Many Faces of Complexity: Evaluation of Water Management in the State of Guanajuato, Mexico

A thesis submitted by
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Abstract

Conventional conflict resolution theory approaches water issues by evaluating watersheds or river basins within a bounded domain. Embedded within the theory is the idea that water is a scarce resource, suggesting competing demands over fixed availability will ultimately lead to conflict. Additionally, it suggests that planning should be driven by experts and scientific analysis rather than centered around stakeholder involvement. This traditional approach has proven to be ineffective in addressing the complexities of today's water problems, often resulting in societal inequities and insecurity of natural resources.

The Water Diplomacy Framework (WDF), pioneered by Islam and Susskind (2012), offers a conceptual tool to guide actionable decision making to manage simple, complicated, and complex water networks. The WDF diagnoses water problems, identifies potential pathways for intervention, and presents actionable solutions that consider uncertainties, as well as diverse viewpoints and competing needs of various stakeholders (Islam & Susskind, 2012). By combining science, policy, and politics in creative and contextually specific ways, the WDF actively seeks value-creation opportunities (Islam & Repella, 2015).

To effectively diagnose and address regional issues, it is imperative to properly characterize the water network in question by evaluating the interactions between the natural, societal, and political domain. Through a critical review of the existing literature and application of the WDF, this thesis evaluates the water crisis unfolding in the State of Guanajuato, Mexico. Rather than evaluating the issues within one clearly bounded

domain, such as state boundaries, the thesis will define and examine the problem-shed – considering the multitude of factors that directly or indirectly influence the complexity of the system in question.

This thesis concludes that water resource management has evolved from a simple system prior to Spanish colonization, to a progressively more complicated system during colonization, to the complex system of today as a result of a variety of factors such as industrialization and urbanization. Uncertainties such as climate change and hydrological variability inherent in any complex system compound existing issues and create bottlenecks for actionable solutions. When evaluating the water management issues within the State of Guanajuato, it is crucial to understand the spatial, jurisdictional, institutional and management characteristics that are unique to this problem-shed. Ultimately, to address the water crisis unfolding in the state, water diplomacy solutions are urgently needed, such as joint fact-finding, value creation, and an iterative and adaptive approach to water resources management.

Acknowledgements

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Introduction

Guanajuato, made up of 46 municipalities, is one of the thirty-two states of the Federal Entities of Mexico (Instituto Nacional de Estadística, Geografía e Informática). Located in central Mexico, it is bordered by the states of Jalisco to the west, Querétaro to the east, San Luis Potosí to the north, Zacatecas to the northwest, and Michoacán to the south. As of 2020, the state population is approximately 6.2 million people, increasing by 12.4% from 2010 (Gobierno de México).

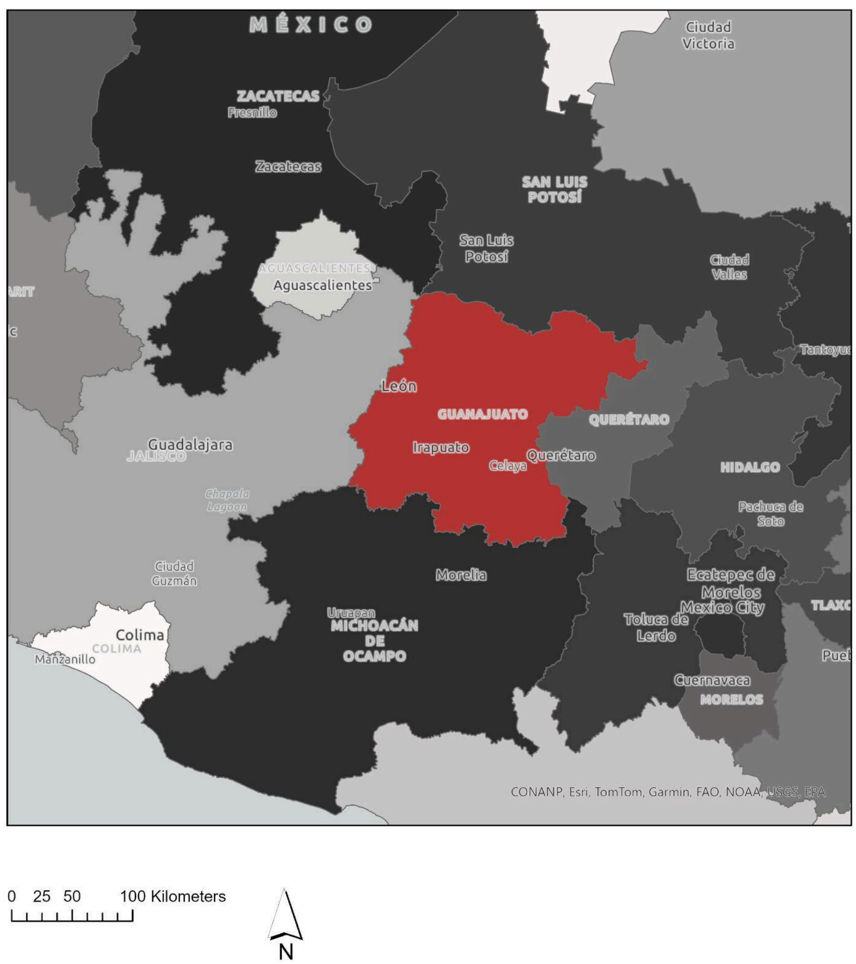

Figure 1. A map of Guanajuato and the bordering states.

Referenced throughout this thesis, El Bajío (The Lowlands) is a key natural and societal domain to contextualize water issues within the state of Guanajuato. Known today as the breadbasket of Mexico, this extensive valley consists of fertile soils and rivers that has historically made it the main agricultural region within the Lerma-Chapala Basin (Wester, 2008). The region covers most of Guanajuato, as well as parts of Querétaro and Michoacánis, producing crops such as sorghum, wheat, corn, barley, beans, avocado, chili, tomatoes, bananas and coffee. It also has the most important trade routes within Mexico, through a wide network of roads, railways, and airports (Agropecuarios). Most of the large cities and industries within Guanajuato are contained within the Bajío region and are characterized by their intensive irrigated agriculture (Wester, 2008).

