not. The distinction is important because the courts have provided strong protection for clearly defined private property rights under the Fifth Amendment of the U.S. Constitution, limiting options for regulatory management in some cases.

There are four general rules used in the U.S. to allocate groundwater to users. These rules govern who has a right to withdraw and use groundwater, how much and for what purposes they can withdraw, and can clarify how to resolve disputes when there is a shortage. They are (Aiken and Supalla, 1979; Kaiser and Skillern, 2001; Peck, 2007)

1. Rule of Capture (also known as Absolute Ownership): holds that landowners own all water that underlies their land and can pump water without limit, except where prohibitions on wasteful use exist
2. Reasonable use doctrine: allows a landowner to use the groundwater underlying his or her land, provided that the water is used for a reasonable purpose and is used on the overlying tract of land
3. Correlative rights: determines rights to groundwater based on ownership of land. Landowners overlying the same aquifer are limited to a reasonable share of the aquifer's total supply based on the amount of land owned by each.
4. Prior appropriation: follows the "first in time, first in right" principle, in which the rights to withdraw groundwater are allocated on a temporal basis, rather than on a land ownership basis, and senior users have priority over more junior ones

While it is sometimes useful to draw distinctions among the four rules that underlie groundwater rights and allocations, nearly all U.S. states have developed governance systems that have elements of more than one rule. Each of the three states included in this paper uses its own combination of property rights and groundwater allocation rules. These form the foundations of each state's groundwater governance institutions as they relate to groundwater quantity and each state has approached the design of these institutions differently. The remainder of this paper describes these institutions and evaluates the extent to which they possess the conditions for WD outcomes by comparing them to Ostrom's eight principles.

Kansas

Irrigated agriculture is central to the economy of Kansas, and the state has approximately 1.2 m hectares of irrigated land, of which approximately 987,000 hectares are irrigated by water from the HPA (Table 1)(Kenny and Juracek, 2013). Agriculture accounts for 80-85% of all water diversions in Kansas, and about 96% of water used for irrigation comes from groundwater (Kansas Water Office, 2015; Kenny and Juracek, 2013). Almost all of the groundwater used for irrigation is withdrawn from the HPA, which underlies western Kansas and a portion of south central Kansas (Kenny and Juracek, 2013) (Figure 1). Groundwater recharge rates in this part of the HPA are very low, with recharge equivalent to about 15% of current irrigation withdrawals (Steward et al., 2013). To date, approximately 30% of the groundwater has been pumped, and at current rates, an additional 39% will be depleted by 2060 (Steward et al., 2013). From predevelopment to 2015, the HPA region of Kansas saw an area-weighted average groundwater level decline of 8.0 meters (Table 1) (McGuire, 2017). There are considerable regional differences in HPA decline in the state. Since 1996, groundwater levels have fallen an average of 10.4 meters in southwest Kansas and just over 3 meters in west-central Kansas (Kenny and Juracek, 2013; University of Kansas, 2015). While groundwater levels continue to decline, recent trends have shown a slowing in the rate of decline (University of Kansas, 2015).

The Kansas Water Appropriation Act of 1945 paved the way for statutory management of groundwater in the state. It asserted that water is dedicated to the use of the people of the state, charged the state with the duty to manage the resource, and adopted the prior appropriation allocation rule (*Kan. Stat. Ann. §§ 82a-701 to -733 (1989 & Supp. 1994)*). The Act was amended in 1957 to designate water rights as real property rights, subject to the principle of "beneficial use," and reasserted the state's duty to manage the resource under these conditions (Peck, 2003). The designation of water rights as a real property right poses an obstacle to managing groundwater because it raises concerns regarding the authority of the state to restrict groundwater use without compensating water rights holders (Peck, 2015).

In Kansas, groundwater is managed through the Kansas Division of Water Resources (KDWR) and through local institutions, called Groundwater Management Districts (GMDs). In 1972, the legislature enacted the Kansas Groundwater Management District Act (KGMDA) in response to extensive groundwater mining (Hoffman and Zellmer, 2013; Peck, 2007). The KGMDA allowed the establishment of GMDs, which have the authority to prepare district management plans, draft and recommend groundwater regulations to the KDWR, and tax, purchase, and sell property and water rights (Griggs, 2014a). A locally elected Board of Directors governs each district (Peck, 2006). There are five GMDs in Kansas, and all are located in areas that overlay the HPA (Figure 2). The GMDs are drawn along political boundaries (section, township, or county lines), and they roughly correspond to the sub-aquifers of the HPA. Collectively, they cover most of the ground overlying the HPA, however, there are areas of the aquifer that lie outside of GMD boundaries (Griggs, 2014a; Kansas Department of Agriculture, 2016).

In 1978, the KGMDA was amended to allow the establishment of Intensive Groundwater Use Control Areas (IGUCAs), which have additional authority to address groundwater use during times of water shortage (Griggs, 2014a). IGUCAs can be established by the Chief Engineer of the KDWR, at the request of a GMD, or by petition of water rights owners in the area (Griggs, 2014a). The IGUCA process allows the Chief Engineer to conduct hearings regarding areas of concern and approve *corrective control provisions* in areas determined to be critical, including limiting groundwater withdrawals (Griggs, 2014b).

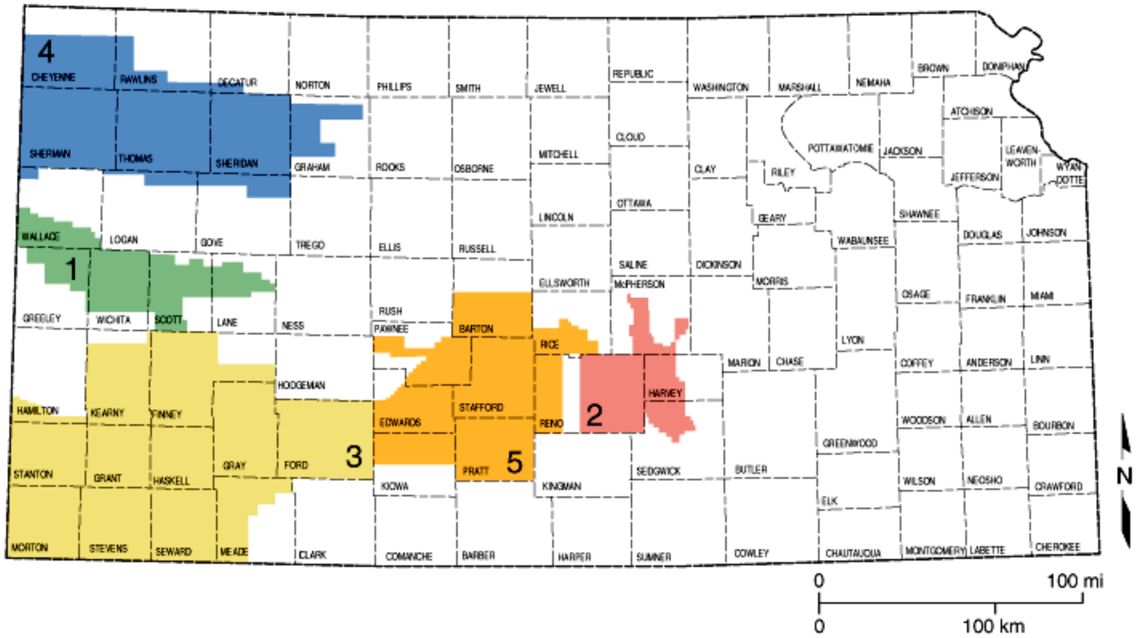

Figure 2: Kansas GMD and county boundaries (Source: Kansas Geological Survey *www.kgs.ku.edu/Hydro/gmd.html. All Rights Reserved)*

In 2012, the state Legislature enacted a statute that allows for the creation of Local Enhanced Management Areas (LEMAs) (*Kan Stat. Ann. §82a-1041*, 2017). The LEMA legislation evolved because irrigators wanted to work collectively and locally to reduce groundwater use, but they viewed the IGUCA process as too unpredictable (Griggs, 2014a). Under the LEMA process, either a GMD or 5% of the irrigators within a GMD can submit a management plan to the state for review (Griggs, 2014b). The statute allows irrigators to self-organize to propose pumping restrictions on all users within a proposed boundary (Peck, 2015). If the state approves the locally developed plan, it is responsible for enforcing the provisions, but can only enforce what is in the plan (Peck, 2015). The LEMA concept combines local control over the development of the plan with the central enforcement and administration of the IGUCA (Griggs, 2014b).

Nebraska

Irrigated agriculture is also central to the economy of Nebraska. With 3.4 m hectares of irrigated crop and pastureland, of which approximately 2.9 m are irrigated with HPA water, Nebraska has more land under irrigation than any other state in the U.S. (Table 1)(Bleed and Babbitt, 2015). Nebraska accounts for almost half of all the irrigated area in the HPA region (Gollehon and Winston, 2013). Similar to Kansas, irrigated agriculture is by far the largest user of groundwater in the state, accounting for 93% of total groundwater withdrawals in 2013 (Hoffman and Zellmer, 2013). Groundwater recharge rates vary considerably across the state, with high positive net recharge rates in the Sand Hills and eastern parts of the state, where precipitation rates are highest, and negative net recharge rates in the southwestern part of the state (Szilagyi and Jozsa, 2013). Between predevelopment and 2015, HPA levels have declined by an area-weighted average of 0.3 meters, or by only 0.5-1% from historical levels (Table 1)(Bleed and Babbitt, 2015; McGuire, 2017; Stanton et al., 2011). Groundwater levels have declined more significantly in some parts of the state, most notably in the southwestern corner and in an isolated part of the western part of the state, but Nebraska has been able to slow or reverse these declines (Bleed and Babbitt, 2015).

In Nebraska, all water is owned by the state "for the benefit of its citizens" (*Neb. Rev. Stat. §46-702 (Reissue 2010)*, 2007). Under this ownership theory, water is subject to state control and never becomes private property. While there is no private property right of the water itself, landowners have a right to use groundwater, and this right automatically transfers with a change in land ownership (Aiken, 1987; Bleed and Babbitt, 2015). Groundwater is allocated through a hybrid of the reasonable use doctrine and modified correlative rights (Bleed and Babbitt, 2015). The approach is unique among states and stipulates that landowners have the right to pump underlying groundwater, but those rights are subject to any current or future regulations, which provides the state with flexibility to legally change the right to withdraw and use groundwater (Aiken, 1987).

Nebraska has a strong history of supporting local management of groundwater, dating back to the Groundwater Conservation Act of 1959 (Aiken, 1980; Bleed and Babbitt, 2015). Historically, natural resource management in the state was the domain of single-purpose districts organized along county boundaries (Aiken, 1980). In 1972, the state reorganized over 150 single purpose districts into comprehensive Natural Resource Districts (NRDs) (Aiken and Supalla, 1979). There are 23 NRDs, which collectively cover the entire state (See Figure 3). The NRDs were developed largely along surface watershed boundaries "to provide effective coordination, planning, development, and general management of areas which have related resources problems" (*Neb. Rev. Stat. § 2-3203*, 2007). A locally elected Board of Directors governs each NRD, and they are charged under state law with 12 areas of responsibility, including groundwater management and conservation (Nebraska Association of Resource Districts, 2013). The NRDs have broad and flexible legislative authority that includes the power to issue and enforce groundwater regulations (e.g. well spacing restrictions, irrigated acreage reductions, and moratoria on the drilling of new wells), levy taxes, and purchase, lease, and dispose of groundwater rights (Hoffman and Zellmer, 2013).

While the NRD system facilitated local management of natural resources, by 2002 it had become apparent that the approach was not effectively addressing management of areas where surface water and groundwater are hydrologically connected (Hoffman and Zellmer, 2013). In response, the state legislature passed LB 962 in 2004, which integrated surface and groundwater management planning by requiring the state Department of Natural Resources (DNR) and the local NRDs to work together to develop integrated water management plans for water-scarce basins (Hoffman & Zellmer, 2013). Under this management structure, the DNR is responsible for all surface water related issues, but the NRDs still have the sole legal authority to manage groundwater (Hoffman & Zellmer, 2013).

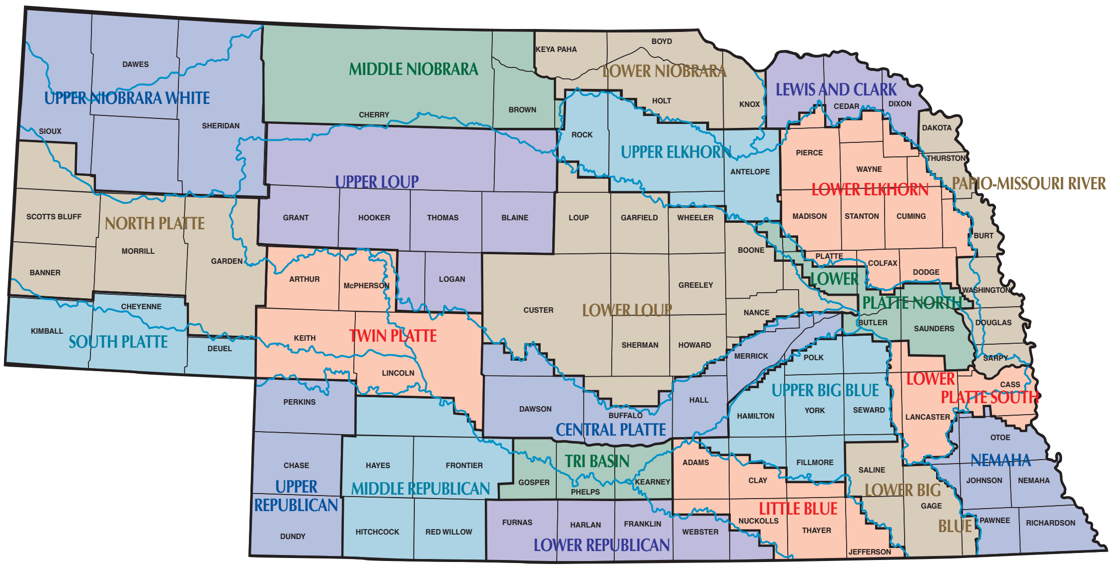

Figure 3: Nebraska NRDs and county boundaries (Source: Papio-Missouri NRD, https://www.papionrd.org/)

Texas

In Texas, the HPA underlies the Northwest, or Panhandle, region of the state. While this region only accounts for 13% of the land area of Texas, it includes approximately 34% of the state's cropland and 1.4 m hectares of land irrigated with water from the HPA (Table 1)(McGuire, 2017; USDA-NASS, 2012). Like Nebraska and Kansas, irrigated agriculture is the largest user of groundwater in the state. It accounts for 79% of total groundwater withdrawals and 82% of the total groundwater used for irrigation is drawn from the HPA (Closas and Molle, 2016). The HPA in Texas receives almost no recharge from precipitation, and extraction for irrigation far exceeds the recharge rate, resulting in a steady decline in groundwater levels (Kaiser and Skillern, 2001). Between predevelopment and 2015, the HPA region of Texas saw an area-weighted average groundwater level decline of 12.5 meters (Table 1) (McGuire, 2017).

Over the course of more than a century of changes, local management and protection of private property rights have remained at the core of groundwater governance in Texas (Closas and Molle, 2016; Maleki, 2016). Groundwater is allocated based on the Rule of Capture, meaning landowners have virtually unrestricted use for any purpose. They can use as much water as they want, even if it harms their neighbor, unless interference with a neighbor's use is malicious or negligent (Aiken and Supalla, 1979; Massey and Gordon, 1984). Additionally, landowners expressly own the groundwater itself, and groundwater is not treated as a public resource (Massey and Gordon, 1984). This governance structure significantly impacts the management of groundwater in Texas because regulations that restrict use without compensation may not be legal under the state constitution.

Litigation around groundwater rights and use has been common in Texas. The courts have repeatedly upheld the rights provided under the Rule of Capture and have ruled that if landowners come under regulation by public agencies, they need to be compensated and can seek damages for a violation of their real property rights (Closas and Molle, 2016; *Edwards Aquifer Authority v. Bragg Pecan Farm*, 2013, *Houston & Texas Central Railroad Company v. East*, 1904; Kaiser and Skillern, 2001). This legal precedent exposes Texas regulatory agencies to costly lawsuits and has made them hesitant to deny groundwater withdrawal permits or enforce regulations (Closas and Molle, 2016).

Groundwater in Texas is regulated through a statewide system of local institutions called Groundwater Conservation Districts (GCDs). The Groundwater Conservation District Act of 1949 allowed for the establishment of GCDs as a political compromise, providing some form of groundwater regulation, while giving local control and recognizing that landowners own the groundwater (Closas and Molle, 2016; Massey and Gordon, 1984). The GCDs are responsible for conserving, preserving, and protecting groundwater and are required to develop groundwater management plans that must be approved by the state (Closas and Molle, 2016; Sophocleous, 2011). They are the only institutions in the state with the legal authority to regulate groundwater, and have the power to implement and enforce rules regarding licensing of new wells, well spacing, production of wells, and cross-county or cross-basin water transfers (Closas and Molle, 2016). A Board of Directors governs each GCD, and members may be locally elected or appointed (Texas Water Development Board, 2017a). There are currently 98 GCDs, and collectively they cover 70% of the state (Texas Water Development Board, 2017a). The GCDs range in size from 259 to 31,079 km^2 and each district can encompass a partial county, a single county, or multiple counties (See Figure 4). There are 8 separate GCDs that overlay the HPA in Texas.

After several decades of limited action in establishing GCDs, the Texas Legislature passed additional laws in 1985, 1997, and 2001 to encourage the formation of more districts (Texas Water, 2014). These laws focused on critical areas to address declining water tables in parts of the state and to mandate establishment of a GCD under certain conditions (Kaiser and Skillern, 2001). The 2001 legislation also gave the Texas Water Development Board (TWDB) the responsibility of creating Groundwater Management Areas (GMAs) (Sophocleous, 2011). The GMAs are delineated along aquifer boundaries to encourage coordination of groundwater management and planning across GCDs located in the same aquifer. There are 16 GMAs, and collectively they cover the entire state (Texas Water Development Board, 2017b). As of 2005, the GCDs within a GMA are required to engage in a joint planning process to determine the desired future conditions for the management area (Closas and Molle, 2016; Sophocleous, 2011). These future conditions must be quantified, such as water levels or volumes, and physically possible, and they must be submitted and approved by the TWDB (Sophocleous, 2011).