Approximately half of Mexico's land cover is arid and semi-arid (Navarro et al., 2005), with a distinct wet and dry season. Compared to the rest of the country, the Mexican Highlands in the central and northern part of the country receive very little precipitation. In semi-arid basins, to compensate for the lack of rainfall, groundwater is often used as the primary source of water. Over the past few decades, over-extraction in semi-arid parts of the country has led to drastic alterations to the hydrogeological balance. These alterations have, in turn, resulted in a rapid decline of the water table, the reduction in spring and river discharges, the deterioration of ecosystems, and changes in water quality (Navarro et al., 2005).

Guanajuato, the second largest consumer of groundwater in the country, is well-known within Mexico for dealing with the severe consequences of overexploitation of groundwater (Navarro et al., 2005). To date, nearly all of the industrial and urban water supply within the state is sourced from groundwater. The water table is dropping at an alarming rate — between 2 and 3 meters every year (Hoogesteger & Wester, 2017). According to the State government, irrigated agriculture accounts for 84% of all extracted groundwater (Comisión Estatal del Agua, 2016), which is significantly higher than the global water usage of 70% in this domain (Margat & Van der Gun, 2014).

Water stress, defined by the World Resources Institute (WRI) as the ratio between the total water withdrawals and available renewable surface water and groundwater, indicates the level of competition between water users relative to surface water availability. Demand from users includes domestic, industrial, irrigation, and livestock activities. Available renewable water supplies include the effects of upstream water users and large dams on downstream water availability. A closer look at the WRI's online database, Aqueduct, reveals that fifteen of Mexico's states, including Guanajuato, face extremely high baseline water stress. The majority of the state is currently facing extremely high baseline water stress, consuming between 80 - 100% of available water every year. The high value seen in Guanajuato would suggest that there is more competition for water resources among the users there.

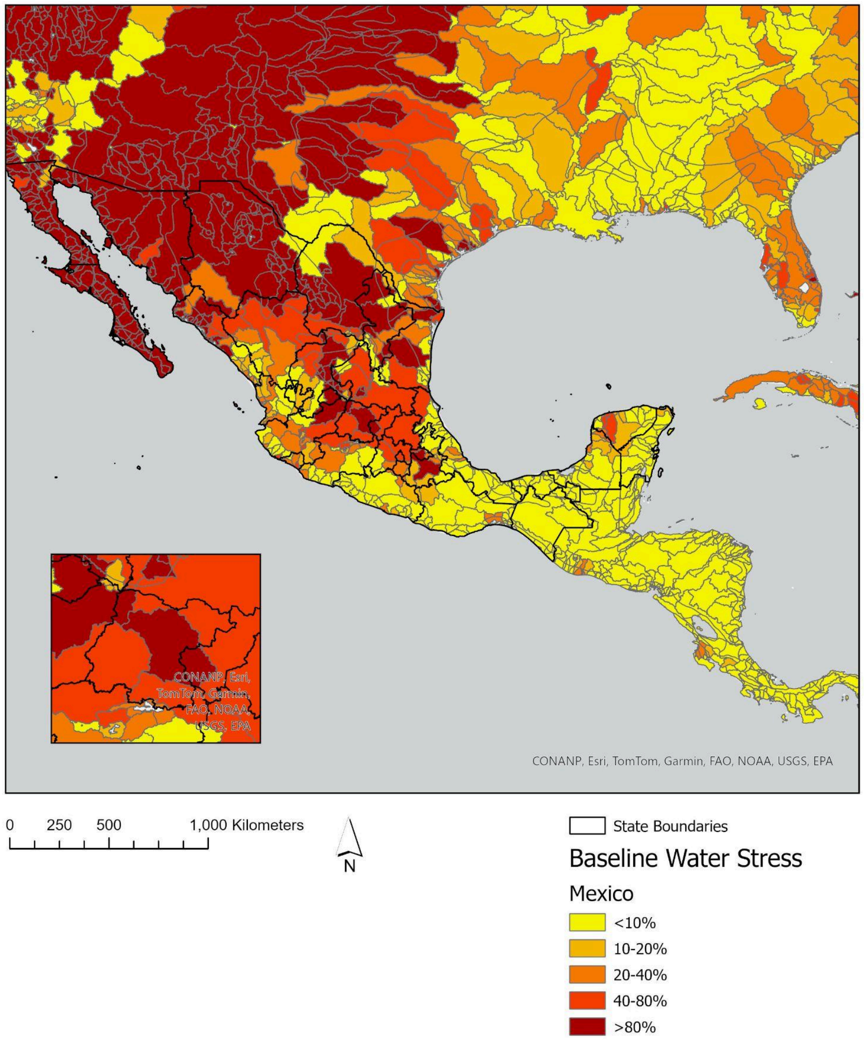

Figure 2. Water stress in Mexico with inset map of Guanajuato state using World Resources Institute Aqueduct data.

Integrating other indicators from WRI's Aqueduct tool (version 2.1) reveals a more generalized view of overall water risk, which aggregates indicators from physical quantity, physical quality, and regulatory and reputational risk. Within physical risks for quantity, it measures risk related to too little or too much water. Indicators include baseline water stress, inter-annual variability, seasonal variability, flood occurrence, drought severity, upstream storage, and groundwater stress. Within physical risks for quality, it measures risk related to water that is unfit for use. Indicators include return flow ratio and upstream protected land. Within regulatory and reputational risk, it measures risk related to uncertainty in regulatory change and conflicts with the public in regards to water issues. Indicators include media coverage, access to water, and threatened amphibians. Through mapping the WRI data, it is evident that the majority of Guanajuato shows an overall high water risk.

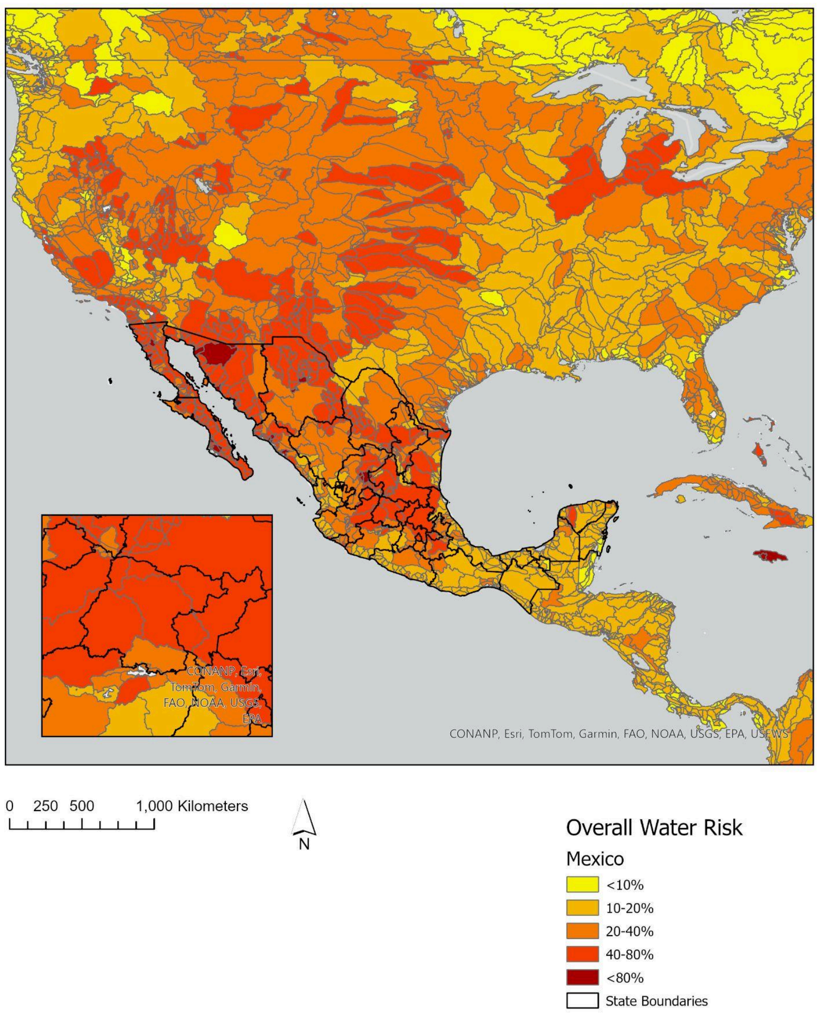

Figure 3. Overall water risk in Guanajuato using World Resources Institute Aqueduct tool (Aqueduct).

Another study completed by Arreguin-Cortes, et al. adapted the concept of global water security index to the state level in Mexico, looking at water availability, accessibility, safety and quality, and management. Guanajuato was among the states flagged to be in a critical situation (Arreguin-Cortes, 2020).

To understand why there is overexploitation of groundwater within the state, it is crucial to look back at political relations between Mexico's North American neighbors. In 1994, the United States, Canada, and Mexico enacted the North American Free Trade Agreement, which ultimately opened up trade amongst borders (NAFTA). This agreement, paired with favorable climatic conditions, cheap labor, and key geographical positioning for reaching the United States market, ultimately attracted both national and international agro-export companies (ETModulo, 2017). A few large agribusinesses from the United States, mostly focused on the frozen vegetable industry, relocated their operations to the Bajío region of Guanajuato and began to plant water intensive crops, such as broccoli, green beans, and okra (Bee, 2016).

The climatic conditions within the state allow for year-round production of a variety of crops. During the winter, the Bajío region of the state serves as an important production zone that the US market lacks internally. Export vegetables proved to have higher economic value than alfalfa and other traditionally grown crops, and the opportunity to benefit from this profitability attracted many farmers to the area. Much of the purchased land involved either ranches that were no longer active, or ranches that were producing fodder (ETModulo, 2017).

Crops such as broccoli are not part of the traditional Mexican diet — it is the global demand for fresh vegetables that drives the industry within Guanajuato. With the rise of the agriculture industry, the region has seen higher profits, an increase in jobs, and a booming economy within the sector. The majority of production is run by medium and large producers, cultivating anywhere from 100 to over 500 hectares of land. These producers are powerful, and have the economic backing to access groundwater no matter how deep they have to drill (ETModulo, 2017).

Within Mexico, an estimated virtual export of blue water – the water in freshwater lakes, rivers, and aquifers (Hoekstra et al., 2011) – used to grow cauliflower and broccoli has increased by 621%, with Guanajuato accounting for 62% of this national blue water consumption (Hartman, 2021). The unsustainable irrigation practices seen in the area put into question the future health of the fragile food supply, for domestic and export markets alike (Hartman, 2021).

The rural communities within the state, particularly in areas of high agricultural production, are the populations most severely affected by the water issues – both in terms of quality and access. As the water table continues to drop due to overexploitation of the aquifer, communities are seeing high levels of arsenic and fluoride in their drinking water — according to the local non-profit Caminos de Agua, up to 22 times the World Health Organization recommendation for arsenic and over 12 times the recommendation for fluoride.

Arsenic is a known carcinogen, confirmed to induce skin, lung, and bladder cancer. Accumulation of the toxic element in the human body has also been linked with negative impacts on memory, intellectual function, and the reproductive system, amongst other ailments (Hong et al., 2014). Although proven beneficial in low quantities, long term exposure to excess fluoride causes a slew of other ailments, including dental fluorosis, skeletal fluorosis, arthritis, bone damage, osteoporosis, muscular damage, fatigue, and joint-issues (Solanki et al., 2022).

Thousands of people in the rural communities of Guanajuato are suffering from dental fluorosis, skeletal fluorosis, and loss of memory. Patricia, from the community of Coporo claims: “The studies completed on our water show excess fluoride, which is affecting our families’ health. Our teeth are affected, people have hurting bones, when we take a shower our skin itches” (ETModulo, 2017).

Mexico has made efforts over the last few decades to improve water services. However, water availability is still very much a prominent issue in the social fabric of the country – an estimated 5 million people do not have regular access to clean water and sanitation and notable inequalities can be seen in the low-income central regions, including Guanajuato (Wilder, 2020). Inequity in water access, including intermittent water provisions and lack of water and sanitation services, is seen in both urban and rural areas, with indigenous communities often being the most vulnerable. Also, there is a high level of distrust in water provisions, leading 73% of Mexicans to rely on bottled water for consumption (Wilder, 2020).