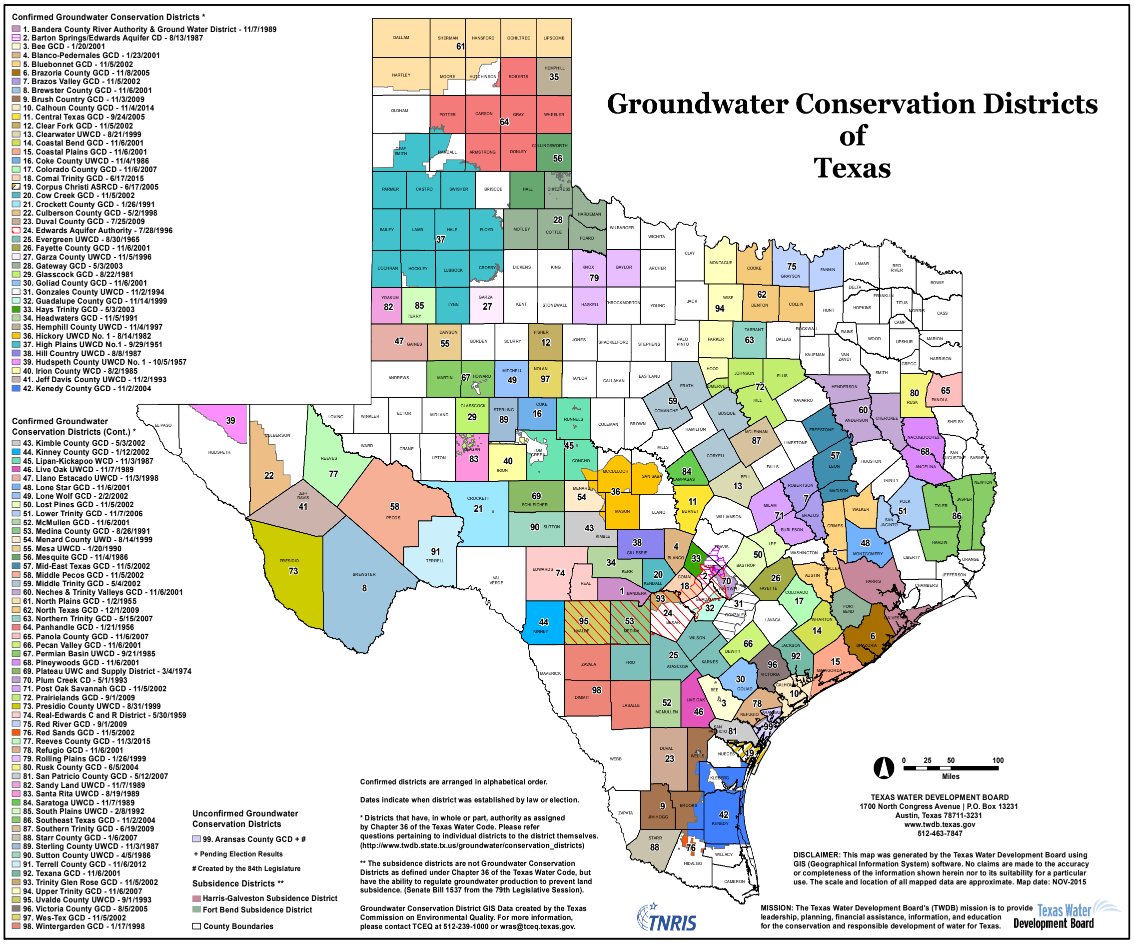

Figure 4: Texas Groundwater Conservation Districts (Source: Texas Water Development Board, http://www.twdb.texas.gov/)

ANALYSIS

In this section, we evaluate the extent to which the groundwater governance institutions in each state resemble the principles of WD. To assess this, we rely on a review of peer reviewed literature, reports, and state government documents[2] and assess them within the context of Ostrom's eight design principles for sustainably governing CPRs (See Table 1 for a summary of results). We begin each section describing our evaluative criteria for each of the eight principles, then follow with an analysis for each state on the extent to which each state meets the principles. The results of this analysis are summarized in Table 1.

Overall, the state of Nebraska most fully meets the design principles, followed by Texas, and finally Kansas. A detailed explanation for these rankings follows in sections 5.1-5.8, and these results in the context of WD and larger governance implications follow in section 6.

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[2] We have also included some references to personal interviews that were conducted as part of other research on Nebraska's NRDs. These are referenced as, "personal interview" in the text.

Table 2: Assessment of the extent to which each state in this study meet Ostrom's eight design principles for sustainably governing CPRs

Sustainable Governance Design Principle	Kansas	Nebraska	Texas
Clearly defined boundaries	*Fully meets*	*Fully meets*	*Partially meets*
Proportional equivalence between benefits and costs	*Partially meets*	*Fully meets*	*Partially meets*
Collective-choice arrangements	*Does not meet*	*Fully meets*	*Partially meets*
Monitoring	*Does not meet*	*Fully meets*	*Partially meets*
Graduated sanctions	*Fully meets*	*Fully meets*	*Fully meets*
Conflict-resolution mechanisms	*Does not meet*	*Partially meets*	*Does not meet*
Minimal recognition of rights to organize	*Partially meets*	*Fully meets*	*Fully meets*
Nested enterprises	*Does not meet*	*Fully meets*	*Partially meets*

Clearly defined boundaries

Criterion: The boundaries of the resource system being governed and the individuals with rights to withdraw the resource must be clearly defined (Ostrom, 2008, 1990). Clearly defined boundaries allow for the exclusion of outsiders and ensures that conservation activities made by those with rights to withdraw the resource receive expected returns on investment (Bleed and Babbitt, 2015; Ostrom, 2009, 1990).

All three of the states' governance systems clearly define the boundaries of the groundwater resource and the individuals who have rights to withdraw the resource (Bleed and Babbitt, 2015; *Kan Stat. Ann. §82a-1033*, 2017; Wagner and Kreuter, 2004). The key difference between the states is in how they address the interconnected nature of surface water and groundwater in some basins, where groundwater acts as a source of water for surface flows and where excessive withdrawal of groundwater can negatively impact surface water. Recognition of this hydrological connectivity goes beyond the common mindset of groundwater and surface water as separate, bounded entities and reflects an increasing understanding of how hydrological systems function holistically.

Both Kansas and Nebraska have established mechanisms to address hydrologically connected water resources. In Kansas, state law allows the Chief Engineer to establish IGUCAs and implement control provisions to protect surface flows from impairment from excessive groundwater pumping (Griggs, 2014b; Peck, 2004). Nebraska has addressed this challenge through its requirement that the DNR and NRDs collectively develop integrated water management plans in interconnected basins where water-scarcity is a problem. Unlike Kansas and Nebraska, Texas regulates groundwater and surface water separately (Maleki, 2016).

We argue that in situations where surface water and groundwater are hydraulically connected, the boundaries of the governance system should be extended to include this interconnectivity; otherwise, the resource cannot be effectively governed. Both Kansas and Nebraska have established measures that do this, while Texas has not. Thus, while all three of the states clearly define the groundwater resource boundaries, technically meeting this design principle, we argue that in hydrological reality, both Kansas and Nebraska fully meet this design principle, while Texas only partially meets it.

Proportional equivalence between benefits and costs

Criterion: Rules specifying the quantity of the resource allocated to a user are related to local conditions and to rules requiring labor, materials, and/or financial inputs (Ostrom, 2008). For these rules to achieve long-term sustainability and for them to be considered fair by users, the rules must be tailored to fit the local problem such that the costs of compliance with the rules do not outweigh the benefits (Anderies and Janssen, 2013; Ostrom, 1990). The first aspect of this principle requires that the approach to water governance reflects the conditions of a given locale. Each of the three states has some way in which the rules specifying the amount of groundwater allocated to users and the regulation of use are related to local conditions.

Of the three states, Nebraska's NRD system most closely aligns with this design principle. Under Nebraska law, all NRDs are charged with the same general responsibilities, but the law provides flexibility for each district to develop its own rules, determine which control measures to use, and take action based on local conditions (Bleed and Babbitt, 2015; Edson, 2005). Additionally, there are procedures that allow the NRDs to establish different rules within sub-areas of a single NRD based on data from a network of monitoring wells across the state, which further enhances their ability to address and tailor control measures to location-specific conditions (Bleed and Babbitt, 2015; Nebraska Association of Resource Districts, 2013; Nebraska Association of Resource Districts (NARD), 2016).

In Kansas, all groundwater users must hold a water right issued by the KDWR, and all water rights are limited to an annual quantity that cannot be increased (Griggs, 2014b; Peck, 1995). However, allocation of these rights is determined through the prior appropriation doctrine rather than being based on local conditions, and there are more water rights granted than there is groundwater to supply the full authorized quantity (Griggs, 2014b). Like Nebraska, Kansas has procedures, through the IGUCA process, to establish different rules in sub-areas of a district to tailor control measures to location-specific conditions. However, while the rules officially exist to address local shortages through IGUCAs, there hasn't been the political will to do so. Griggs (2017) points out that IGUCAs have only been established in areas where the groundwater supplies are renewable and connected to surface water bodies, where they have actually restored some degree of hydrological balance. However, he goes on to note that neither the GMDs nor the Chief Engineer have sought to establish IGUCAS in any of the areas above the HPA with the most severe depletion problems. IGUCAs were supposed to enable local irrigators to take the lead in reducing groundwater withdrawal by encouraging the Chief Engineer to reduce pumping, even if it conflicted with prior appropriation, but they have proven too powerful a tool to use (Griggs, 2017).

In Texas, all GCDs are tasked with the same general responsibilities, and each district develops its own local management plan, goals, and rules to regulate groundwater based on local conditions. Texas has developed limits on total groundwater pumping that are set for a specific period of time and that can fluctuate based on local climate conditions – they can be lifted in wet years when recharge is higher and increased under drought conditions (Kelly, 2010). This approach was incorporated into legislation applicable to all

GCDs and requires GCDs in a GMA to agree to desired future conditions for the aquifer (Kelly, 2010). It is designed to create limits on how much water can be extracted from an aquifer over a 50 year planning period, and gives groundwater rights holders the flexibility to sell water to third parties willing to pay for their water rights (Kelly, 2010; Wagner and Kreuter, 2004). On paper, Texas's GCD system allows for adaptability to local conditions and for the flexibility of users to comply in ways that benefit them. However, efforts by the GCDs to enforce rules limiting groundwater use are hindered by the legal limitations that the Rule of Capture places on them. The fact is that, aside from a small number of case studies of how GCDs operate, there is little information beyond what the legislation prescribes about how these institutions make decisions and with what effect.

The second aspect of this design principle requires congruence between the rules that assign benefits and the rules that assign costs. Both Kansas and Nebraska have funding streams that allow them to collect taxes to fund regulatory and incentive-based control measures that can be tailored to local conditions and provide benefits to water users. In Texas, the state provides GCDs little financial or technical assistance, and some are restricted from imposing *ad valorem* property taxes, making them dependent on pumping fees, which can actually create a perverse incentive for more pumping in order to collect fees (Kelly, 2010).

In summary, only Nebraska fully meets this design principle. Kansas and Texas partially meet this design principle because while they have the laws officially on the books to meet it, prior appropriation allocation and limited IGUCA establishment in Kansas, and the Rule of Capture and the reliance on pumping fees in some GCDs in Texas, prevent them from meeting the principle in practice.

Collective-choice arrangements

Criteria: When multiple users are dependent on the same resource for economic activity, the well-being of individuals is tightly interconnected to the actions of others in the same resource system (Bleed and Babbitt, 2015). The basic problem they face is in organizing a governance system to avoid allowing individual water users to act independently of each other, and in creating a system in which they adopt coordinated strategies to achieve higher collective benefits and/or reduce collective harm (Bleed and Babbitt, 2015; Ostrom, 1990). In other words, the collective-choice criterion is thought to represent the key to reducing the likelihood that water governance will lead to a "tragedy of the commons." To achieve collective-choice, most individuals affected by governance rules should be included in the group who can modify them (Ostrom, 1990). This does not mean that legally authorized decision makers must yield authority to the collaborating group; rather, stakeholders must have an active role in joint problem solving, formulating alternatives, and ranking preferred solutions (Bleed and Babbitt, 2015; Bruns, 2003).

This design principle appears to be strongest in Nebraska because the institutional structure of the NRDs encourages collective-choice arrangements, and the NRDs have broad regulatory and enforcement authority. Any citizen of an NRD may run for director or for the board, and the members, who make the rules, are part of the local community and must follow the rules themselves (Bleed and Babbitt 2015; personal interviews). In effect, those governed by the rules are able to participate directly in developing and modifying the rules by serving on the board, and indirectly through the public meeting process of the NRD boards, where stakeholders can provide input as rules are created or modified.

While the Kansas GMDs were created with local management and stakeholder participation in mind, in practice this participation is narrowly drawn (Peck, 2006). Peck (2006) points out that the GMD Boards of Directors are made up primarily of irrigators, landowners, and other water users and that few positions on the boards are reserved for other stakeholders, such as municipal interests, environmental interests, or businesses that do not use large quantities of water or hold water rights, or for the public at large. The Boards are locally elected, but the KGMDA defines an eligible voter narrowly as an adult person, or corporation, municipality or any other legal or commercial entity that: 1) owns 16.2 ha (40 acres) of land within a GMD and not within the corporate limits of any municipality, and 2) that withdraws at least 1,233 m^3 (1 acre-foot) of groundwater from within the GMD annually (*Kan Stat. Ann. §82a-1021*, 2017). This definition of an eligible voter excludes the participation of all stakeholders who are affected by the rules and is problematic for this design principle. Additionally, while the GMDs are local institutions, they have limited authority to make and modify the rules regarding groundwater allocation and regulation because the state has primary authority. Thus, we argue that Kansas does not meet this design principle.

Local control is central to the GCD system in Texas, but unlike Nebraska and Kansas, not all GCD bylaws require that their boards of directors be locally elected (Lesikar et al., 2002). As in Nebraska, the GCD system allows for rules to be made and enforced at the local level, which meets conditions for the collective-choice design principle. However, Texas only partially meets this design principle for two key reasons. First, because in some GCDs board members can be appointed rather than elected, individuals affected by the rules in these districts do not have the opportunity to be included in the group that modifies them. Second, the way in which the GCD boundaries are drawn, almost totally by those individual people who form and propose creation of a GCD and primarily along county lines, negatively impacts collective-choice arrangements, albeit somewhat tangentially. The county-based GCD system means that, in some cases, the larger aquifer is carved up into multiple management jurisdictions. These smaller jurisdictions are more easily influenced by interests in one part of the aquifer. This can dilute the representation of stakeholders in the larger resource system and gives disproportionate weight to certain local constituencies, often leading to management decisions that may be counter to the interests of the stakeholders in the resource system as a whole (Dupnik, 2012). If this is accurate, we would expect the consequence to be an inability to affect groundwater depletion. Indeed, although significant collaboration seems to have taken place among researchers and stakeholders in the two most prominent GCDs – the Panhandle Groundwater Conservation District and the North Plains Groundwater Conservation District, this collaboration does not seem to have altered the patterns of water consumption or depletion there (Johnson et al., 2011). This fragmented nature of groundwater governance is not unlike Nebraska, where some groundwater basins are governed by multiple NRDs. But, Nebraska has largely overcome this through the required coordination between the NRDs and DNR in water-scarce hydrologically connected basins, and by the legal precedent that NRDs must regulate groundwater in their districts to protect users in another NRD if the districts are hydrologically connected (Bleed and Babbitt, 2015; Hoffman and Zellmer, 2013; *Upper Big Blue NRD v. State, DNR*, 2008).

Monitoring

Criterion: Monitors who actively audit the resource and user behavior are at least partially accountable to users and/or are users themselves (Ostrom, 2008, 1990). With communication and neutral monitoring, no user can expect to over extract without other users learning of the noncompliance (Bleed and Babbitt, 2015; Ostrom, 1990).

Only Kansas and Nebraska actively monitor groundwater conditions and user behavior for all districts and make those data publicly available. In Kansas, every GMD requires meters on almost all irrigation wells, and every groundwater right owner must report annually to the Chief Engineer data such as quantity pumped, type of use, pump rate, and place of use (Griggs, 2014b; Sophocleous, 2012). At the state level, the Kansas Geological Survey maintains a network of about 1,400 monitoring wells that are tested annually in January, when irrigation activity is at a minimum (Sophocleous, 2012).

In Nebraska both the state and NRDs have widespread monitoring systems, but the extent and quality of monitoring varies by NRD. The Nebraska DNR has extensive, publicly available data on every registered well across the state (see https://dnr.nebraska.gov/data). Most NRDs require certification of groundwater irrigated acres, permits for new wells, installation of meters on high-capacity wells, reporting on groundwater use, and have instituted moratoria on drilling new wells or on adding new irrigated acres without water use offsets (Nebraska Association of Resource Districts (NARD), 2016). Depending on the NRD and the monitoring measures, these regulations may be implemented district-wide or in sub-areas of the district where water quantity is a concern (Bleed and Babbitt, 2015). Only two of the 23 NRDs require no metering or water use reports, and one of those is located along the Missouri River, giving it access to a steady surface water source (Nebraska Association of Resource Districts (NARD), 2016)

Only 86% of Texas GCDs actively monitor aquifer storage levels (Closas and Molle, 2016). At the state level, the TWDB monitors groundwater and provides models for most aquifers in the state to facilitate the process of defining a sustainable yield for a given area (Kelly, 2010; Wagner and Kreuter, 2004). This program has been successful in providing accurate, publicly available models for regional water planning and in raising stakeholder awareness of the importance of groundwater management (Kelley et al., 2008; Sophocleous, 2010). State law requires all wells to be registered and for GCDs to establish permitting programs for drilling new wells and for substantial alterations of existing wells (Lesikar et al., 2002). However, GCDs are authorized to exempt any and all wells from permitting requirements if those exemptions are documented in the district’s management plan and if rules are in place allowing these exemptions (Lesikar et al., 2002). Finally, most GCDs do not require meters on wells, and as a result, data for monitoring withdrawal levels is not very accurate (Closas and Molle, 2016; Lesikar et al., 2002).