A closer look at Guanajuato, home to roughly 6 million inhabitants (Guanajuato), reveals that water access is a huge issue. The state consists of 8,936 localities broken into 46 municipalities, 12 of which have a population size of over 50,000 inhabitants. Of these 8,936 localities, 8,821 of them suffer from very low levels of water coverage (Sandoval-Minero, 2005). In one study from northern Guanajuato, 62% of 810 families only had access to water for six hours daily as a result of water being shared with nearby communities.

The lack of water is also negatively impacting livelihoods – small-scale farmers are simply not able to compete with large, powerful commercial farms with irrigation-fed crops (Bee, 2016). A pattern has emerged where as wells dry up and collapse in on themselves, increasing numbers of farmers are looking to sell part, or all, of their water concession – they do not have the capital necessary to replace or deepen their wells. According to Hoogisteger and Wester, “this economic water scarcity of smallholders is leading to processes of increased social differentiation and capitalist accumulation of groundwater.” Essentially, a market has emerged to meet the growing demand for groundwater, but only for those who can afford the increasingly high cost. Ultimately, the existing market is compounding inequality and continuing the over-exploitation of the aquifer (Hoogisteger & Wester, 2017).

For rural communities, such as Coporo, there is no access to running water at all. In other communities, such as La California, community members are only receiving water three days a week, and they must store it in *tambos* (buckets), rationing the water between their animal and domestic needs. While some rural communities struggle to get by with their five liters of water a day, there are agricultural producers extracting water from wells continuously throughout the day and night (ETModulo, 2017).

Chapter 1: The Problem

The agriculture industry is a powerful entity within the state of Guanajuato. A few medium and large ranch owners, supported by the ever-growing demand for fresh vegetables, are reaping the benefits of the limited water resources that lay underground. In many ways, these producers are indeed water secure — at least in the short term. They have the economic backing to drill deeper and deeper wells, undisturbed by any regulatory body demanding sustainable usage of the precious resource. Meanwhile, the rural communities are left with extreme water insecurity issues that will only continue to worsen if no actions are taken by the state. The Mexican constitution calls for the human right to water, however these words have thus far proven empty in protecting these rural communities.

It is simply not enough to look at the water insecurity issues in the region as a problem of water scarcity perpetuated by natural physical conditions and limitations. Although the semi-arid climate of Guanajuato already makes the state prone to water problems, the severity of the issues are human caused and directly correlated to over-extraction of groundwater resources by industry and the economic gains associated with supporting the United States in areas of food security. As climate change continues to unfold, there is an added layer of complexity and urgency that must be considered. Decades ago, conditions were ripe for the emergence of a booming agro-industry in Guanajuato and expensive large-scale operations continue to flourish – but what will happen when all of their wells eventually also run dry?

When Mexico signed NAFTA in 1994 to encourage trade across borders and boost the economy with the rise of the agriculture sector, it would have been impossible to predict the emergence of arsenic and fluoride contamination in the State of Guanajuato. The resulting water insecurity issues are inherently complex and are intrinsically linked to three domains (natural, societal, and political), as well as scales (space, time, jurisdictional, institutional). Furthermore, in order for agencies and relevant stakeholders in the state to achieve actionable agreement, it is crucial that there is agreement over both social (the behaviors and decisions of people) and scientific facts (Islam & Susskind, 2012).

In my thesis, I will first trace back and summarize the history of water resource management in the state of Guanajuato, from pre colonial era to present day. Next, I will dive into problem specific questions and the causes and conditions surrounding them. Lastly, I will address an actionable solution space as a starting point for steps that can be taken to tackle the problem specific questions. Overall, my thesis will use the Water Diplomacy Framework, here on out referred to as WFD, as a guide to map out the complexities of the water issues faced in Guanajuato, Mexico and provide actionable recommendations for a path forward.

Chapter 2: Theoretical Approach

Modern water management problems are complex and arise from the interplay of natural and societal processes within a political domain. The interconnectedness of water quantity, quality, and ecosystems in the natural domain may lead to the emergence of conflict. There are also often complex interdependencies among social values, cultural norms, economic resources, and governance institutions within the societal domain. According to the WDF, when strong boundaries exist between the natural and societal domains, it becomes difficult to form a resolution of complex water management problems. Using Guanajuato, Mexico as a case study, this thesis explores the WDF, which offers a negotiated problem-solving approach to tackle complex water challenges. The framework, initiated by Islam Susskind (2012, 2018) is based on complexity theory and a mutual gains approach to negotiation. Ultimately, the framework aims to outline how the natural, societal, and political domains interact and how they should be managed.

The WDF recognizes the inherent complexity of water systems and the challenges posed by traditional reductionist problem-solving approaches. Complex water problems often lack scientific certainty and societal consensus, necessitating a negotiated approach involving interdisciplinary collaboration, fact-value deliberation, and joint fact-finding with stakeholders. The framework integrates the concept of emergence, where cause-effect relationships are ambiguous, and uncertainty is broad, requiring long-term, adaptive management strategies.

According to the framework, water diplomacy must strike a balance between principled and pragmatic problem-solving. It rejects solutions that involve compromising values while acknowledging the need for actionable outcomes that might require some compromise in interests. The framework holds the notion that negotiated problem-solving through inclusive dialogue enables discerning values and interests from stated positions, leading to sustainable and equitable resolutions to water conflicts.

The WDF has three uses: (1) conflict resolution, (2) incentive for cooperation, and (3) adaptive water governance. Water diplomacy is most applicable when water serves as a source of conflict. It addresses value conflicts arising from conflicting water use priorities, identity conflicts caused by disproportionate harm to marginalized communities, and distributional conflicts related to disagreements over water rights. Negotiated problem-solving offers the best chance for resolving these conflicts effectively. However, even in the absence of ongoing conflicts, introducing water-based incentives into negotiations can foster cooperation among stakeholders. Water's flexibility and connectivity across sectors create opportunities for multi-party cooperation, benefiting larger peacebuilding processes or contexts where conflict is absent. Complex water challenges often demand ongoing adaptive water management and governance. Water diplomacy provides foundational ideas for navigating uncertainties, pluralism of interests, values, and perspectives, and fostering an inclusive approach to problem-solving in these contexts.

Water diplomacy is versatile and can be applied at various scales, including transboundary water conflicts, distributional inequities within a state, and disputes between different stakeholder groups. While the framework provides a common foundation, it is not a one-size-fits all cookbook. Rather, it requires tailored operationalization at different scales to address specific challenges effectively.

Chapter 3: History of Water Management in Guanajuato

The history of water management in Guanajuato spans several centuries and has been shaped by the Bajio region's unique geographic and social factors. In order to understand how the water problem has evolved over time, we can use the simple-complicated-complex lens embedded in the WDF. By examining the historical context, changing agricultural and industrial practices, and shifts in water management policies, insights can be gained into the growing complexities and relationship between water resources and economic development within the state.

3.1: Precolonial Water Practices

Despite the belief that gods control their environment, prehistoric farmers in the Bajío region (which includes present day southern Guanajuato) succeeded in developing irrigation techniques as a way to secure water for their crops. Evidence suggests they invented irrigation and refined the process into a science (Dolittle, 1984). This innovation allowed them to harness the perennial water supply of the region's rivers for agricultural purposes, freeing themselves from the uncertainties of deity intervention (Dolittle, 1984).

In ancient agricultural Mexican societies, water deities held immense religious significance. Tlaloc, often referred to as "he who makes things grow," served a central role within the Aztec civilization (Dolittle, 1984). Often portrayed carrying a water vase, Tlaloc was known to be benevolent and generous, yet possessed a fear-invoking wrath. To appease Tlaloc and secure water resources, rituals involving the sacrifice of prisoners and children dressed as the deity were performed by priests (Dolittle, 1986). Interestingly, despite these beliefs, prehistoric farmers managed to harness a measure of control over their water supply by inventing and extensively utilizing irrigation methods, thereby liberating themselves to some extent from the unpredictable nature of deities like Tlaloc (Dolittle, 1986).

While there is limited evidence to support the existence of pre-Hispanic canal irrigation in the Bajío, it is widely accepted that indigenous communities settled in the floodplains near Río Querétaro (Querétaro River) – a location that offered access to perennial water sources suitable for irrigation. Ampaseo, situated at the confluence of Río Querétaro and Río Laja (Laja River), boasted a significant natural spring that could be easily manipulated for irrigation (Dolittle, 1986). While some historical literature suggests that it was the Spaniards who introduced the first canals in the Bajío during colonization, the cultivation of major indigenous crops through irrigation before their arrival implies the potential existence of pre-colonial canal systems. It is within the realm of possibility that pre-Columbian hydraulic technologies influenced the shaping of subsequent colonial water management techniques (Doolittle, 1984, 1990).

3.2: Spanish Colonization (15th and 16th Century)

During the 15th century, the Bajío region was inhabited by nomadic and semi-nomadic groups referred to as the “Chichimecas” by the Spanish (Davis, 1990). The Spanish conquistadors, led by Cristóbal de Olid, arrived in the region that is now known as Guanajuato in 1522 (History), quickly recognizing the significance of water for the establishment of both settlements and mining activities. The population growth that emerged from silver strikes in Zacatecas in 1543 and Guanajuato in 1552 led to a wave of colonization in the region and the subsequent increase in demand for wheat flour (Boyer & Sedrez, 2012).

The 16th century marked a period of change and migration, as settlers from various indigenous communities arrived in the Bajío region. During this time, irrigation practices were introduced through the process of apportionment of land to new cities, villages and settlements (Boyer & Sedrez, 2012). This period saw the establishment of towns like San Miguel el Grande, San Felipe, Santa Fe de Guanajuato, and Leon (Endfield, et. al, 2004). The Spanish Crown awarded land grants to encourage settlement and agricultural development (Endfield, et al., 2004). For example, during the 1570s, 9 of 12 grants were awarded to residents of Celaya, including the right to access water on certain days – a trend that appears to have been less common after 1600 (Endfield, et. al). According to Endfield, the awards that were made between the 1550s and 1630s are thought to hold the most influence in the determination of the nature and form of the region's agrarian development for the remainder of the colonial period. However, it is important to note that the regional economy was very much centered around livestock until the 18th century, including cattle ranching (Boyer & Sedrez, 2012).

Maize, a staple in the region prior to colonization, was the dominant food crop for early settlers. However, the Spanish soon began experimentation of growing wheat (Davis, 1990), a crop imported from their monarchy. It is within the realm of possibility that settlers realized that maize was an unacceptable crop for autumn or winter due to its high sensitivity to frosts (Murphy, 1986). Wheat has its own sensitivities – it is sensitive to drought and therefore, farmers would have faced difficulties in planting the crop before May. During the months of May through August, they would have also faced issues such as crop damage from disease and thunderstorms. Droughts in the dry season would have resulted in loss of the crop during summer or crop failure during august (Davis, 1990).

In the late 16th century, farmers settled along the floodplains of the Río Laja and Río Apaseo (Apaseo River) discovered a method to successful grow wheat – they began irrigating the crop during winter months by constructing earth diversion dams across river courses and diverting water into canals and old river channels for distribution to river terrace farms (Davis, 1990). This newfound ability to irrigate wheat in a way that withstood frost and produced high yields quickly transformed the eastern Bajío into a center of production (Davis, 1990).

Water scarcity was a challenge, yet this did not deter settled Indigenous communities moving to the Bajío in the 16th century. The Crown allocated land grants to up-and-coming towns for distribution among new residents, incentivizing settlement. These land grants were measured in *caballerias* (a unit of land measurement used in the Americas during the time of the Spanish Empire), with each citizen entitled to 2.5 caballerias, equivalent to 265 acres. The 1550s witnessed the introduction of land grants called "mercedes reales" for agriculture and livestock. Cattle and sheep ranching gained momentum, particularly in areas like Salamanca and Guanajuato. Celaya emerged as a center for agricultural development, receiving numerous awards of agricultural land. Over time, water rights became increasingly relevant, with some towns receiving the right to access water on specific days (Davis, 1990).