While some form of monitoring is in place in all three states, only Nebraska fully meets and Texas partially meets this design principle. Ostrom (1990) indicates that the individuals and organizations who monitor the resource conditions and user behavior must be at least partially accountable to the users of that resource and/or should be users themselves. Kansas does not meet this requirement because the Chief Engineer is not a user, and because he is appointed rather than elected, is not accountable to groundwater users. Texas has the lowest rate of active monitoring of the three states, and most GCDs do not require meters on wells, but, where monitoring and metering are in place, the data are submitted to the GCDs. Since the GCD boards are comprised of groundwater users, where monitoring is in place, Texas meets this design principle.

Graduated sanctions

Criterion: Groundwater users who violate the rules are likely to be assessed graduated sanctions, dependent on the seriousness and context of the offense, by other users and/or by officials accountable to these users (Ostrom, 1990).

All three of the states include some form of graduated sanctions in their governance institutions. Kansas law allows for sanctions that vary based on the severity of the violation, including increasing civil penalties per violation, varying degrees of misdemeanor charges, and in extreme cases, jail sentences (*Kan. Stat. Ann. §82a-1214*, 2017, *Kan. Stat. Ann. §82a-1216*, 2017; Kansas, 2017). Further, groundwater users can have their water rights revoked for non-use or for failure to follow conditions imposed by the KDWR (Peck, 1995). Bleed and Babbitt (2015) indicate that Nebraska's NRD system employs sanctions dependent on the seriousness and context of the offence. They note that the NRDs have shown flexibility in sanctioning, in some cases granting variances to their rules to allow a violator who is acting in good faith time to comply without incurring additional penalties. The Texas Water Code allows GCDs to issue civil penalties in the form of fines that are reflective of the severity of the violation (*Tex. Water Code §13.102*, 2017).

Conflict-resolution mechanisms

Criterion: Groundwater users and their officials have rapid access to low-cost, local avenues to resolve conflict between users and officials or among users (Ostrom, 1990). Users who possess a legal water right should be able to initiate action to enforce compliance without having to rely on a higher-level entity, such as costly and time-consuming lawsuits, to resolve non-compliance (Bleed and Babbitt, 2015). Absent these mechanisms, users and their officials can feel powerless and ineffective in their efforts to manage the resource (Bleed and Babbitt, 2015; Ostrom, 2009, 1990).

While none of the states fully meet this principle, Nebraska does provide a mechanism that meets these criteria for certain types of conflicts. In Nebraska, disputes among groundwater users can be resolved through a formal complaint process through the NRDs, which offers local, low-cost arenas to resolve conflicts among groundwater users (Bleed and Babbitt, 2015). Nebraska state law also allows for disputes over hydrologically connected surface and groundwater, either between NRDs or between an NRD and the DNR, to be taken to an *ad hoc* five-member board appointed by the Governor, the Interrelated Water Management Board (Bleed and Babbitt, 2015; *Neb. Rev. Stat. §46-717-71*, 2005). However, Nebraska state law has not established formal institutional alternatives to lawsuits to resolve disputes between individual surface and groundwater users or between groundwater users, or for any other entity that is not the DNR or an NRD who has a dispute with water officials (Bleed and Babbitt, 2015).

In Kansas, disputes over groundwater are resolved either by the Chief Engineer or in state general court (Griggs, 2014b; Joshi, 2005). While dispute resolution through the Chief Engineer offers a low-cost solution, we do not consider this a local arena because the he is a central representative of the State. In Texas, disputes over groundwater are settled in the courts (Closas and Molle, 2016). The reliance on courts as the only mechanism to resolve disputes is troublesome because it is neither a local nor low-cost arena (Bleed and Babbitt, 2015).

In summary, we find that none of the states fully meet this design principle. We argue that Nebraska partially meets the principle because while it has no state law establishing alternatives to lawsuits, it has mechanisms for certain situations that can be resolved by individual NRDs and through the Interrelated Water Management Board. We argue that neither Kansas nor Texas meet this design principle due to no local avenue for conflict resolution or reliance on the courts.

Minimal recognition of rights to organize

Criterion: The rights of groundwater users to devise their own institutions are not challenged by external governmental authorities, and users have long-term tenure rights to the resource (Ostrom, 2008, 1990).

Recognition of rights to organize is present in each of the three states. In each state, users have long-term, transferrable rights to groundwater. In Kansas, users can organize by petitioning the Chief Engineer to establish a GMD, IGUCA, or LEMA. However, because these institutions require approval of the non-local Chief Engineer and have limited authority to make rules, this principle is only partially met. In Nebraska, users organize through their local NRD and the rights of the NRDs to devise their own rules to regulate groundwater are clearly recognized (Bleed and Babbitt, 2015). In Texas, users can organize by petitioning the Texas Commission on Environmental Quality to create a GCD, and GCDs have clearly recognized rights to develop their own rules to regulate groundwater (Wagner and Kreuter, 2004). This principle is fully met in both Nebraska and Texas.

Nested enterprises

Criterion: Governance activities are organized in nested enterprises in which appropriation, monitoring, enforcement, conflict resolution, and other governance activities are organized in multiple layers (Bleed and Babbitt, 2015; Ostrom, 2008, 1990). Nested enterprises help ensure that management of the resource across different scales does not create harmful impacts to others without mitigation or compensation, and support from higher-level institutions helps overcome pressure to reduce use restriction from local users on local institutions (Bleed and Babbitt, 2015; Peterson et al., 1993; Wiek and Larson, 2012)

We argue that only the institutional structures of Nebraska and Texas qualify as nested enterprises with regards to groundwater governance, though to differing degrees. The exclusion of Kansas is due to the fact that the primary authority to regulate and control groundwater rests with the central authority of the Chief Engineer of the KDWR. In practice the GMDs play only an advisory role, making recommendations, while the power to implement regulations remains at the state level in the hands of the Chief Engineer (Griggs, 2014b; Hoffman and Zellmer, 2013; Peck, 2006).

In contrast, Nebraska's governance structure fully meets this design principle. NRDs are part of a nested hierarchy, with significant power to act at the local level, and with coordination between NRDs when a groundwater basin underlies multiple districts and between NRDs and the DNR in areas with hydrologically connected surface water and groundwater (Bleed and Babbitt, 2015; Hoffman and Zellmer, 2013). Bleed and Babbitt (2015) point out that the Nebraska state government has very limited authority in the hierarchy, which impacts its ability to engage at multiple scales and across NRD boundaries. For example, the state Department of Environmental Quality (DEQ) can set standards for groundwater quality, but the NRDs have extensive flexibility in how to achieve those standards. DEQ has ultimate authority in verifying that these standards are met but does not necessarily have the resources for enforcement across the state (personal interviews). This does not mean that the NRDs are not part of a nested system, they are simply part of a nested system in which the state has granted them broad authority.

In addition to being nested within the state regulatory agencies, NRDs are nested above counties and municipalities. They encompass multiple counties or parts of counties and municipalities, and in turn, some counties may be part of more than one NRD. Some NRDs have been able to address some of the complexity that comes with these jurisdictional overlaps by establishing bridging organizations that allow for stakeholders to collaborate and find solutions at the appropriate scale (Bleed and Babbitt, 2015).

The institutional structure of groundwater governance in Texas clearly represents a nested hierarchy in which the state and local communities interact to regulate and manage groundwater (Closas and Molle, 2016). GCDs were created by the Texas Legislature to act as local supervisory authorities, under which counties and municipalities are nested – though there is no legal connection between GCDs, county governments, and municipal governments, the connections are largely informal and, in some cases, symbiotic. However, groundwater in Texas is, in practice, governed by two opposing forces, the

GCDs and the Rule of Capture (Maleki, 2016). The Texas Supreme Court has reaffirmed the Rule of Capture as the law of the land and has repeatedly deferred to the legislature to develop rules to manage groundwater. The Court has asserted that the legislature has the constitutional authority to abolish, modify, or change the rule and replace it with state or local regulations (Kaiser and Skillern, 2001). At the same time, the Court has also made it clear that landowners should be entitled to compensation if they are harmed by the regulations. So, while the legislature is constitutionally allowed to regulate groundwater use, there are legal barriers to doing so, and it is not clear at what point restrictions on groundwater withdrawal would constitute a taking. This effectively hamstrings the actual authority of GCDs to govern groundwater, which then brings into question whether, *in practice*, Texas represents a nested hierarchy. For this reason, we argue that Texas only partially meets this design principle.

DISCUSSION AND CONCLUSIONS

In section 2 of this paper we argued that at its current nascent stage as a discipline, WD largely represents a subset of Ostrom's work in the context of water governance. As such, this WD analysis occurred through the lens of Ostrom's institutional design principles. It is important to note there is nothing in the Ostrom design principles that guarantees any particular result. It's entirely possible that a water governance system might have all the characteristics identified by Ostrom and still produce outcomes unfavorable to some stakeholders, i.e. aquifer depletion. Of course, the argument is that when these characteristics are present, then the conditions necessary for WD are more likely. And when the conditions necessary for WD are more likely, interpersonal interactions will take place in a way that improves the likelihood of better outcomes, i.e. agreements will be reached to yield less water depletion.

Our analysis suggests that multiple variables impact the extent to which a groundwater governance institution exhibits the characteristics of WD and is thus more likely to achieve the goal of less groundwater depletion. Kansas demonstrates the extent to which the lack of an empowered local institutional setup can negatively impact achieving the design principles for sustainably governing CPRs. The state's reliance on the central, state-level authority of the Chief Engineer was responsible for it only partially meeting two of the principles and prevented it from meeting four of them.

Texas demonstrates that groundwater allocation rules can negatively impact achieving the eight design principles and can severely limit the options for managing the resource. Despite having legislatively created a local groundwater governance system that, at least partially, meets collective-choice principles, the Rule of Capture has created conditions where GCDs are wary of imposing limits on pumping for fear that they will be drawn into costly lawsuits over whether the restrictions constitute a taking of property rights. The Texas Supreme court recently declined to hear a case that could have added much needed clarity, which sets the stage for years of costly litigation over groundwater (Malewitz, 2015). Meanwhile, groundwater levels continue to drop.

Like Texas, Kansas has designated groundwater as a property right. This poses a potential challenge to the state's ability to regulate groundwater use more sustainably.

We noted in section 5.2 that there have been more water rights granted in Kansas than there is sustainable supply of groundwater. Currently, most groundwater users comply with their annual pumping limits, but this compliance does not address the problem of depletion because the resource itself is over appropriated (Griggs, 2014b). If the state attempts to increase limits on pumping, it could find itself in a similar situation to Texas, where these restrictions are considered a taking of property by the government.

Nebraska no doubt faces important challenges with continuing to manage its supply of groundwater sustainably. There are parts of the state where groundwater levels continue to decline, and the nature of groundwater means that there is a lag between management actions and their impacts (Bleed and Babbitt, 2015). Because of this, it could be too soon to fully judge the success of Nebraska's current governance action (Bleed and Babbitt, 2015). However, Nebraska is one of the most intensely irrigated and productive agricultural regions of the world, and it has achieved this without widespread groundwater depletion and has managed to reverse or slow depletion across much of the state (Bleed and Babbitt, 2015). This is in stark contrast to the HPA regions of Kansas and Texas, where governance institutions are limited by allocation and property rights choices, and where decades of groundwater governance have not abated the problem. This depletion has already made vast stretches of land in these states unable to support irrigated agriculture (Wines, 2013). For an example of the scale of the problem, one need only look at the estimate that the HPA in Texas is expected to lose 52 percent of its volume by 2060 (Galbraith, 2010).

It is important to note that Nebraska is fortunate to overlay the largest share of the HPA and has more favorable hydrogeology for recharge than do Kansas and Texas. However, the state's relative success in managing groundwater sustainably is attributable to more than fortunate geography. Nebraska has demonstrated the ability to adapt to conditions as monitoring data indicates control measures are necessary. The NRD system deserves a great deal of credit for helping to reverse or stabilize groundwater levels in areas of the state, even in areas with low recharge rates. Nebraska demonstrates that a groundwater governance system built around Ostrom's eight principles can create adaptive, collaboratively managed governance institutions for the sustainable management of this CPR. The NRD system appears to be gaining recognition for its achievement. Experts on the NRD system, interviewed by one of the authors for ongoing research, indicated that NRD representatives have been consulted by the state of California as it has developed its Sustainable Groundwater Management Program, and that they have been invited to present on their governance system at national and international conferences.

This analysis provides insight on how to improve governance of groundwater through the lens of WD. The field of WD is new and evolving, and its application to the sustainable governance of groundwater is virtually absent in the existing literature. In this paper, we extended WD principles to the macro, governance level by viewing it as a sub-set of Ostrom's work on CPR management. Further research is needed on how best to develop a WD framework and set of analysis tools that are specific to the discipline and that are focused on water. At its core, the WD Framework developed by Islam and Susskind (2013) has a good deal of synergy with Ostrom's eight principles. Both call for adequate stakeholder participation, and the Framework's joint fact-finding component that seeks to develop a shared understanding of the resource and the key variables that affect it is similar to Ostrom's monitoring principle. Nested enterprises relate to the Framework's fourth principle of linking informal problem-solving to formal decision-making processes at the higher governance level. Nested enterprises and collective choice arrangements are related to adaptive collective management and enable governance institutions to respond to new conditions and information over time (Ostrom, 2000). They are also related to the Framework's sixth principle of capacity building and societal learning among individuals, organizations, and networks.

Further research is needed on expanding the WD Framework for specific application to governance institutions. Ostrom's principles are necessary conditions but not necessarily sufficient, and variables specific to water or other variables such as political will could be potential additions to a WD Governance Framework. Recent work by Bleed and Babbitt (2015) represents a useful step down the path to this process. Their assessment of Nebraska's NRDs expanded upon Ostrom's principles and incorporated additional ones for a total of 14 criteria. While not intended as a study on WD, their work was referenced extensively in this paper and contributes to the discussion in the literature on the development of a WD Governance Framework. We hope that this paper represents an important contribution on refining this evolving field.

ACKNOWLEDGEMENTS

This work was supported by the National Science Foundation under Grant #0966093, Integrative Graduate Education and Research Traineeship (IGERT) Program on Water Diplomacy at Tufts University.

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CHAPTER 4: Nebraska's Natural Resource District System: Synergistic Approaches to Groundwater Quality Management

Written in the style of *Journal of Soil and Water Conservation*

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ABSTRACT:

Nonpoint source pollution of nitrates into groundwater from agricultural activity is an emerging problem for which developing effective policy approaches has proved difficult. There is little empirical information on effective governance to address agricultural nonpoint source pollution into groundwater and on what regime attributes can accomplish sustainability goals within this context. Nebraska's Natural Resource District system presents a rare example of a groundwater governance regime demonstrating the conditions likely to generate sustainable groundwater quality outcomes. We focus on three groundwater nitrate management programs in the state that are collectively representative of the broader Natural Resource District system. This research shows that two overarching enabling conditions are responsible for the successful trend in addressing groundwater nitrates: 1) Nebraska's polycentric, locally empowered groundwater governance regime and 2) the synergistic and collaborative management approaches to the groundwater quality programs. We find that these aspects of the NRD system have created the enabling conditions for adaptive, collaborative governance that positions the state well to address emerging groundwater quality challenges. We present generalizable aspects of the governance regime that are applicable to other U.S. states as efforts to address nitrate pollution in groundwater increase.

Key Words:

Nonpoint source pollution, polycentric governance, groundwater quality, local governance, nested regimes, nitrates

INTRODUCTION

Nonpoint source (NPS) pollution of nitrate into groundwater represents a slow onset disaster (Twigg 2004). Nitrate is the most common chemical contaminant in groundwater worldwide, and its principal source in the U.S. is from the long-term, widespread application of nitrogen fertilizer for agriculture (Spalding and Exner 1993, Rupert 2008, Exner et al. 2014). The most extensive contamination in the U.S. occurs in groundwater under intensively irrigated areas (Spalding and Exner 1993, Burow et al. 2010). Because it is the cumulative result of prolonged fertilizer application and its sources are diffuse, it can take decades for nitrate problems to materialize. Most often, regulation of NPS pollution does not occur until water quality problems become overt, and regulation generally faces the fiercest resistance in areas with strong agricultural interests (Craig and Roberts 2015).

Developing effective policy approaches for governing groundwater NPS nitrate pollution has proved challenging for two fundamental reasons: 1) because nitrates are diffuse and infiltrate into groundwater at the landscape scale, efforts to address them require changes in farm management among multiple, diverse actors across large areas, and 2) due to the long timescales of groundwater processes and impacts, groundwater policy timeframes are often inconsistent with the hydrogeologic context in which they must function (Gleeson et al. 2012). This means that NPS governance regimes need to be set up to achieve behavior change among a range of stakeholders and must do so under conditions of complexity and long-term uncertainty.

Governance regimes are defined as, "the wide range of rules, norms, traditions and other institutional arrangements (laws, policies) by which decision making is exercised, enforced and modified, over time, by different actors" (Narayanan and Venot 2009, 321). Huitema et al. (2009) identified four conditions that are necessary for successful water governance regimes:

1) Polycentric governance, meaning that they are in fact 'nested governance regimes' made up of multiple independent decision making entities with overlapping and redundant authority who coordinate on governance decisions (Ostrom et al. 1961, Marshall 2008, Huitema et al. 2009);
2) Public participation, meaning collaboration between governmental and non-governmental stakeholders (Huitema et al. 2009);
3) Experimentation, meaning that different policy interventions, involving multiple stakeholders at various comparable locations, are applied and evaluated for effectiveness to foster learning from multiple perspectives and build trust, thereby increasing the ability of governance regimes to deal with uncertainty (Moberg and Galaz 2005, Huitema et al. 2009, Lejano and Ingram 2009); and
4) Congruence between the boundaries of the resource being governed and the management institutions governing it, which can be accomplished through collaboration of existing jurisdictions or by transferring responsibility to an organization that manages water at the aquifer or basin scale (Young 2002, Blomquist and Schlager 2005, Huitema et al. 2009).

In view of these conditions, polycentric governance thus implies a combination of centralized/decentralized, top-down/bottom-up governance, a combination of steering and self-organization, and a good policy instrument mix (Marshall 2008), to achieve synergies in nested governance regimes. While it is not a principal critique of polycentric governance, it has been noted in the literature that in complex resource management situations, higher-level government authorities may be reluctant to yield their decision-making power to lower-level authorities (e.g. Marshall 2008, Ross and Dovers 2008, Huitema et al. 2009, Ross and Martinez-Santos 2010).

The literature base on agricultural NPS pollution governance regimes is relatively small, comprised mostly of theoretical models, and lacks empirical studies of policy implementation (Dowd et al. 2008). A review of environmental interventions by Parker et al. (2009) concluded that mixed intervention approaches – consisting of some combination of voluntary, compulsory regulatory, financial support/penalties, education, audits, and business advice instruments – are the most effective means through which to achieve sustainability goals. A mixed intervention approach accounts for the variability in views, understanding, and goals by different producers (Parker et al. 2009, Borrás and Edquist 2013). A review on agricultural NPS water pollution policy by Dowd et al. (2008) mirrors Parker et al.'s (2009) conclusion on polycentric governance, that mixed intervention approaches are the most successful policy framework for addressing agricultural NPS pollution.

In the U.S., the governance regime type and policy mixes vary by state, with roughly two-thirds of states having nested regimes granting some level of oversight and enforcement authority to local agencies (Megdal et al. 2015). In 36 states, groundwater quantity and quality are managed by different agencies (Megdal et al. 2015). Each state thus applies a different regulatory approach to groundwater based on institutional structure and policy mixes.

Agricultural NPS policy mixes by most states heavily favor voluntary, incentive-based approaches because they are the most politically feasible policy option and are relatively low-cost (Claassen 2003, Dowd et al. 2008, Reimer and Prokopy 2014). However, these measures are not always effective, and do not seem to follow all elements of polycentric governance. The polycentric water governance approach has been applied to other water management areas in the US (e.g. river basin management and groundwater quantity) (Garrick et al. 2011, Cosens and Williams 2012, Bleed and Babbitt 2015, Closas and Molle 2016), but there is limited knowledge of polycentric governance for groundwater management and what makes it effective (Megdal et al. 2015). This is particularly true with regards to groundwater quality. This is where this paper aims to make its contribution.

We do this by studying the state of Nebraska’s Natural Resource District (NRD) system, which is a unique groundwater governance regime that offers a promising approach through which to address NPS groundwater nitrate pollution. The groundwater governance regime in Nebraska is a nested hierarchy built on 23 empowered local institutions, called NRDs (Ostrom 2010, Bleed and Babbitt 2015). Sixt et al. (2018) and

Bleed and Babbitt (2015) demonstrated that the NRD system represents a robust governance regime for the sustainable management of groundwater *quantity*. This paper expands upon that analysis to examine the NRD system as it has evolved to include groundwater *quality* governance over the last 30 years. We present the state of Nebraska as a case study for the development of synergistic governance regimes to address agricultural NPS groundwater nitrate pollution.

This paper contributes to the limited literature base on agricultural NPS pollution governance regimes and is highly relevant to the U.S., where states will increasingly need to improve or develop their groundwater governance regimes to address the emerging slow-onset disaster of NPS nitrate pollution into groundwater. Globally, this paper is relevant as it contributes the limited literature on governances efforts in other countries to reduce groundwater nitrate concentrations that have either not succeed e.g. in Canada (Wassenaar et al. 2006), where or where desirable trends in nitrate leaching have been observed e.g. in Denmark (Hansen et al. 2011).

The goal of this research is to identify characteristics within Nebraska's NRD groundwater governance regime that are likely to lead to the eventual reduction of nitrate levels in groundwater to within safe concentration levels. Due to the long timescales associated with groundwater processes, there are few examples of where this has been achieved. Nebraska, however, provides a case of where mitigation programs have achieved a downward trend in nitrate concentrations or of where they have been developed in a way that research indicates they are likely to achieve sustainable outcomes (e.g. Ostrom 2009). We identify generalizable lessons that can be applied elsewhere as multiple states seek to develop and improve plans to address agricultural NPS groundwater pollution.

The rest of the paper is structured as follows: In the next section we discuss the methodological approach to this study, followed by a description of the Nebraska NRD groundwater governance regime and a brief description of the three study areas that are the focus of this research. We then discuss key research findings on the NRD groundwater quality governance regime, highlighting important aspects of successful nitrate management or self-organizing to collaboratively address NPS nitrate pollution. We close with a summary of the research findings and a discussion on generalizable lessons on effective polycentric groundwater quality governance.

METHODS

Methodological approach

This study uses qualitative analysis to assess the factors that affect the likelihood of the formation of programs to address the sustainable use of nitrogen inputs and nitrate remediation efforts in the state of Nebraska. We focus on three programs addressing different aspects of the groundwater NPS nitrate pollution problem in the state and that, collectively, are representative of the larger groundwater governance regime in Nebraska. These programs present examples of how a polycentric governance regime built on empowered local governance can create the enabling conditions for synergistic approaches to addressing the widespread emergent problem of groundwater nitrate pollution from agricultural activity.

In line with ideas on polycentric governance by Huitema et al. (2009), we utilize the the social-ecological system (SES) approach. We used the SES framework, developed by Ostrom (2007, 2009) and refined by McGinnis and Ostrom (2014), to develop interview questions aimed at identifying the enabling conditions that led to the self-organizing that formed these three programs, and that in some have achieved downward trends in groundwater nitrate concentrations.

The SES framework provides the researcher with a means to analyze how social and ecological domains interact through the activities of human actors involved in governing a common-pool resource (CPR) (de Loë and Patterson 2018). Groundwater is a common-pool resource (CPR) governed within the context of an SES.

An SES is an ecological system connected to and impacted by one or more social systems; it is a subset of social systems in which interdependent human relationships are deeply intertwined with interactions involving biophysical and non-human biological units (Anderies et al. 2004). A CPR is a shared natural resource having two characteristics: it is sufficiently large to make it difficult to exclude users, and each individual's use reduces benefits to other users who share the resource (Ostrom 2000).

To assess the factors that created the enabling conditions, we conducted a series of semi-structured key informant interviews (primary data), complemented with a literature review (secondary data). Semi-structured interviews provide flexibility for the interviewer to focus on interesting comments and on aspects of the topic on which interviewees have greater levels of expertise (Bruges and Smith 2009, Turner et al. 2016). The question format consisted of 23 overarching questions with probing follow-up questions designed to elicit in-depth responses (See supplementary materials for interview questions).

We conducted a pilot study in Nebraska in spring 2017 to refine the scope of the research and interview questions and to develop a list of interviewees. For this pilot, we informally interviewed 10 experts on the NRD system and nitrate mitigation efforts in the state. Using snowball sampling, we identified a list of potential interviewees and scheduled interviews for June of 2017.

34 interviews were conducted with a diverse set of subject matter experts representing: NRD staff and board members, Nebraska Association of Resource District (NARD) staff, Nebraska Department of Environmental Quality (DEQ) and Department of Natural Resources (DNR) employees, University of Nebraska-Lincoln water scientists and researchers, agricultural producers, City of Hastings Utilities staff, NRD groundwater management area project staff, agricultural extension experts, and staff from the Groundwater Foundation, a groundwater focused nonprofit organization. The identity of each respondent is protected by randomly rearranging the order of their interviews and assigning an anonymous interview number (e.g. Interview 1).

Each interview was conducted either in-person or over internet telephony and took 45 to 90 minutes. The interviews were recorded and transcribed for analysis using the NVivo for Mac software package (Version 11.4; QSR International). Secondary data sources were consulted to supplement interviews and, where possible, to verify certain claims by interviewees. Secondary data include state government and NRD reports and documents, Groundwater Management Area plans, Wellhead Protection Area plans, and peer reviewed literature.

Study Area – Groundwater governance in Nebraska and the Natural Resource District System

Nebraska has more land under irrigation than any other state in the country, and 85% of its 3.4 Mha of irrigated land relies on groundwater as its source (Bleed et al., 2015). Corn production is central to the economy of the state. Nebraska is ranked third in production nationally, and irrigated corn accounts for 66% of its irrigated area (USDA-NASS 2016).

The economic importance of agriculture, and more specifically corn, is central to groundwater quality concerns in Nebraska. Nitrogen fertilizer used in agriculture is the primary source of nitrate contamination in Nebraska's groundwater; more nitrogen fertilizer is applied to corn than to any other crop, and irrigated corn production is more nitrogen intensive than non-irrigated (Exner et al. 2014). Considering that approximately 88% of Nebraskans, and almost 99% of rural residents, rely on groundwater as their drinking water source, the impact on drinking water quality from agricultural activity is of great concern to state policy makers (NDEQ 2017). The situation is even more concerning in the central and eastern parts of the state, where 83% of the irrigated corn hectares are grown and where most of the population lives (USDA-NASS 2016). Monitoring data indicate that between 1981 and 2010, the area in this part of the state with groundwater nitrate concentrations exceeding the EPA's Maximum Contaminant Level (MCL) of 10 mg/L have nearly tripled from 0.35 to 1.3 Mha (Exner et al. 2014).

In Nebraska, efforts to address NPS nitrate pollution of groundwater are managed locally through the state's NRD system. The NRDs were created by legislative action in 1972, when the state reorganized over 150 single purpose districts into 23 comprehensive NRDs organized around watershed boundaries (Figure 1) (Aiken and Supalla 1979). The NRDs are governed by locally elected boards of directors and have broad and flexible legislative authority that includes the power to issue and enforce groundwater regulations and the power to collect property taxes to fund operations (Hoffman and Zellmer 2013).

Nebraska is home to two "firsts" in the nation with regards to addressing groundwater NPS nitrate pollution. Its Central Platte NRD Groundwater Management Area was the first program in the country to implement regulations on nitrates (Schneider 1990, Aiken 1993). The Bazile Groundwater Management Area, a collaborative effort between four NRDs and the state Department of Environmental Quality (DEQ), is the first EPA-approved plan to use CWA Section 319 funding exclusively to address nonpoint source groundwater pollution.

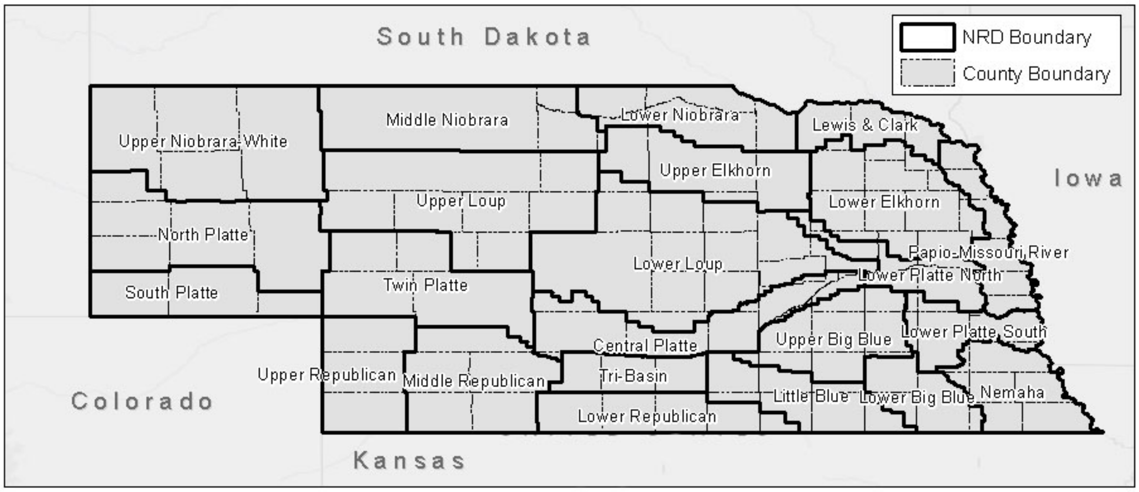

Figure 1: Nebraska Natural Resource District and County Boundaries (Map by B. Zapatka)

Initially, the NRDs' groundwater regulatory authority was limited to protecting groundwater quantity. By the early 1980s, nitrate contamination in groundwater had become a significant problem (Schneider 1990). In 1986, the NRDs were given the authority to establish Groundwater Management Areas (GMAs) to protect water quality and to require the use of best management practices (BMPs) and attendance at education programs to protect water quality (Exner and Spalding 1987). Further legislation was passed in 1991 requiring NRDs to revise their groundwater management plans to more adequately address groundwater quality issues (Exner et al. 2014).

Certain characteristics of groundwater pollution (i.e. quality) make governing it different than the extractive quantity context for which the NRDs were originally intended, and the boundaries used in governing quantity in Nebraska may not align with the boundaries necessary to govern quality. Because groundwater pollution is NPS, it cannot be regulated at individual points like quantity can, e.g. at wellheads. Nitrate pollution flows between different NRDs, and some parts of the state have sufficient groundwater quantity to last generations, but all irrigated areas, and all areas where fertilizer is applied for that matter, can be impacted, regardless of how much quantity they have. Thus, areas that may not have significant challenges in terms of quantity may face serious quality problems. For example, the Central Platte NRD (CPNRD) has significant groundwater reserves with high net recharge rates, but large parts of the district suffer from nitrate levels that exceed the MCL.

Each NRD has up to four groundwater quality management tiers, based on nitrate concentrations, with increasingly strict reporting and regulatory requirements at each tier (Exner et al. 2014). Regulations for each tier may differ slightly between NRDs and are revised occasionally by each NRD, but generally, they are set relative to the federal MCL and they encourage producers to adopt BMPs (Ferguson 2015, NARD 2017). Some general examples of phase requirements include: mandatory classes for nitrogen fertilizer operators, limitations on seasonal nitrogen fertilizer application, mandatory soil and water sampling, and mandatory crop reporting (NARD 2017)

To conduct our analysis, we look at three specific programs in the state (Figure 2). Together, they demonstrate a diversity of problems and approaches within the same statewide governance regime. These three programs are: 1) the Central Platte NRD Groundwater Management Area (CPNRD-GMA), which is the oldest NPS nitrate program in the state and which has demonstrated a successful trend in reducing groundwater nitrate concentrations; 2) the Bazile Groundwater Management Area (BGMA), which brings together four NRDs to address nitrate pollution through a CWA Section 319 funded project, the first in the nation; and 3) the city of Hastings Wellhead Protection Area (HWPA), which is a collaboration between two NRDs and the city of Hastings, and represents a rare example of a regulatory program that successfully bridges the rural-urban divide to address NPS nitrate pollution that is threatening the city's drinking water source.

These three nitrate management programs collectively offer useful insight into how a nested groundwater governance regime can be structured to be sufficiently adaptive to respond to emerging groundwater challenges, and into how that structure can lead to synergistic regulatory approaches to managing groundwater quality. They represent different aspects of the NRD groundwater governance regime and collectively are representative of the broader dynamics present in the groundwater governance regime in the state. Nine interviewees indicated that these three programs stand out in the state because they were the first areas where the nitrate problem reached a critical level, because the nitrate problem crosses jurisdictional boundaries, or because of they represent creative solutions to addressing the cost of supplying safe drinking water to an urban area. They also indicated that they believed the factors that enabled these programs are present throughout the NRD system.

The CPNRD-GMA covers the entire district (Figure 2), and different areas of the district are designated into different phases based on the severity of nitrate contamination (Ferguson 2015). The district is broken up into four phases based on nitrate contamination. We provide these phase levels as a demonstration on how they may exist in any given NRD: Phase 1- 0-7.5 mg/L , Phase 2- 7.6-15 mg/L , Phase 3- >15.1 mg/L , Phase 4, areas where nitrate levels are not declining at an acceptable rate (CPNRD 2017). Currently, there are no areas of the NRD under Phase 4. The program began in 1987 and was the first GMA in Nebraska and the first nitrate regulatory program in the country (Exner and Spalding 1987, Schneider 1990, Aiken 1993). Since the project started, average nitrate levels throughout the district have declined from 19.2 mg/L to 13.3 mg/L (CPNRD 2017). While average nitrate levels still remain above the MCL, the decline in nitrate concentrations represents a steady trend achieved largely through changes in agricultural management practices by producers. The CPNRD-GMA program has utilized a combination of regulatory and voluntary BMPs supported by cost-share incentives and information and education (I&E) activities (Interviews 13, 14, 15, 34). The program has become the model for nitrate management programs in other NRDs across the state (Exner et al. 2014).