In the latter half of the 16th century, mining activities commenced in Guanajuato and the growing population of Mexico City drove increased demand for wheat and livestock (Davis, 1990). This transformation, fueled by the ever-growing agricultural and mining industries, was a turning point for water issues in the state from simple to complicated.

3.3: 17th Century Sees Agricultural Expansion

In the 17th century, the Bajío region witnessed the development of diverse types and scales of irrigation systems near Río Apaseo (Davis, 1990). The demand for wheat from Mexico City and northern mines drove prices up, allowing many farmers to expand their land holdings and water control systems (Davis, 1990). However, by the end of the century, the expansion of wheat fields faced limitations due to droughts and reduced water flows caused by extensive water diversion for irrigation (Murphy, 1986). Despite challenges posed by poor soil quality and the steepness of upland areas, farmers in the Bajío began to maximize areas with favorable soil and slight slopes for agriculture. The 17th century saw the expansion of agricultural production into uplands, facilitated by the construction of large masonry dams for water storage. These dams also enabled the supply of water to growing cattle and sheep herds during winter months and drought periods (Murphy, 1986).

Around the mid-1600s, wheat farmers in the river valleys of the eastern Bajío region expanded their original holdings into medium-sized haciendas and a few large estates. However, this expansion was not accompanied by new land grants (Davis, 1990). By 1632, the presence of *cajas* (water storage units) and *bordos* (flooded fields) such as near Celaya contributed to increased wheat production and the number of fields (Davis, 1990). The diversion of water into storage tanks did not necessitate specific water grants, enabling the opening of new irrigation lands that previously lacked water access or grants (Murphy, 1986). During this time, the region began to supply various grains including wheat, corn, barley, and beans to the rest of Mexico (Maganda, 2003).

3.4: 18th Century: Urbanization and Integration of Complex Technologies

Due to the strategic position of Guanajuato in the center of the country, the 18th century made way to high levels of urbanization unusual for traditional societies during this time (Maganda, 2003).There was more movement and migration into the area, as Spaniards, Indigenous communities, Blacks, and mixed races settled primarily in big towns and small cities encompassed by large commercial landholdings (Davis, 1990). Movement of settlers into the area led to the restructuring of land and water to produce wheat, cattle, and sheep (Davis, 1990). Landowners recognized that they would need to make better use of hydrological resources in order to increase production, considering precipitation was concentrated during the months of June through September (Boyer & Sedrez, 2008). In the 16th century, farmers had already begun to modify streams, but they did not yet have the means to expand irrigation networks or allow for shifts from corn and bean cultivation to wheat (Boyer & Sedrez, 2008). Technological advancements in the 18th century made way for the emergence of a complex network of water diversion channels, dams, canals and reservoirs (Endfield, et al., 2004) to support crops, animals, and humans (Davis, 1990). Flatland *cajas* expanded and became systems of interconnected and interrelated embankments and *bordos* (Davis, 1990). According to Boyer and Sedrez, the single most important innovation in the 18th century was the adoption of flood farming, which captures seasonal river flows in *cajas*, ultimately allowing for fields to stay flooded for a few weeks prior to farmers releasing water to plant winter wheat (Boyer & Sedrez, 2012).

By the second half of the 18th century, a time of further population growth and commercial expansion, there was clear inequality and class divide. The majority of rural residents lived as estate dependents and the Spanish allowed provincial gentry to monopolize the best land and water resources (Endfield, et al., 2004). Economic growth fueled by the mining industry only benefitted a small minority of the region (Endfield, et. al, 2004).

During this time, estates in the Bajio region began concentrating efforts on wheat, fruit, and vegetable production due to their higher returns than maize, a staple in lower-income communities. Extreme weather and variation in the intensity and frequency of summer rains would occasionally threaten harvests and ultimately the economic well-being of the agrarian dependent society. There were at least nine years of severe drought-induced hardships, and in 1785, the region faced the wrath of the "Year of Great Hunger". Droughts and frosts in the mid-1780s had led to widespread harvest failure and starvation, stimulating water disputes (Endfield, et. al, 2004).

By the late 18th century, as *bordos* expanded in scale, so did infringement on land use. Water regulations had started to become a necessity and issue for communities through the Bajío region (Davis, 1990).

By the end of the 18th century, interconnected valleys of Río Querétaro, Río Pueblito, and Río Apaseo were covered with embanked fields for water storage and flood-water farming (Davis, 1990). Embanked fields collected, stored, and regulated excess water supply, which could be stored or diverted to non-embanked winter wheat fields and summer maize fields depending on water availability and crop requirements (Murphy, 1986). *Presas* (dams) controlled and regulated flow into the *bordos* via *tomas* (water catchment gates) and *acequias* (canals) directed water through or around embanked fields (Murphy, 1986).

Certain embanked fields were flooded in April or May to produce early maize crop or in August and September for an autumn wheat crop (Murphy, 1986). When non-embanked fields had dried from summer rains during November or December, stored water was released from *bordos* to flood fields. After the last hard frost in late January, non-embanked fields were flooded again and wheat seed sown in fields and within *bordos* (Davis, 1990). During October and November, late maturing maize fields were flooded by *bordos* and harvested in November or December (Davis, 1990) During March or April, a third flooding would occur to provide enough water for the rest of the wheat season, to be harvested in May or June (Davis, 1990).

Towards the end of the 18th century the dynamics of water movement within the *bordo* system were complex. Arrays of compact sluice gates – a movable gate that allows water to flow underneath – managed the water flow into the acequias nestled within the embanked plots. Immense sluice gates and water enclosures governed the storage and transfer of water between different *bordos* and interconnected networks of both minor and major *acequias*. Upon departing from the embanked plots, water was subsequently dispensed through small irrigation canals to non-embanked fields (Davis, 1990).

3.5: 19th Century: Export Agriculture, Industrialization, and Political Change

As the Bajío region continued to urbanize and industrialize, water resources faced increasing pressures and management became complex. Political changes introduced new approaches to water management and by the turn of the century, there was a shift toward more active citizen participation in water-related decisions. Challenges related to water transfers and inter-state agreements became contentious issues, leading to a push for regional self-determination in water planning.