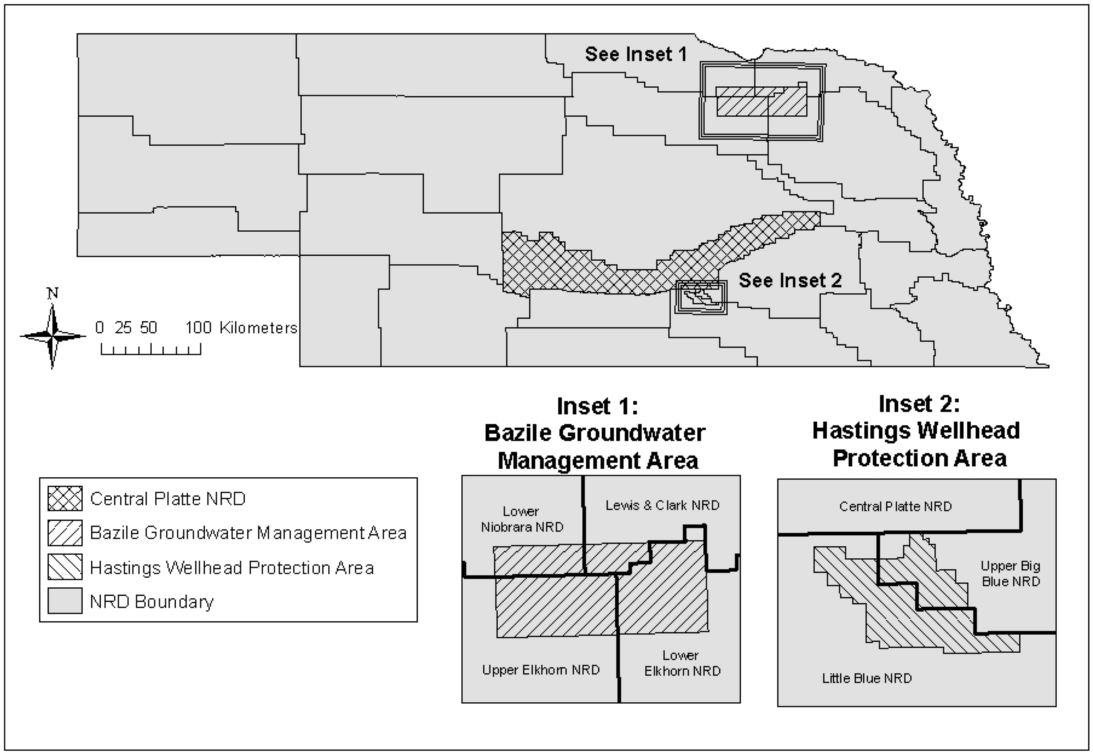

Figure 2:Map of the Three Nitrate Management Programs (Map by B. Zapatka)

The BGMA encompasses 1,958 square kilometers and covers parts of four NRDs: the Lewis and Clark, Lower Elkhorn, Lower Niobrara, and Upper Elkhorn (Figure 2) (NDEQ 2016). It is a collaborative effort by the four NRDs and the state DEQ focused on reducing nitrate levels below 10 mg/L through the widespread implementation of BMPs (Radford and Johnson 2017). The BGMA program utilizes a combination of regulatory and voluntary BMPs supported by cost-share incentives and information and education (I&E) activities (NDEQ 2016). The BGMA plan was approved in 2016, and the program has recently begun implementation (Radford and Johnson 2017). The program was is the culmination of efforts dating back to the 1980s on an earlier program with three of the NRDs, called the Bazile Triangle (NDEQ 2016). Self-organizing by the four NRDs to form the BGMA was a result of monitoring data showing the nitrate problem was transboundary in nature, and of the shared belief that the problem could be more effectively addressed, and that more resources would be available, through collaborative action (Interviews 3, 4, 6, 7, 9, 10, 17, 20, 30). The four NRDs are currently in the process of aligning some of their regulatory and management rules and regulations in an effort to streamline management across district boundaries (Interviews 3, 10, 17, 30).

The Hastings-WPA was initiated in 2013 as a collaborative effort by the City of Hastings Utilities, the Little Blue NRD, and the Upper Big Blue NRD. The program encompasses the city of Hastings and parts of the two NRDs, between which the city is divided (Figure 2). The quality of the city's municipal water has traditionally been of very high quality, requiring no treatment before distribution into the system (Hastings Utilities 2013). However, Hastings Utilities is currently operating only 17 out of 33 supply wells due to nitrate contamination and the recent discovery that nitrates have mobilized naturally occurring uranium in the soil, contaminating some of the wells (Stange 2017). The city itself is implementing a unique set of practices to treat and restore the aquifer (Stange 2017). The NRDs are focused on limiting NPS nitrate pollution into groundwater in the outlying agricultural areas through a combination of regulatory and voluntary BMPs supported by incentives and I&E (Little Blue NRD et al. 2012).

RESULTS AND DISCUSSION

Our research findings on these three programs demonstrate that the Nebraska NRD system meets Huitema et al.'s (2009) four conditions for successful groundwater governance, with respect to quality. This manifests in two overarching themes: 1) the type of groundwater governance regime present in the state, and 2) the synergistic management approaches to groundwater quality programs. In the following sub-sections, we provide research results and detailed analysis of how the NRD governance regime and the management approaches create the conditions for successful groundwater quality governance.

Empowered local groundwater governance regime creates enabling conditions for resolving the complex problem of nonpoint source nitrate pollution

All 34 interviewees spoke on some level about the role of local governance in nitrate management in Nebraska. 33 individuals specifically identified the local nature of the NRD governance regime as the most important element in the state's efforts to address NPS nitrate pollution, and in its relative success in managing groundwater more broadly. The one interviewee who did not speak explicitly on this, an extension specialist who instead focused on the technical aspects of BMPs in the CPNRD-GMA, still spoke in the context of the local, community-oriented approach that has led to a successful trend in this project. The other 33 interviewees noted that the locally elected boards, taxing authority, and independence of the districts to tailor activities to local conditions and engage with locally appropriate stakeholders formed the core of what makes the NRD system uniquely successful.

We found that there are four elements of the regime type that increase the likelihood of successfully achieving nitrate mitigation goal or of self-organizing to address emerging NPS nitrate pollution problems. These are: 1) the nature of local governance in the NRD system builds trust; 2) the state has granted NRDs significant authority empowering them to develop locally-tailored solutions; 3) the collaborative nature of the NRD system allows for potential scale imbalances to be overcome; and 4) the taxing authority granted to NRDs enables them to fund locally-tailored management solutions. We will now further explain and illustrate these with quotes from the interviewees.

Element 1: Local governance builds trust. "Without trust, there is no government" (Interview 2). Eleven interviewees spoke of trust in the NRDs as being a central element to the successful trend in the CPNRD-GMA and to the successful self-organizing for the BGMA and Hastings WPA that the respondents believe has put those programs on the path to success. Three producers said they felt their NRD acts in their best interest as farmers and gives them a voice in the regulatory decisions that impact them. One said, “It's locally governed, so we're a part of it. Working together builds trust” (Interview 33).

Our results indicate that this trust stems from the polycentric regime type, in which the locally-elected NRD boards (rather than a central state regulatory agency) are the principal regulatory actors that producers interact with most frequently (Figure 3). Four interviewees said that because board members are elected from the communities they govern, people feel like they have a participatory role in the NRD that is governing them. One extension expert said, “the more local control the better,” and that people “feel like they're part of the decision. It’s their problem, and they take ownership of the problem, and they take [more] ownership of the solution” (Interview 12). An early organizer of the program that became the BGMA summarized his views on the importance of the locally-elected NRD boards as follows (Interview 20):

> Local solutions for local problems. And, probably the biggest thing is it's not big government coming in and telling someone what to do, it's the guy you voted for, your neighbor, who is voting, making a policy decision that impacts you. And so, if you don't like it you can certainly pick up the phone and talk to him, or better yet you'll see him down at the coffee shop or diner and you can speak your piece to it. The key that a lot of people don't realize is that when a NRD board member votes for something, whether they be a producer or businessman or whatever, they're voting for something that impacts them as well.

It is important to note that not all interviewees felt that the NRDs were fully trusted by producers. One NRD general manager indicated that people generally trust their NRD, but that the level of trust varied by the specific regulatory issue (Interview 29). A minority of respondents indicated that the NRDs aren’t trusted at certain levels because they represent a form of government, and the more an organization is viewed as a regulatory governmental agency, the less trust it has (Interviews 1, 23, 25). These views were, however, nuanced. Two interviewees indicated that the boards of NRDs are trusted because of their being made up of locally elected stakeholders, but that the NRDs staff (non-elected officials ranging from the general manager to field technicians) receive less trust (Interviews 23, 25).

These comments on trust in NRDs were also framed in the context of comparative trust and bottom-up versus top-down governance. So, NRDs are trusted more than state and Federal agencies, but less than agricultural industry actors (i.e. agronomists, co-ops, seed and fertilizer dealers, and crop consultants), who provide services to agricultural producers. In summary, due to the makeup of their locally elected boards, NRDs are the most trusted governance institutions in the state, but because they serve a regulatory purpose, they are still viewed with some level of mistrust by a minority of stakeholders.

Element 2: The state has ceded significant regulatory authority to NRDs but maintains higher-level oversight, which empowers NRDs to develop locally-tailored policy mixes while also maintaining sufficient oversight to require them to address water quality problems. In Nebraska’s polycentric groundwater quality governance regime, the state DEQ sets the standards for groundwater nitrate concentrations based on drinking water standards, and state law requires every NRD to have nitrate management plans in place (Figure 3) (Interview 22). NRDs are empowered to develop their own local approaches to achieve these standards. Five interviewees indicated that this nested state oversight provides an effective check against NRD boards setting insufficiently strict standards for addressing nitrate problems, for fear of being voted out of office. In describing the uniqueness of the NRD system, an interviewee from the University of Nebraska-Lincoln (UNL) said, “In other states, most [state governments] don't want to give up their power. So, Nebraska is unique in how much power the state willingly gave away, and to another elected body at that” (Interview 11).

An interesting caveat noted by two DEQ staff members is that while the state has ultimate authority to regulate nitrates and has parallel authority to put management areas under phase controls, the DEQ does not have the resources to do so if it needed to on a wide scale. One DEQ staff member noted that other states may have hundreds of staff who work on NPS groundwater pollution, while Nebraska’s DEQ has fewer than ten. Three interviewees did indicate that the state DEQ does have the resources to step in to enforce NRD compliance on a limited basis, however the state has never needed to because NRDs have been predominantly compliant (Bleed and Babbitt 2015).

The DEQ focuses on coordinating with NRDs and other stakeholders in its regulatory role and encourages multiple districts to work together on nitrate issues that cross NRD boundaries (Interviews 1, 21, 25). The non-governmental, state-wide NARD is an additional actor that helps facilitate information sharing between NRDs, and through a liaison, helps coordinate between NRDs state agencies (Interview 7). The UNL also supports NRD activities through its research ties with agricultural extension and coordinates with NRDs on different groundwater quality programs (Figure 3).

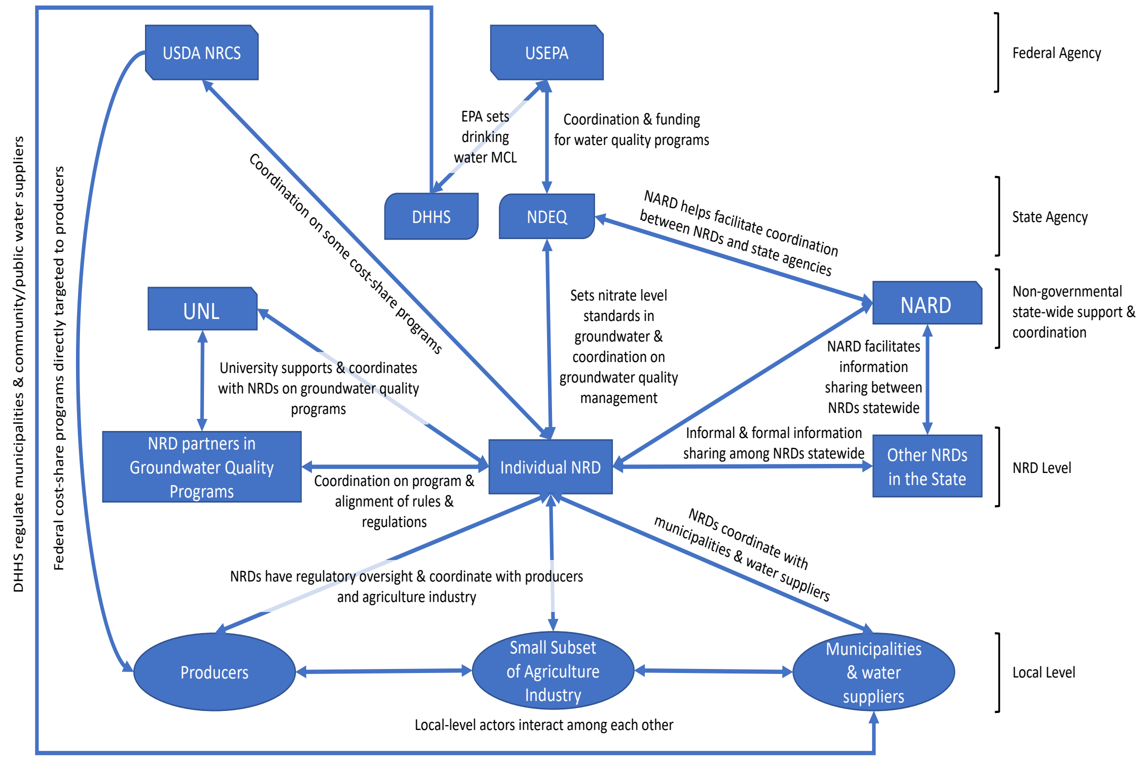

Figure 3: Simplified polycentric governance regime model showing key actors and how they interact

This small DEQ regulatory footprint is by design. As described in Element 1, local governance is highly valued in Nebraska. The localized governance that state law has granted to NRDs allows them to set up programs that are reflective of local conditions, promoting different BMPs and setting different benchmarks for phase levels, and gives them the flexibility to adapt to new problems as they emerge (Interviews 7, 9, 10, 15). They have so much flexibility, in fact, that if necessary, they can manage nitrate problems at the individual field level, a scale made possible because NRD staff know their districts and producers (Interview 15).

While most states have traditionally focused on reducing nitrates through voluntary programs that focus on education and awareness, the seven NRDs in this research have focused on mixed intervention approaches, preferring voluntary and incentive-based measures, but instituting regulatory measures at certain nitrate concentration phase levels (Table 1). The polycentric governance regime empowers the NRDs to develop their own policy mixes, and the different policy instruments are often exercised in collaboration or coordination with other actors in the regime (Figure 3 and Table 1).

The most common types of BMPs being promoted include: nitrogen inhibitors, soil sampling, water sampling, no fall application of fertilizer, variable-rate applicators, center pivot irrigation, fertigation (applying fertilizer via center pivots), flow meters, cover crops, moisture sensors, split feeding, spoon-feeding, and factoring in the nitrogen present in the irrigation water and accounting for that when deciding how much fertilizer to apply.

With the exception of limits on fall fertilizer application – which is usually a regulatory phase requirement and also carries some potential risks around weather impacts to planting in the spring – all of the nitrate management BMPs in these programs have proven potential to increase producer profitability and maintain or improve yields (Interviews 16, 20, 22, 24). The increase in profitability stems from the lower marginal input costs for fertilizer and on the cost of electricity or fuel for pumping water (where BMPs reduce water use).

Cost-share programs are important policy instruments because they lower BMP adoption costs to farmers, which can help make some BMPs financially beneficial when they might not have been if the farmer were responsible for the full cost (Interviews 13, 23). Some of the BMPs that require specialized equipment have high costs of entry, and the flexibility granted to NRDs to develop their own programs has allowed them to implement cost-share programs that reflect local priorities (Interview 3, 5, 17).

Regulatory policy instruments include phase-level-specific mandatory BMPs and required I&E. Most of the NRDs in this project have a requirement that producers who apply nitrogen fertilizer be certified and go through yearly educational programming on nitrogen management (some require it at specific phase levels). At those trainings, information on different BMP options and on the impacts of excess nitrogen fertilizer application is shared (Interviews 9, 16, 23, 28).

I&E is an important component of the nitrate management programs in this study. Interviewees described a multi-pronged approach to educating stakeholders on the nitrate management programs, on groundwater monitoring data, and on the NPS nitrate pollution problem in general. These approaches include: newsletters, pamphlets, public meetings, individual interaction with producers, print and social media, local radio and television, demonstration plots, and field day tours. Three interviewees noted that being persistent with the messaging and getting NRD staff out to meet with producers repeatedly has been an important component in BMP adoption. Six interviewees also noted that as individual producers see the benefits from adopting BMPs, they communicate that to other producers through informal communication, which has benefited adoption of the practices.

Table 3: Summary of primary policy mixes utilized in nitrate NPS groundwater pollution programs

Policy Instrument	Type of Instrument	Primary Actors Behind Policy Instrument	Description
I&E to agricultural producers on nitrogen fertilizer impacts and BMPs	Voluntary Mandatory	NRDs, Agriculture Service Providers, DEQ, UNL/Extension, USDA-NRCS, Other Agricultural Producers	▪ Education on impacts of nitrogen fertilizer on groundwater quality, benefits of BMPs, and BMP practices reaches producers via multiple actors, and is often coordinated among the actors by NRDs. ▪ Participation is usually voluntary, except when there is a regulatory requirement for fertilizer applicators to attend classes and/or be certified. ▪ Information on BMPs is shared between agricultural producers informally in social settings and formally via demonstration plots, usually coordinated by the NRDs
I&E to broader community on nitrogen fertilizer impacts and groundwater nitrate contamination	Voluntary	NRDs, DEQ, UNL/Extension	▪ Information on the nitrate pollution problem and activities to address it is shared via multiple formats, including: NRD newsletters, at NRD meetings, workshops, local TV and print media, and social media
Cost-share programs to encourage BMP adoption by agricultural producers	Incentive-based Voluntary	NRDs, USDA-NRCS	▪ NRDs choose which BMPs they want to incentivize through cost-share, and cost-share programs may differ by NRD and within NRDs (based on groundwater nitrate concentrations) ▪ USDA-NRCS has multiple cost-share programs, which are a source of federal funds to producers ▪ Some NRDs top-up USDA-NRCS cost-share funding to increase the level of support to producers and add additional incentive to BMP adoption ▪ Participation by producers in cost-share programs is voluntary
Regulatory requirements for the use of specified BMPs	Mandatory	NRDs	▪ NRDs may require the use of some BMPs (e.g. soil sampling, crop reporting, and seasonal limits on fertilizer application) at different groundwater nitrate concentration phase-levels.

I&E activities presenting well-regarded, long-term monitoring data showing the extent and historical sources of the nitrate problem have played an important role in alleviating tensions over the sources of the pollution (i.e. crop production vs. animal feeding operations), the efficacy of BMPs, or new regulatory requirements (Interviews 7, 28, 30). In the CPNRD-GMA in particular, there were tensions early on around increasing regulation and the source of the nitrate problem, but extensive I&E with producers led to widespread acceptance of nitrogen fertilizer as the source and buy-in in the program (Interviews 13, 14, 34). One producer said that showing the benefits of the BMPs, that they work, and that producers can save money and still get the farm production they desire has been crucial to the success of the program. "It's been education the whole time," he said (Interview 34).

Finally, the involvement of agriculture industry actors is an important component in multiple aspects of the policy mixes. A survey of farmers in 11 Corn Belt states (including Nebraska) by Loy et al. (2013) showed agricultural industry actors have the greatest level of influence on land management decisions by producers and are among the most trusted sources of information on conservation practices. Fourteen interviewees indicated that the NRDs in this research have engaged with these agriculture industry actors to build trust among producers, which has helped to overcome conflicts over the science, data, and efficacy of the BMPs being promoted. The NRDs have engaged these actors in the following ways: by paying crop consultants a per-acre fee to help producers implement nutrient and irrigation BMPs, by involving them in BMP demonstrations, by having them assist producers calculate nitrogen fertilizer needs from soil and water samples, and by having them assist producers in filling out required reporting forms.

Element 3: The empowered local governance regime supports formal and informal networking and encourages collaboration, allowing NRDs to overcome potential scale imbalances from emerging problems. Long-term collaboration and coordination promotes the development of strong social networks and trust that can make polycentric governance both efficient and effective (Imperial 2005, Huitema et al. 2009). The legislative action granting all NRDs the same authority and responsibilities and requiring that they achieve safe nitrate levels encourages collaboration where mutually beneficial, such as in the BGMA and Hastings-WPA (Interview 21). One NRD public relations manager spoke of the ability to form partnerships as follows (Interview 27):

> The authority to get into these local agreements has paid so many dividends. It's made it so much easier for us to legally get into contracts and work together. I can't stress enough the leveraging of partnerships it just helps because now you've got all these different resources: financial, technical, volunteer, boots on the ground resources to help in all these kinds of projects that [NRDs] can't do on [their] own.

From their inception, the regulatory independence of the NRDs has encouraged extensive informal communication among boards and managers from different NRDs (Interview 21). The NARD also plays a coordinating role, arranging multiple formal meetings per year, where NRD boards and staff and the public meet and share ideas and experiences (Interviews 3, 13, 21, 22). One NRD manager also indicated that there are five formal meetings per year that bring together all NRD managers, and in the BGMA, the four NRD managers get together monthly to discuss the project.

This networking and collaborative polycentric governance has allowed Nebraska to address potential scale imbalances between groundwater quantity management, for which NRD regulatory authority was originally granted, and the emergent problem of NPS nitrate pollution in groundwater. Groundwater pollution in two of these projects, the BGMA and Hastings-WPA, initially appears to present a potential scale mismatch between the governance boundaries of the NRD, which were drawn along surface watershed boundaries for managing quantity, and the nitrate pollution patterns, which flow between four NRDs in the BGMA and two in Hastings (Cumming et al. 2006). These two groundwater quality programs show an adaptive capacity in the NRD system to address potential scale mismatches that have developed with the emergence of the nitrate problem.

The BGMA and Hastings-WPA demonstrate that the governance system is sufficiently flexible to allow NRDs to self-organize to adapt to problems that do not align with the original governance boundaries. Those boundaries are still relevant for the overall management of groundwater, and it would be impractical to create different management boundaries for quantity and for quality. Instead, the governance regime is set up so that state-level regulatory oversight requires individual NRDs to meet groundwater quality standards, and they are empowered to address the challenges in the way that is most appropriate for the scale of the problem. In some situations, acting collectively may be the best approach for addressing a problem at the appropriate scale.

In describing the formation of the BMGA, nine interviewees described the realization that nitrate pollution went beyond individual NRD borders. By self-organizing, the four NRDs could leverage EPA funding to address the common problem present in the larger aquifer. And, their case for receiving federal funding could be made stronger by demonstrating a collaborative approach. At the local-level, getting more partners involved in the project and having a larger critical mass of participants, made selling the program easier to individual NRD boards (Interview 5). Additionally, as part of the collaboration, the four NRDs in the BGMA are in the process of aligning their nitrate concentration phase levels in order to streamline reporting requirements to the benefit of producers who farm across district (Interview 3). The authority granted to the local NRDs allows for the flexibility to adapt their regulatory approaches in ways that benefit their constituents, as small step in building more trust (Interview 3).

In the Hastings-WPA, the city drove the self-organizing process, but because the municipal boundaries are split between two NRDs, and because nitrate pollution is primarily from agricultural activity in the surrounding farmland in both NRDs, it needed to organize with the districts to achieve its goals (Interviews 7, 9, 26, 29). The city and the NRDs recognized that they could leverage their resources collaboratively to better address the problem (Interview 27). Because the NRDs have been granted significant regulatory authority, they had sufficient flexibility to develop the collaborative program that is now in place.

Element 4: NRD taxing authority supports locally-tailored policy mixes for BMP programs. The final component of the governance regime that has been beneficial to these programs is the ability of the NRDs to collect property taxes to fund operations. The regulatory and taxing authorities granted to the NRDs provides them with the resources to enforce regulations and enables them to develop locally-based incentive and I&E programs for promoting nitrogen management BMPs (Interviews, 12, 15, 16, 25, 30). One NRD general manager spoke of the uniqueness of this institutional arrangement by saying, "there're no other states that have taken that step to allow a local elected political subdivision to have taxing authority, or the state has never given them the ability to make those types of decisions at the local level" (Interview 15).

The NRD tax base also insulates the districts from the variable nature of outside funding sources, such as grants, allowing them to continue with nitrate management programs once grant cycles are complete (Interviews 9, 25, 30). An NRD water resources manager said that taxes provide a reliable base for district activities that are not available to local governance institutions in other states. Finally, the taxes give the NRDs the ability to top-up Federal USDA-NRCS and state BMP cost-share programs (in some cases up to 90%) to provide additional incentive for producer adoption of BMPs that individual NRDs prioritize for their district (Interviews, 3, 5, 7, 9, 13, 17, 23).

Synergistic approach to program development and management supports nitrate management goals and BMP adoption

The synergistic approach to the development and management of the nitrate management programs in this study is central to achieving groundwater quality goals through widespread BMP adoption. This approach is enabled by the elements of the polycentric groundwater governance regime discussed in section 3.1. Figure 4 shows the components of the NRD groundwater quality governance regime and the primary factors influencing the success of the BMP programs and BMP adoption. Below, we highlight key aspects of the model.

NRDs are the principal drivers behind the synergistic approach[9]. The central strategy to synergy is the collaboration and coordination with stakeholders shown in Figure 3 and described in section 3.1 to develop locally-tailored policy mixes.

The informal and formal coordination described in Section 3.1 encourages information sharing between NRDs and together, these support self-organizing between NRDs (in relevant situations), which helps overcome potential scale imbalances and promotes BMP adoption. Informal and formal coordination and information sharing between NRDs directly contribute to the synergistic approach.

Taxing authority granted to NRDs described in Section 3.1 funds some of the coordinated approach and monitoring activities. Monitoring data, in turn, inform policy mix decisions

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[9] A caveat to this is with regards to the Hastings-WPA. The initial effort was driven by the City of Hastings Utilities, and the WPA action plan was a collaborative effort between the City, the Little Blue NRD, the Upper Big Blue NRD, and local stakeholders. However, as described in section 3.1 Element 3, the partnership with the two NRDs is necessary to achieve nitrate goals, and the NRDs play the central role in BMP adoption efforts.

(regulatory, voluntary, cost-share), are used in I&E activities that build trust, and support program monitoring and evaluation at both the DEQ and NRDs. Individual NRDs are empowered to experiment with different policy mixes, which are partially funded through local taxes. Experiences with different approaches are shared between NRDs, supporting synergistic approaches to programs and creating a larger community that can draw on the experimentation of other NRDs in the development of local solutions.

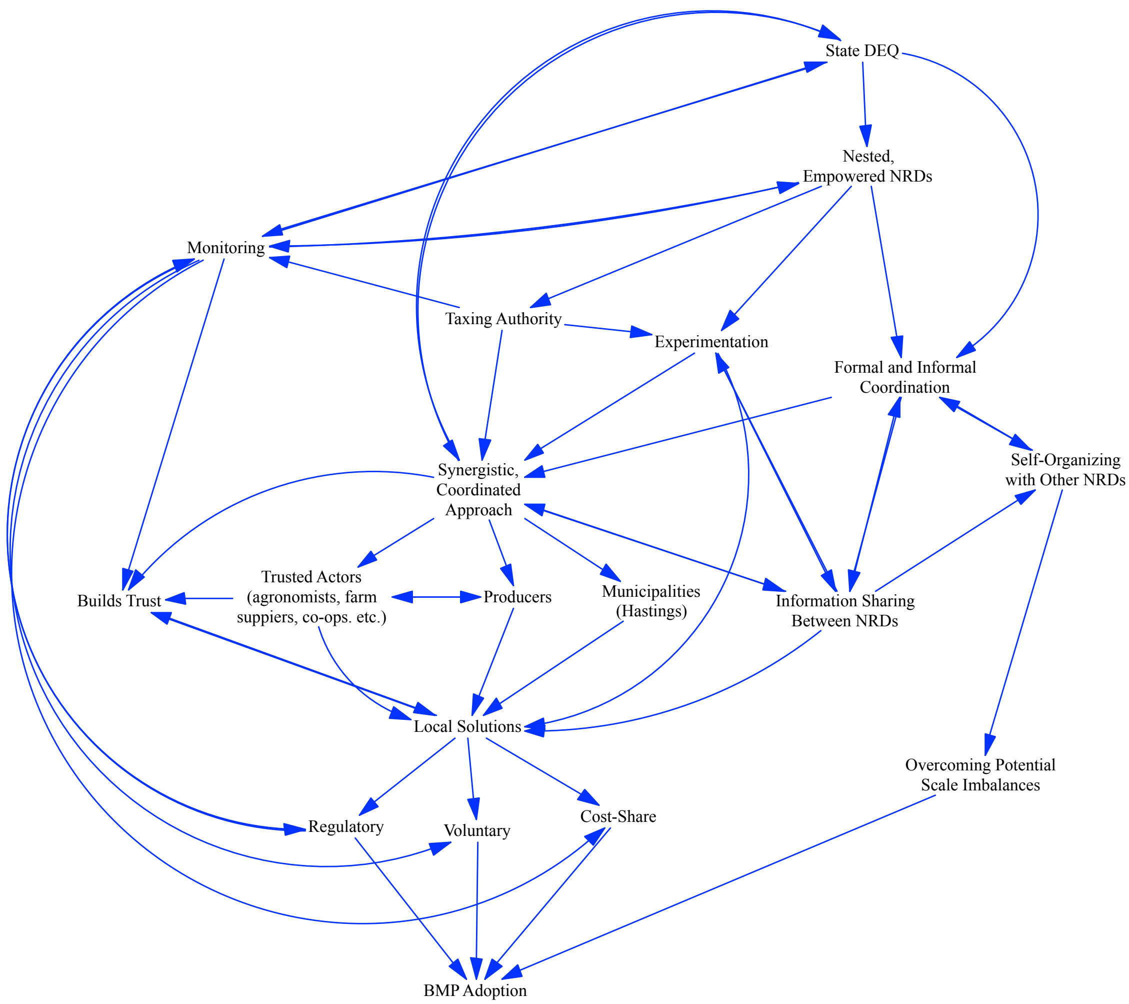

Figure 4: Nebraska NRD governance regime and factors influencing BMP programs and adoption

SUMMARY AND CONCLUSION

Nebraska's NRD system presents a rare example of a groundwater governance regime demonstrating the conditions likely to generate sustainable groundwater quality outcomes. The long-term success of these programs remains to be determined. A significant and desirable trend in nitrate concentrations has already been achieved in the CPRND-GMA, and every interviewee who discussed the program expressed confidence that this trend will continue and achieve groundwater quality goals. The other two programs, the BGMA and Hastings-WPA, have not existed long enough to show significant results in groundwater nitrate levels. What they have demonstrated, however,

is that they have successfully utilized the authority granted to the NRDs to self-organize and develop collaborative programs built on principles proven to be successful in the CPNRD-GMA and adapted to the local conditions in each geography.
This research has shown that two overarching enabling conditions are responsible for the successful trend in addressing groundwater nitrates: 1) Nebraska's polycentric, locally empowered groundwater governance regime and 2) synergistic management approaches to the groundwater quality programs in this study.

The four elements of regime type discussed in Section 3.1 demonstrate how empowered local governance can create the conditions for resolving complex CPR problems. Figure 5 shows that the elements of the polycentric regime are complementary, and the NRD system works because all of the parts connect. Elements 1, 2, and 3 are reciprocal: local governance builds trust needed to implement policy mixes, and trust is necessary for self-organizing; conversely, I&E policy instruments and the culture of networking and collaboration that support self-organizing help to build trust in the NRDs. Element 4, NRD taxing authority, provides a funding mechanism for local governance, locally-tailored policy mixes, and some activities in collaborative programs formed through self-organizing (e.g. the BGMA and Hastings-WPA). The synergistic approach to program development and management described in Section 3.2 is an outcome of the polycentric regime discussed in Section 3.1 and shown in Figure 5. Collectively, these conditions build the legitimacy, transparency, accountability, inclusiveness, fairness, integration, and capability that build stakeholder support for a governance system (Lockwood 2010, Kiparsky et al. 2017).

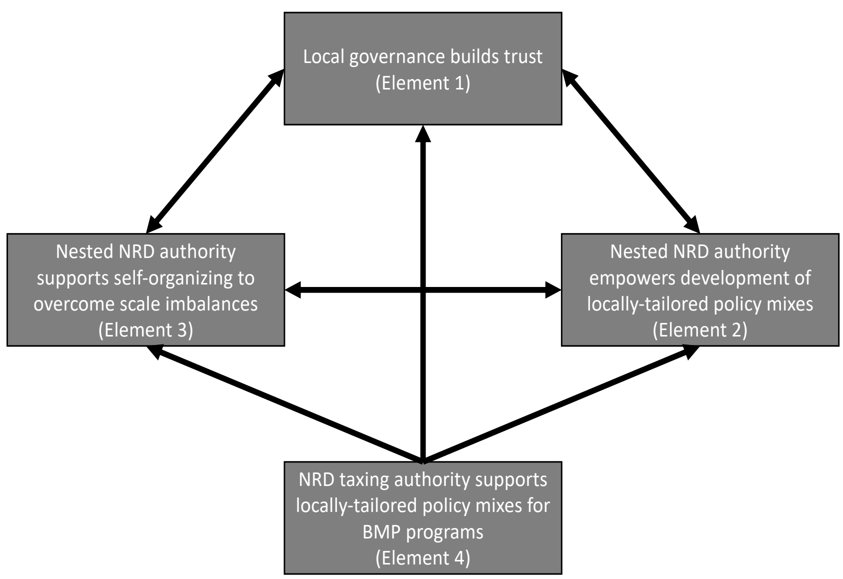

Figure 5: Interaction between polycentric governance regime elements

The goal of this paper was to identify characteristics within Nebraska's groundwater governance regime that are likely to limit NPS pollution of nitrates into groundwater and lead to the eventual reduction of nitrate concentrations to safe levels. Ultimately, our goal was to derive generalizable aspects of the governance regime for application elsewhere as efforts to address nitrate pollution in groundwater grow. These aspects are:

1. A nested, polycentric regime that grants significant regulatory authority and flexibility to local-level governance bodies, while maintaining regulatory oversight on overall sustainability goals at the state-level
2. Local-level governance bodies whose leaders are elected by the stakeholders they serve, which encourages transparency and accountability and builds trust
3. Granting of taxing authority to local-level governance bodies so that they can fund general operations, mixed intervention approaches, and collaborative efforts
4. The importance of achieving synergies among key actors in the nested regimes, which includes the ability to self-organize to overcome potential scale imbalances, information sharing between local-level and between local-level and higher-level governance bodies, and the involvement of multiple actors in mixed intervention approaches

While this study focused on just three programs in Nebraska, it includes seven NRDs, representing almost one third of the NRD system. These three programs also cover different aspects of nitrate management efforts – single-district responses, multi-district self-organizing, and multi-district-urban self-organizing, that are collectively representative of the broader NRD regime. The enabling conditions for self-organizing and synergistic approaches are present statewide, and we expect to see an increase in their application as the need for more NRDs to scale up nitrate mitigation efforts increases due to the continuing emergence of the nitrate problem.

Using the NRD system as an example, we provide empirical evidence showing that Huitema et al.'s (2009) recommendations for designing groundwater governance regimes are applicable to the design of groundwater quality governance regimes capable of addressing agricultural NPS pollution. We highlight the importance of synergistic approaches to NPS pollution program development and management and the need for local-level governance bodies to have access to a reliable source of funding (in this case taxing authority). Finally, we present an empirical counterpoint to skepticism of higher-level authorities' willingness to yield decision-making power to lower-levels in polycentric regimes governing complex resource systems.

Policy implications from this work are perhaps most relevant to the U.S. state context. That is because the NRD system exists under conditions shared by other states: it is nested under the same Federal oversight as the other 49 states; it is part of a uniquely American type of federalist system; it is culturally similar to other states in the same region of the country; and its agricultural production system is similar to other states in the region.

The analysis in currently most relevant to California's Sustainable Groundwater Management Act (SGMA), which was passed in 2014 and which is not yet fully implemented. Kiparsky et al. (2017) noted that the institutional design of California's SGMA provides a model for other states as they develop their own groundwater governance regimes. It is true the SGMA is noteworthy as a polycentric groundwater governance regime, and because it is still in the initial implementation stages, the experiences of the state will be invaluable to the development of governance regimes elsewhere in the U.S. However, Nebraska's NRD regime has been in place since 1972, and NRDs have been developing groundwater quality plans, both individually and collaboratively since the 1980s. Many of the polycentric approaches intrinsic to the SGMA are reflective of the NRD system, and consultation with experts from Nebraska could be beneficial to California as it implements the SGMA (in fact representatives from the NARD have been consulted by the state of California recently). We recommend future paths of research include comparative analysis of the experiences of these two polycentric regimes, as they could benefit efforts to enact robust groundwater quality governance elsewhere.