In the 19th century, the Bajío region witnessed notable changes as railroads emerged, connecting it more closely to Mexico City and enabling the exportation of local grains to a broader market. During this time, the agriculture sector relied on investment and labor to construct more irrigation systems and multiple irrigation channels (Maganda, 2003). Approaching the late 19th century and up to the revolution, new hydraulic systems, canals, dams, levees, and sluice gates were constructed, ultimately expandings the reach of agriculture and transforming the environment of the Bajío (Boyer & Sedrez, 2008).

As the 19th century began, the Bajío region experienced further growth in commercial and industrial sectors, particularly in areas near Guanajuato, where tanning and manufacturing gained prominence (Maganda, 2003). The early 1940s marked the establishment of the National Program of Regional Planning for Hydraulic Basin

Commissions. In 1950, Guanajuato joined the Lerma-Chapala-Santiago commission, tasked with promoting regional development and conducting studies (Maganda, 2003). The commission struggled to accomplish their goals due to bureaucratic issues, depending on executive power and the federal government for resource management.

The mid-20th century brought accelerated demographic growth and industrial development in Guanajuato's cities, triggering increased water demand within the context of regional regulation (Maganda, 2003). During the 1940s and 1950s, the construction of substantial infrastructure, such as highways and industrial facilities, took place, such as the construction of the Queretaro-Guanajuato-Aguascalientes Highway, the International Airport of the Bajío, and a refinery and thermoelectric plant in Salamanca (Maganda, 2003). In the last three decades of the 20th century, the construction of eleven industrial parks took place and many enterprises were established, including manufacturing, export products, auto parts, automobiles, automotive batteries, chimneys, refrigerators, and chemical compounds (Maganda, 2003).

The government began to strategically focus efforts on agricultural exportation in the region due to its perceived comparative advantage in terms of climate, labor costs, and land and water accessibility, ultimately leading to a huge expansion in the sector. The Green Revolution saw farmer subsidies and the construction of the Solís and Allende dams. During the 1960s, horticulture and fruit production for export was established, with multinational agro-industrial enterprises including Bird's Eye, Green Giant, Campbell Soups, and other vegetable packers moving operations to the Bajío region (Maganda, 2003). National companies, including San Antonio, Mar Bran, and

Covemex arrived as well, setting down operations on the expansion of the highway between Celaya-Salamanca-Irapuato and Silao (Maganda, 2003). Due to the movement of large corporations into the region, the Bajío gained the reputation as the "environmental bonanza" (Maganda, 2003). This new reputation can be characterized as a social fact – a shared consensus amongst people – however it lacked scientific backing such as geohydraulic studies of actual water availability.

Accelerated demographic growth, industrial development, and the rise of the service sectors led to an increasing demand for water and the need for institutional frameworks for regulation at the regional level. The Basin Council, an interstate authority for the management of the Lerma-Chapala region, was established to oversee water distribution in the area (Maganda, 2003).

In 1975, the federal government attempted to institutionalize water planning with the enactment of the National Hydraulic Plan (PNH) with the establishment of the Secretary of Water Resources (SRH) (Maganda, 2003). They intended to consolidate water management and go beyond simple construction of physical water works, but rather promote changes in agricultural production and restrict irrigation (Maganda, 2003). In 1976, the Commission of the National Hydraulic Plan (CNPH) was created to oversee PNH execution (Maganda, 2003). From 1976 to 1982, the government sought to create a water network, merging SRH with the Secretary of Agriculture to become the Secretary of Agriculture and Water Resources (SARH). CNPH planners continued their studies of annual national water supplies (Maganda, 2003). Despite good intentions, it was found that national programs were difficult in reality to implement locally. Conflicts of interests emerged between CNPH and SARH, as CNPH focused on unifying water planning, while SARH focused on agricultural needs (Maganda, 2003). In 1985, CNPH became the Mexican Institute for Water Technology (IMTA) and a new version of the PNH, based on the centralized management model for basins used in the 1940s, was drafted (Maganda, 2003).

In the 1980s, governments around the world looked towards Integrated Water Resource Management (IWRM) as the solution for groundwater management and Mexico became an early adopter (Wester, et. al, 2009). In 1989, former President of Mexico, Carlos Salinas, created the National Water Commission (CNA) (Wester, 2008). The CNA acted as a semi-independent organism of SARH, taking over normative, operational, financial, and promotional roles for water development (Maganda, 2003). That same year, the National Development Plan was published, endorsing IMT along with a wider water reform (Wester, 2009). The CNA became responsible for the creation and presentation of national water programs and initiators of water resource planning in regional contexts (Maganda, 2003).

By the mid-1990s, Guanajuato began to implement political and institutional programs in-line with the water reforms occurring at the national level to achieve IWRM for surface and groundwater (Wester, et. al, 2011). Initiatives included strengthening the Guanajuato State Water Commission (Comisión Estatal del Agua de Guanajuato, CEAG) and the formation of 14 Technical Water Councils or Aquifer Management Councils (Consejos Técnicos de Aguas, COTAS). COTAS were essentially constructed as local IWRM organizations consisting of all the water users within an aquifer that would collaborate to regulate groundwater. The intention was that COTAS would help reduce the level of groundwater over-extraction through self-regulation of users with the technical and financial support of the state government (Wester, et. al, 2011).

In 1993, the CNA reported that there was a hydraulic imbalance in Lerma-Chapala Basin's underground water supply: the average annual flow of 1,364 Mm^3 decreased due to a demand of 1,557 Mm^3, leading to a deficit of -193 Mm^3 in one year (Maganda, 2003). In 1998, the State Water and Sanitation Commission of Guanajuato (CEASG) generated geo-hydrographic studies highlighting the depletion of the aquifers (Maganda, 2003). Since 1995, CEASG's official diagnostic publications state that aquifers in the state are overexploited and threatened due to growing demands of urban-industrial users (Maganda, 2003).

At a national level, the Institutional Revolutionary Party (PRI) dominated Mexican politics until 2000 and was historically involved in the decision-making processes related to basin agreements (Maganda, 2003). However, there was a political shift in the early 1990s as the National Action Party (PAN) came to power. PAN proposed new forms of governmental participation within the water sector (Maganda, 2003). In 1995, Vicente Fox, a member of PAN, became governor of Guanajuato. In the campaign, he ran on the platform of more active citizen participation in water issues, saying the famous line: "... starting today. Not a drop of water leaves Guanajuato", referring to the disapproval of water transfers to Chapala that was established by the Basin Council agreements. (Maganda, 2003).