Whether the NRD system is replicable elsewhere in the U.S. is a topic that deserves further research. Governance regimes are complex networks influenced by diverse interests and power relations (Pahl-Wostl 2015). Policy instruments that work in one place may fail in another. Thus, governance isn't just the organizations that manage a resource; it is the people, culture, and collective experience involved in the path to sustainable decisions. Effective governance is as much about the context of the governance system as it is about the policy instruments developed to govern them. As Ostrom (2007) points out, there are no institutional panaceas that guarantee effective governance. Nebraska may possess characteristics that limit the applicability of its groundwater governance regime beyond its borders. For example, it is the only state in the U.S. to have a unicameral legislative body, and it is possible that the NRD system is a result of optimal conditions that were present in the early 1970s (i.e. right time, right place, right people). We advocate for additional research on how the geographic and temporal contexts during the creation of the NRDs may have influenced the regime as it exists today, and whether this may limit applicability of the NRD model elsewhere. However, our findings add to a growing body of evidence showing that governance regimes that are likely to lead to sustainable CPR outcomes can be developed across a wide range of geographical, political, and resource system contexts, and that where these regimes do exist, they express a common set of enabling conditions for their formation.

ACKNOWLEDGEMENTS

This work was supported by the National Science Foundation under Grant #0966093, Integrative Graduate Education and Research Traineeship (IGERT) Program on Water Diplomacy at Tufts University. We wish to thank all interviewees for their participation in this study and Laura Johnson, Carla McCullough, and Sam Radford who generously answered every request for additional information.

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CHAPTER 5: Conclusion

BROAD THEMES OF RESEARCH AND RESULTS

"When the well is dry, we know the worth of water" (Benjamin Franklin).

A more apt statement could read, "When the well is dry *and polluted*, we know the worth of water." Anthropogenic impacts to water systems pose a serious threat to human societies globally, as discussed in Chapter 1. While there are many human activities that cause water problems, agriculture stands out for its centrality. It is the largest user and one of the primary polluters of water globally (FAO, 2012; Mateo-Sagasta et al., 2017). These impacts, combined with the demand that will be placed on the agricultural sector to feed approximately two billion more people in the coming decades, mean that the impending global water crisis cannot be resolved without making agriculture more sustainable.

Water problems are complex in both their causes and solutions. Many are the result of governance failures at multiple levels (Pahl-Wostl, 2017). Thus, good water governance is essential for overcoming many of the complex water problems societies face today and the emergent problems that will challenge the future. Chapter 1 noted that there are a range of observable characteristics that are often present in social-ecological system (SES) governance regimes that achieve or are likely to achieve sustainable common pool resource (CPR) management.

This dissertation presented analysis on different scales, aspects, and contexts of agricultural water governance. Chapter 2 focused on sustainable transition efforts in a sub-system of the Jordanian agricultural sector, water harvesting in rainfed agriculture, and the barriers and opportunities to achieving that transition. Chapter 3 was interested in sustainable groundwater quantity governance at the sub-regional scale of an aquifer system, comparing the extent to which three different U.S. states govern agricultural groundwater use using Water Diplomacy principles. Chapter 4 focused on the evolution of one state's groundwater governance system, Nebraska's, to addressing agricultural nonpoint source pollution of nitrates into groundwater and on the conditions within that system that are likely to lead to sustainable outcomes.

Chapter 2 recommended two policy priorities for overcoming the current challenges facing the innovation and implementation of water harvesting practices. These were: 1) improving coordination across government ministries and donors to develop a holistic vision for water conservation in agriculture and for how water harvesting innovation and utilization fits into that vision; and 2) supporting technological innovation system (TIS) development for water harvesting practices, including resource mobilization for the formation of a market for water harvesting and for the involvement of entrepreneurs in that market. The analysis highlighted that donors are currently fundamental to developing the water harvesting TIS, and thus should play a central role in efforts to achieve these policy priority areas.

This research reinforces findings that the TIS approach is a useful tool for studying different types of developing country innovation systems in the context of sustainability transitions (Tigabu et al., 2015). The research highlighted the impacts of donors and the role of informal institutions in developing country innovation systems. A broader theoretical implication that nuances earlier findings on donor support of TIS development is that donors can contribute to directionality problems that favor one form of the technology over another. By not building sufficient capacity to ensure continued innovation activities upon project completion, donors can provide insufficient protection of the TIS until markets for technologies form. Another finding is that formal and informal institutions go hand in hand in a country like Jordan; for example, the lack of clarity on which aspects of land tenure institutions are formal and which are informal is a condition that is highly influential. This confirms earlier work on regimes and innovation system contexts in developing countries, where informality and instability are common (e.g. Arocena and Sutz, 2000; Verbong et al., 2010; Wirth et al., 2013).

Chapter 3 makes an important contribution to the discipline of Water Diplomacy. Earlier studies involving Water Diplomacy concepts had primarily focused at the micro level. The predominant focus has been on water negotiations utilizing trained negotiators, or on training people to be negotiators, in the principles of the Water Diplomacy Framework described by Islam and Susskind (2013). Largely absent from the literature were macro level Water Diplomacy studies, where the aim is identifying governance factors leading to robust governance institutions that produce sustainable water management outcomes. This dissertation represents one of the first forays into expanding Water Diplomacy analysis to the water governance context. It extends Water Diplomacy principles to the macro, governance level by viewing it as a sub-set of Elinor Ostrom's work on CPR management.

Chapter 4 marks a contribution to the limited literature base on governance of agricultural nonpoint source (NPS) pollution. The research identifies characteristics within Nebraska's Natural Resource District (NRD) groundwater governance regime that are likely to lead to the reduction of nitrate levels in groundwater to within safe concentration levels. It draws upon those findings to highlight generalizable institutional design principles for the governance of agricultural NPS groundwater pollution. Policy implications from this work are most relevant to the U.S. state context, with particular relevance to the state of California, which is currently implementing its recently passed Sustainable Groundwater Management Act.

SUMMARY OF FINDINGS

The main findings of the dissertation can be summarized as follows:

Chapter 2

1. Limited financial resources within the Jordanian government negatively impacts every other function in the TIS and increase reliance on international donors, hindering development of the water harvesting TIS.
2. Lack of a common vision for water harvesting and for the agricultural system among multiple actors, including ministries and international donors, creates a

cascade of negative impacts to every function in the TIS, limiting innovation for water harvesting.

3. Informal (cultural) and formal (government policies) institutional problems impede the creation of legitimacy for water harvesting.

Chapter 3

1. Findings from analysis of Nebraska's NRD system empirically show that a groundwater governance regime reflecting Water Diplomacy principles can create the conditions for adaptive, collaborative governance for the sustainable management of groundwater quantity.
2. Two variables had the biggest impact on blocking Water Diplomacy outcomes in groundwater governance: 1) the absence of empowered local-level groundwater governance and 2) the designation of groundwater as a property right. Kansas demonstrates that reliance on a central, state-level authority for making groundwater allocation decisions can block Water Diplomacy outcomes. Texas shows that groundwater allocation rules designating groundwater as a property right can hinder the effectiveness of local-level governance bodies and can severely limit options for managing the resource.

Chapter 4

1. Four elements of Nebraska's groundwater governance regime have created the enabling conditions for resolving NPS nitrate pollution to groundwater in the programs that were the subject of this research:
    a. The way in which local governance manifests in the NRD system builds trust.
    b. The state has granted NRDs significant authority empowering them to develop locally-tailored solutions;
    c. The collaborative nature of the NRD system allows for potential scale imbalances between NRD boundaries and groundwater pollution patterns to be overcome;
    d. The taxing authority granted to NRDs enables them to fund locally-tailored management solutions.
2. One of the goals of this research was to identify generalizable aspects of the NRD groundwater quality governance regime that can be applied in other states for addressing nonpoint source nitrate pollution. These are:
    a. A nested, polycentric regime that grants significant regulatory authority and flexibility to local-level governance bodies, while maintaining regulatory oversight on overall sustainability goals at the state-level;
    b. Local-level governance bodies whose leaders are elected by the stakeholders they serve, which encourages transparency and accountability and builds trust;
    c. Granting of taxing authority to local-level governance bodies so that they can fund general operations, mixed intervention approaches, and collaborative efforts;
    d. The importance of achieving synergies among key actors in the nested regimes, which includes the ability to self-organize, information sharing

between local-level and between local-level and higher-level governance bodies, and the involvement of multiple actors in mixed intervention approaches.

DIRECTIONS OF FUTURE WORK

There are 5 key areas of future research that are warranted based on the findings of this dissertation. These are:

1. *Assessing the role of retro-innovation in sustainability transitions*

A concept that emerged from Chapter 2 warranting additional research is the role of retro-innovation in sustainability transitions. Retro-innovation involves the adaptation of traditional practices into a modern innovation system (Stuiver, 2006), as is the case with water harvesting. This topic has received little attention in the developing country transitions literature, with Marques et al.'s (2010) paper on novelty production of medicinal plants in Brazil being a rare example. Additional research on retro-innovation and the role of locally-driven development and adaptation in the process warrants additional attention in transitions and innovation systems studies, as it is a means to counteract, often by simple interventions, the negative side effects of modern technologies (such as irrigation technologies in this case).

2. *Adapting the structural-functional analysis approach to pre-project/pre-program assessment*

In assessing the Jordanian water harvesting TIS, it became apparent that the clear picture of the innovation system that developed from the methods used could be helpful for developing a thorough understanding of the system into which a new project or program occurs. TIS methods could be applied during the project inception phase to align them with a common vision and to reduce redundancy and waste by better understanding how the new activities fit into the broader context of activities by other actors and institutional conditions. This has particular relevance for international donor projects, in light of the findings from Chapter 2.

3. *Further research is needed on expanding the Water Diplomacy Framework for specific application to governance institutions.*

The methods from Chapter 3 drew heavily on Ostrom's principles for sustainable CPR governance (Ostrom, 2008, 1990). Considering Water Diplomacy principles as a sub-set of Ostrom's work was appropriate for this early research into expanding Water Diplomacy analysis to the governance context. However, in this context, Ostrom's design principles are necessary conditions but not necessarily sufficient, and variables specific to water or other variables such as political will could be potential additions to a Water Diplomacy Governance Framework.

4. *Comparative analysis of the groundwater governance regimes of Nebraska and California*

Nebraska and California present two examples of polycentric groundwater governance regimes addressing both quantity and quality. The more recent California regime also reflects principles that were present in Nebraska's many years before. Future research on both the regime structure and the experiences of the stakeholders involved in crafting the regimes could benefit efforts to enact robust groundwater governance elsewhere and potentially improve the existing systems in these two states.

5. *Assessing the extent to which the Nebraska NRD governance regime is replicable in other geographies.*

While Chapter 4 provides another empirical example of the applicability of established SES governance principles, it is possible that institutional and cultural conditions endemic to Nebraska may limit the applicability of its governance model to other geographies. Additional research should look at what aspects of groundwater governance in Nebraska can be applied to other geographies, both in the U.S. and internationally. It would be particularly interesting to see if there is any adaptability of this model to the developing world, and to tie this in with concepts explored in Chapter 2.

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Appendix 1: Supplementary Material for Chapter 2

S-1: Types of water harvesting practices suitable for use in Jordan. Descriptions of the types of catchment systems were adapted from Critchley & Siegert (1991); Oweis et al. (2001); USAID (2015); and from interviews. Practices have been grouped into micro-and-macro catchment systems.

Micro-catchment systems: typically employed on an individual farms and collect surface runoff from a small catchment area (ranging in size from a few square meters to 1000 m^2,) with sheet flow over a short distance to be stored in the root zone for direct use by plants or into small reservoirs for later use	
Contour ridges	Bunds or ridges constructed along the contour line of a slope, 5-20 m apart, upslope from which crops are planted. These simple catchments can be formed manually or with animal or tractor driven implements
Semi-circular and trapezoidal bund	Semi-circular earthen bunds facing upslope, usually 1-8 m in diameter. Cutting the soil to create the bund creates a slight depression where runoff is intercepted and stored in the plant root zone
Small pit	Range in size between 0.3-2 m in diameter and 5-15 cm deep into which manure or mulch are mixed with the soil are typically used for the cultivation of annual crops. Pit water harvesting systems are an effective way to restore agricultural and rangelands. Machine operated pitting machines have been employed in Jordan for rangeland restoration
Small runoff basin	Usually constructed for tree crops and are diamond or rectangular areas surrounded by low earth bunds oriented so that the maximum land slope is parallel to the long diagonal of the diamond, where the crop is planted
Runoff strips	Used on gentle slopes, usually to grow field crops such as barley. The slope is divided into strips along the contour, alternating strips of compacted soil and cultivated soil. The compacted upslope strip is used as a catchment for crops grown on the strip immediately downslope from it
Macro-catchment systems: characterized by having runoff water collected from a catchment area greater than 1000 m^2. The catchment is often a natural landscape feature such as a *wadi*, rangeland, or steppe.	
Marab system	A *Marab* is a natural formation at the end of a *wadi* (a valley or channel that is dry except for in the rainy season) where the water flow terminates. In a *Marab* system, a series of check dams or bunds are built to slow the flow of water. As one check dam fills to capacity, the water flows around the edges and down to the next dam. Behind each check dam or bund, water and sediment accumulate allowing for cultivation of crops, usually barley. Marab systems are appropriate for the Badia. Research by ICARDA has shown *Marab* systems to be more productive than nearby fields that do not implement the practice, even in very dry periods
Hafir system	In a *hafir* system, a water channel is built off of a *wadi* and divert part of the flow to fill up a holding pond or reservoir, known as a *hafir*, for supplemental irrigation or watering livestock.

S-2 : The seven functions of a TIS (Andersen, 2015; Bergek et al., 2008; Hekkert et al., 2007; Hekkert and Negro, 2009; Turner et al., 2016).

1.	*Knowledge development*	Fundamental to the innovation process and involves the learning processes related to developing and utilizing new knowledge on a technology or set of practices. The development of new knowledge can occur through formal research (e.g. at universities and governmental and non-governmental research centers), the private sector (e.g. agri-business), or at the individual level (e.g. farmers).
2.	*Knowledge diffusion through networks*	The exchange of information through networks, where research and development (R&D) meets government and markets. Policy decisions should be guided by the latest technological research, and R&D agendas should be affected by changing environmental, market, and social conditions.
3.	*Influence on the direction of the search*	Refers to the creation of a vision for the innovation system and mobilization of incentive structures towards that vision. Incentive structures may change in response to factor prices and regulatory pressures (e.g. product prices, taxes, and subsidies), expectations in market growth potential, new knowledge, expression of interest by customers, cultural changes, and external events.
4.	*Entrepreneurial activities*	Turn the potential of new knowledge, networks, and markets into concrete actions to develop and capitalize on business opportunities.
5.	*Market formation*	Is about creating demand for the outputs of the innovation process. New technologies or practices often have difficulty competing with the *status quo*, so a market must be created via institutional change. Market creation can occur through changes in regulation and taxes and/or investment in infrastructure complimentary to the innovation.
6.	*Creation of legitimacy*	It is necessary to overcome resistance to a new technology or set of practices from the existing production, trade, and consumption systems. The innovation must be considered appropriate and desirable by incumbent actors for resources to be mobilized and not blocked.
7.	*Resource mobilization*	Is closely linked to the creation of legitimacy and concerns financing investment in innovation in the form of access to credit, seed funding, venture capital, investment in human and social capital, and the development of complementary products, services, infrastructure, etc..

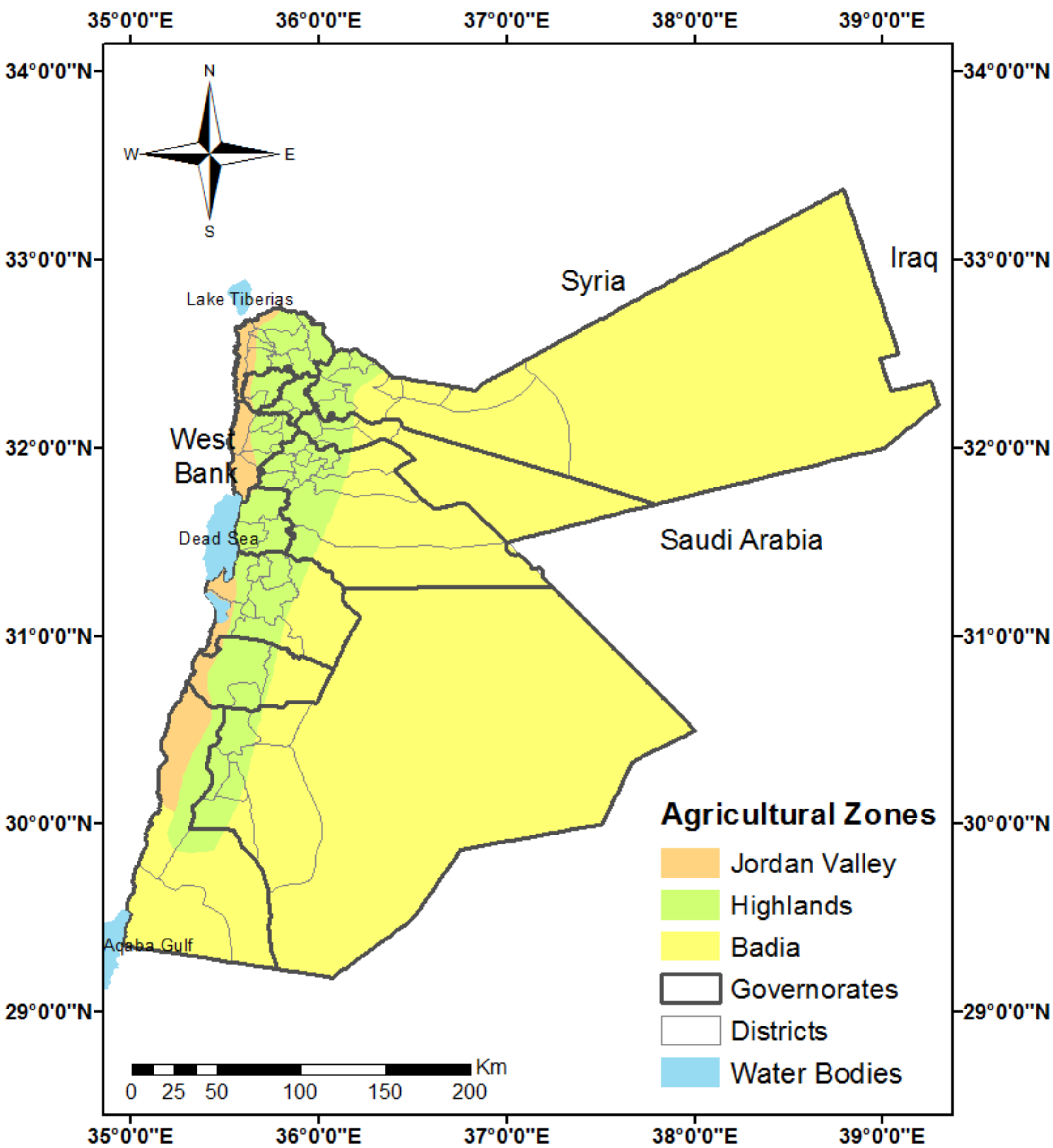
S-3: Structural Components of a TIS (Klein-Woolthuis et al., 2005; Turner et al., 2016; Wieczorek and Hekkert, 2012)

Actors	Individuals and organizations and can include: government, non-governmental organizations (NGOs), civil society, private sector companies (ranging from small enterprises to multinationals), knowledge institutes (universities and research centers), international donors, and financial and legal organizations. They and are delineated based on their role in economic activity rather than their role in the innovation process because of the ambiguity between producers and users in most innovation systems
Institutions	Established practices, or shared habits, cultures, and routines, used by actors in repetitive situations (soft institutions) organized by institutional measures, such as regulations, policy, and standards (hard institutions)
Interactions	The relationships between actors, and they can be analyzed at the level of individual contacts or at the levels of networks or actors
Infrastructure	Consists of three categories: (1) physical infrastructure, consisting of roads, buildings, ports, data networks, and machines; (2) knowledge infrastructure, which includes research, expertise, and agricultural extension; and (3) financial infrastructure, such as, subsidies, grants, and financial programs

S-4: Systemic problems in the context of transformative change (Weber & Rohracher, 2012; Klein-Woolthuis et al., 2005)

	Type of Problem	Systemic Problem Mechanism
Structural system problems	Infrastructural problems	Shortfalls in existing physical infrastructure that inhibit innovation
	Institutional problems	There are two types of institutional problems: 1. Hard institutional – (regulations) institutional measures, such as regulations, policy, and standards, that impede innovation 2. Soft institutional – (established practices) political, economic, and social cultures and norms that hinder innovation
	Network problems	There are two types of network problems: 1. Strong network – interactions between actors within an organization are too dense, leading to an absence of weak ties with other actors and strong dependence on a few key actors. 2. Weak network – insufficient exchange with third parties, which limits opportunities for learning through these interactions and stifles innovation
	Capabilities problems	A lack of capacity to adapt to changing conditions and take advantage of new technological opportunities – this reflects underinvestment in research but also captures the systemic problem of path dependency and the inability of an organization to absorb new knowledge.
Transformational system problems	Directionality Problems	Directionality is necessary to guide the direction transformative change. The direction is defined by identification of major problems or challenges for which solutions are needed. The solutions are developed with the help of innovation.
	Demand articulation problems	Reflects not anticipating and learning about user wants and needs
	Policy coordination problems	The absence of interaction between different levels and areas of policies relevant to the technology are necessary for transformative change. There are two types of policy coordination problems: 1. Vertical coordination –between ministries and subordinate agencies in charge of implementation, or between different levels of government (local, regional, national, and international/donor). 2. Horizontal coordination – between research, technology and innovation policy, sectoral policies (e.g. environmental, energy, and agriculture), and cross-cutting policies (e.g. tax policy, economic policy, and regional policy).
	Reflexivity problems	The absence of continuous monitoring of progress towards transformation goals. Reflexivity needs to be built into the innovation process – the system must be able to monitor and to involve actors in the process of self-governance.
Market problems	Information asymmetries	Uncertainty about outcomes and short-term demand on investment by private investors leads to undersupply of research and development.
	Knowledge spill-over	Knowledge created by one actor is used by another actor without compensation, creating a sub-optimal investment environment for basic research and development.
	Externalization of costs	The ability to externalize costs leads to innovations that can damage the environment and social goods.
	Over-exploitation of commons	Common pool resources are over-exploited in the absence of institutional rules that limit their use.

S-5: Agricultural Zones of Jordan (Map by Samer Talozi, 2016)



S-6: Semi-structured key informant interview questions

1. **Participant information – Confirm name, organization, and title** (This personal data will be kept on a separate password-protected spreadsheet and this section will use substitute identifier)

2. **How long have you been in this position (in months)?__________**

3. **Please indicate what your <u>organization/program/department</u> contributes, or can potentially contribute, to projects focused on increasing water harvesting in Jordanian Agriculture (choose as many as apply).**

Project/program funding	Expertise other than agricultural water management
In-kind resources (e.g., meeting space and equipment)	Community Connections
Staff	Financing for construction of water harvesting systems
Policy development	Management/Leadership of individual projects/programs
Research on development, improvement, and use of water harvesting technologies and practices	Advocacy for water harvesting projects
Monitoring and evaluation	Specific agricultural water management expertise
Equipment/materials for constructing water harvesting systems	Extension services
Other (please specify)	

4. **What is your <u>organization</u>'s most important contribution to projects focused on developing, improving, and implementing water harvesting in Jordanian agriculture? (Choose one.)** {**Please pick one from list of those selected in Q3**}

5. **How do you define water conserving agricultural practices? Why do you have this definition?**

6. **How important are agricultural <u>water harvesting</u> practices to continuing farming in the rainfed agricultural regions of Jordan?**
   [PROBING QUESTION: Why do you believe it is this important/unimportant?] what goals do they serve?

7. **Can you provide some examples of water conserving agricultural practices that are either currently in use or that you think are appropriate for Jordan?**
   [PROBING QUESTION: Can you tell me something about how the current system came about? What were key moments?]

[PROBING QUESTION: What happened in the past that led to today?]

8. **In your opinion, what are the strengths and weaknesses of current <u>water harvesting technologies and practices?</u>**

9. **Which practices in your view are not widely used, but should be in widespread use in Jordan?**
   [PROBING QUESTION: Why these? Why are practices you think should be used not used?]

10. **What do you think of the current system for developing, improving and promoting <u>water harvesting?</u>**
    [PROBING QUESTION: Has it been effective?]
    [PROBING QUESTION: How has it been effective/ineffective?]
    [PROBING QUESTION: Why do you think that is?]

11. **Do you think there is a clear and shared vision on how water harvesting should be organized and implemented in Jordan?**
    [PROBING QUESTION: Why yes/no?]

12. **Which are the most important organizations, people, and/or groups for driving activities that increase the use of <u>water harvesting practices</u> (or water conservation if person isn't that familiar with water harvesting)?**
    [PROBING QUESTION: What makes them important? How are they valuable? What kind of resources do they contribute? How powerful/influential are they?]
    [PROBING QUESTION: Are these the same organizations/people/groups responsible for developing and introducing water harvesting practices?]
    [PROBING QUESTION: What roles do they play/why are they so important?]
    [PROBING QUESTION: How do they play this role? Is it positive or negative?]
    [PROBING QUESTION: How do they influence activities, such as creating demand for water harvesting or education on the design, construction, and use of WH systems?]
    [PROBING QUESTION: How effective are they? – why are they effective/ineffective?]
    [PROBING QUESTION – How frequently do you/your office interact with these people/organizations/groups?]
    [PROBING QUESTION – How do you interact/work with with them?]
    [PROBING QUESTION – To what extent are they (work it out for each one):
    - Reliable
    - In support of the development, adaptation, and implementation of WH?
    - Open to discussion and feedback on methods, practices, changes

13. **Is there private sector involvement with the development, construction, and/or marketing of water harvesting technologies and systems?**
    [PROBING QUESTION: If yes, who are they? How are they involved? What role do they play?]

[PROBING QUESTION: If no, why is that]
[PROBING QUESTION: What type of private sector involvement is necessary? What is missing?]

14. **What is your view on the type of technologies and practices that are developed for agriculture in Jordan?**
    [PROBING QUESTION: Are they well adapted to user circumstances? Why yes/no?]
    [PROBING QUESTION: Who creates them?]
    [PROBING QUESTION: Do you think those that create them are well connected with those that use them? Why yes/no?]

15. **How are the organizations, people, and/or groups connected to each other and how do they coordinate amongst themselves?**
    [PROBING QUESTION: How successful is this coordination?]
    [PROBING QUESTION: Why is this the case?]
    [PROBING QUESTION: What can be improved in terms of interaction/coordination?]
    [PROBING QUESTION: Are organizations that should be involved in coordination not involved? Which ones? Why?]
    [PROBING QUESTION: Are there organizations that should be more involved in coordinating with other organizations than they currently are? Which ones? Why?

16. **How does change in agricultural practices occur in Jordan?**
    [PROBING QUESTION: Which actors/organizations are the drivers of change?]
    [PROBING QUESTION: How do farmers find out about new practices and technologies?]
    [PROBING QUESTION: What factors influence how a new set of agricultural practices and technologies is viewed – as favorable or unfavorable?
    [PROBING QUESTION: What roles do the different institutions play in this process?]
    [PROBING QUESTION: What role does financing and funding play in this process? Where does it come from? Why does it play this role?]

17. **What are influences from the institutional setting in Jordan on creation and adoption of water harvesting technologies and practices? In other words (if clarification is needed) how do local customs, laws, different policies influence the development and adoption of water harvesting technologies and practices?**
    [PROBING QUESTION/APPROACH: Be sure to dig deep with interviewee on how each one influences water harvesting – TEASE OUT THE DIFFERENT TYPES OF INSTITUTIONS]

18. **Are there tensions/contradictions between different institutional factors? E.g. Contradicting policies/laws/cultures?**
    [PROBING QUESTION: Are there long term visions in local customs, laws, and development policies for how the agricultural system should look in 10 years, 20

years, 50 years? If so, what is that vision? If not, why do you think there is a lack of this vision.
[PROBING QUESITON: Do the different institutions share similar values and visions on how the agricultural system will look in the future? What are these values and vision? How are they formed? How do these values and visions interact among different actors in the system? If they are different, how different? Why are they different?]
[PROBING QUESTION: Proceed with ‘5 Whys’ analysis here]

19. How is the development, improvement, and use of water harvesting (or water conserving if interviewee is not knowledgeable on WH) technologies and practices supported in Jordan?
[PROBING QUESTION: Who are the most important actors/organizations in this process?]
[PROBING QUESTION: How does the development of WH accommodate the needs of farmers? Are farmers included in the development/improvement of WH technologies/practices? How?
[PROBING QUESTION: How is adoption supported by research and extension? Why does it happen this way? If support is limited – what are the main barriers to greater involvement?

20. What is the role of funding for innovation and adoption in water harvesting?
[PROBING QUESTION: How does funding from international donors influence the water conservation and agricultural policy priorities of the Government of Jordan? is this positive/negative? Why?]
[PROBING QUESTION: How is funding coordinated between donors and government offices?]
[PROBING QUESTION: What are the other big sources of funding for water conservation in Jordanian Agriculture? How? Why?]
[PROBING QUESTION: How well have current funding arrangements performed to achieve widespread WH use? Why?]

21. What is your view on the extent to which water conserving agricultural practices have been adopted by farmers in rainfed agriculture in Jordan?
[PROBING QUESTION: What types of water conserving agricultural practices have been adopted in the Jordanian rainfed agricultural system?]
[PROBING QUESTION: What are the main factors influencing this level of adoption?]
[PROBING QUESTION: How appropriately are the types and sizes of the water harvesting systems matched to the needs in agriculture? Why do you think this is?
[PROBING QUESTION: Are there specific types of infrastructure and equipment that need to be in place to increase the use of water harvesting practices? Are these there? Why yes/no?]
[PROBING QUESTION: How are farmers supported? Is this adequate? Can they get the goods and services to implement WH? Why yes/no?]
[PROBING QUESTION: What is the role of finance/costs of WH?]

[PROBING QUESTION: What is the role of incentives/disincentives? Are their contradictions in incentives to farmers? Of what nature, why?]

22. Please summarize, what in your opinion are, the biggest barriers to the development and widespread use of water harvesting practices in rainfed agriculture in Jordan?

[PROBING QUESTION: What are the main factors, and how do these factors interact to keep the system from changing?]

[PROBING QUESTION: Who are the main actors hindering change? Why? How?]

[PROBING QUESTION: What is being done or can be done to overcome these barriers? How is it working out?]

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Appendix 2: Supplementary Material for Chapter 4

Nebraska Interview Questions

Note: some respondents will be informants for only one of the management institutions (Central Platte NRD, Bazile Groundwater Management Area, Hastings Wellhead Protection Area), while others will have knowledge about multiple management institutions. The specific phrasing of the questions will be adapted depending on this.

Once the recorder has been turned on, the following two questions will be asked to the respondent, "Just to confirm now that I've turned on the recorder, do you consent to participate in the interview? Do you consent to be recorded?"

NOTE TO THE PARTICIPANT THAT IF THEY DON'T KNOW THE QUESTION IT IS OKAY TO SAY THAT AND WE WILL SKIP THE QUESTION

1. Can you tell me a bit about your role in managing groundwater quality?

2. How do people perceive the issue of high nitrates in groundwater in this area? Why do you think that is?
    a. How does this determine their actions in terms of groundwater management?

3. How many people are impacted by the elevated nitrate levels in the groundwater in this management area?
    a. How many farmers are in the project area?
    b. How many drinking water users?
    c. Are the farmers also using the drinking water that has been impacted by nitrate pollution?
    d. Is this project aimed at reducing nitrate levels for all users, or only for municipal water? Why?
    e. What about private wells? Will this project address nitrate levels in those?

4. Can you tell me a bit about the history of what led to this particular program? (Note: Question is tailored depending on which programs the respondent is familiar with)
    a. Was there a key moment or key point that led to the decision to develop this program?
    b. Was there any stakeholder involvement and if so, what did it look like?
    c. How was it decided who would have a seat at the table? Why?

5. Can you describe how the different stakeholders fit in with the management of the program and how this has made this program successful?
    a. What has enabled people to work together on this program?
    b. Has that collaboration been successful? How? Why?
    c. Were there any tensions in this process? If so, how were they resolved?

6. What does the management structure of the program look like? In other words, how strong of a role do the Federal government and state play versus local-level management (NRDs, municipalities)? Who has the power in ensuring this project meets its goals?

7. How was the size of the management area determined?
    a. Does the management area of this program go beyond the boundaries of earlier groundwater management activities in the state?
        i. In what way? Why?
    b. Do you think this program crosses boundaries? How? Why?
    c. How were the boundaries of the management area chosen? Why?
    d. What were the issues of debate in this process?
    e. Is the management area large enough to address the nitrate problem?
    f. If not, why isn't it bigger?

8. [*For Bazile Groundwater Management Area (BGMA), Hastings Wellhead Protection Area (HWPA)*], what influenced the decisions go beyond the boundaries of individual NRDs and approach the problem more collaboratively?
    a. What did that process look like?
        i. How was the process governed?
    b. Were there any tensions in the process? What did they look like? Why did they occur?
    c. What went well? Why do you think that is?

9. What are the Best Management Practices (BMPs) that have been put in place to address the nitrate problem in groundwater?
    a. How are the BMPs communicated to farmers?

10. How were the specific set of BMPs and other control measures chosen?
    a. Were there some that were left out?
        i. If so, why?
    b. Who was involved in this process?
        i. What was their role in establishing them?
    c. What does the implementation process for these BMPs look like?
    d. What works and what does not work in the implementation of BMPs?

11. What measures are in place to ensure that individual irrigators will practice fertilizer application BMPs?
    a. How do these work out? Why do you think that is?

12. In your opinion, are the BMPs and rules that were established achievable by farmers?
    a. Why yes/no?
    b. What have been the results of this?
    c. How has adoption of these BMPs by farmers been going?

   d. What incentives are in place to get farmers to participate in adopting BMPs?

13. Has there been any pushback by farmers on these programs?
    a. If so, what did that look like?
    b. Are their concerns being addressed?

14. Can you tell me a bit about how data on fertilizer, groundwater quality data, and effectiveness of certain BMPs is shared and communicated to various stakeholders?
    a. How are those data perceived by the different stakeholders in the management area?
    b. Have there been any tensions over the data? What were these tensions? Why did they occur?
    c. What went well in sharing this information? Why?

15. What is the planning horizon for the program in terms of years?
    a. Where there any issues or tensions in developing the timeline for the program?
    b. If so, what were they? Why did they occur?

16. How is uncertainty about how BMPs will affect nitrate levels over time accounted for?

17. How has the structure of the NRDs impacted this program? Why?
    a. In what way did this enable the formation of this program? Why?
    b. Has this particular program led to changes within the NRDs that are involved in this program? What were they? Why?

18. In what ways to the NRDs involved in this program align (in terms of interests, policies, priorities, management structure/style)?
    a. In what ways are they different. What causes those differences?

19. Why do you think projects focused on nonpoint source nitrate pollution have occurred in the Central Platte NRD, Bazile Groundwater Management Area (BGMA), Hastings Wellhead Protection Area (HWPA) and not elsewhere in the state? Elsewhere in the country?

20. Are you aware of any other organizing to address the nitrate pollution problem elsewhere in the state, or even additional activities within the program areas?
    a. What are they? How are they similar/different to these programs?

21. Can you tell me a bit about some of the key challenges that may have arisen over the course of these programs?
    a. Why have they arisen?
    b. What has gone well in this program? Why?

22. Can you summarize what mix of factors makes this program work in terms of what makes it unique, the collaboration, the tools used, communication, and the governance/policy?
    a. What are the key things that could be learned by other parts of the state or country as they work to address nonpoint source nitrate pollution?

23. Do you have anything else you would like to add that you feel would be useful to this project?