3.6: 20th Century

In 1910, the national government, with involvement from the states, established the Ley de Aguas de 1910 (Water Laws of 1910). This law states that all waters are public property for common usage (Hoogisteger & Wester, 2017). In 1917, the Political Constitution of the United States of Mexico was enacted, including Article 27 which states that water is originally property of the nation and its management is to be provided by the federal government. Furthermore, water was not to be privately owned (Mestre, 1997). The language recognized the rights of a landowner to prospect for and use the water underlying his land as established in the civil code of 1884 (Hoogisteger & Wester, 2017). Article 27 underwent additional modifications in 1948 and 1956 to enhance the legal powers of the federal government in regards to groundwater use (Hoogisteger & Wester, 2017).

The early 2000s saw the emergence of regional infrastructure projects to sustain the industrial sector, such as the Interurban train connecting the industrial corridor from Celaya to San Francisco de Rincon and the Colinas industrial park (Maganda, 2003). This expansion, supported by federal, state, and local policies, was ultimately a compromise between the use of limited water resources and the activities of a growing industrial sector (Maganda, 2003). Despite significant contributions to national production and the local economy, industrial growth also led to water resource contamination and overexploitation, highlighting the need for more comprehensive water planning (Maganda, 2003).

During the period of 1960 to 1980, the spike in economic growth significantly deteriorated water quality and water demand surpassed water availability in the Lerma

River basin (Mestre, 1997). Mexico was experiencing rapid development throughout the country, not just in Guanajuato. To contend with the stress that development was putting on the water supply, the Federal Water Law was enacted in 1972 (Mestre, 1997). The Federal Water Law of 1972 stipulated that the national government must regulate groundwater use through the issuing of groundwater use permits and by the establishment of rules and regulations for areas placed under veda (areas where it is prohibited to sink new tube wells without prior consent from the national water authority) (Hoogisteger & Wester, 2017). Between 1984 and 1964, as well as in 1983, ten veda decrees were issued in the Bajío region and northern Guanajuato. Regardless, the number of tubewells and extracted volumes continued to increase at a rapid rate (Wester, 2008). Although touted with initial praise, the legal tool was not met with the necessary level of actual law enforcement that would result in sustainable change.

In 1976, the Lopez-Portillo administration introduced changes to the scope, merging the Hydraulic Resources Secretariat (the federal ministry responsible for irrigation, river management, and control activities, as well as municipal water and wastewater works) with *Secretaría de Agricultura y Ganadería (SAG; Ministry of Agriculture and Livestock*). This new entity known as *Secretaría de Agricultura y Recursos Hidráulicos (SARH;* Ministry of Agriculture and Hydraulic Resources) essentially made water a resource to support agricultural activities. During this time, no policies were established to reduce the overpumping of aquifers or find solutions to conflicts among users (Mestre, 1997).

The Bajío's incredible transformation over the course of history into the urbanized and interconnected region we know today involved the dynamic interplay between water resources, agricultural and industrial development, and economic growth. From precolonial reliance on water deities to the sophisticated irrigation systems of today, the region has undergone significant transformations. The challenges of industrialization and urbanization have underscored the importance of sustainable water management practices. As the Bajío region continues to evolve, finding a balance between economic expansion and responsible water use remains a pressing concern for the region's future.

Chapter 4: Current Policy Issues

Mexico's National Water Commission (CONAGUA) claims that supply-side policies were replaced with demand management in the 1980s and that there has been a shift in focus to sustainability-oriented policies along with an increase in public participation in decision-making (McCulligh, Tetreault, 2017). However, McCulligh and Tetreault argue that due to the increase in water-related socio-environmental conflicts throughout Mexico, neither demand management nor sustainability have guided water policy.

At the 1992 United Nations Conference on Environment and Development in Rio de Janeiro, the Integrated Water Resources Management (IWRM) framework emerged as a blanket solution to contend with existing and future water management problems. That same year, Mexico began IWRM reform with the enactment of the National Water Law and formed the Lerma-Chapala Basin Council in 1993 to serve as a water governance forum (Jimenez, 2018). Unfortunately, the IWRM model utilized by the council has not yet shown to serve as a usable water governance system, shown by the slow progress in water user participation and the decentralization of functions (Jimenez, 2018). Conflicts have arisen between state governments, water uses, and water-based stakeholders over the use of water within the basin and water pollution and scarcity issues are still very much a reality.

The council was initially created to implement water allocation policies, improve water quality and water use efficiency, and conserve natural resources and the ecosystem of the basin. Yet, the official documentation is ambiguous, only glossing over objectives that were to be achieved through the formation of specialized workgroups, consensus building mechanisms, and a participatory approach (Jiminez, 2018). This established document was the outcome of an extensive water governance procedure, during which water users and government delegates from the five basin states engaged in negotiations over the course of two years to achieve consensus. The primary aim of this agreement is to provide legitimacy, transparency, regulations, and clarity to the annual allocation of surface waters, thereby addressing conflicts arising from water distribution within the basin.

The state of Guanajuato is at the center of the conflict among the basin states. Since the 1950s, specifically during times of drought, the agricultural stakeholders in Guanajuato, the environmental groups in Jalisco, and the utility services in Guadalajara using water from Lake Chapala have clashed over issues concerning the availability and allocation of Solis Dam surface waters (Jiminez, 2018). The Lerma Chapala Basin Council serves as the platform for discussions involving the distribution of surface water and the formalization of an agreement or treaty for this purpose.

Institutional conflicts also exist between the state of Guanajuato and the federal government over the overexploitation of groundwater. To contend with the overexploitation issues, the state government created Technical Water Councils as subsidiary organizations within the council without involving the National Water Commission (NWC). In turn, the NWC did not recognize the councils nor has allowed authority or responsibilities to manage groundwater under COTAS (Jimenez, 2018).

In 1992, Mexico introduced the National Water Law with the intent of establishing a comprehensive water rights framework, encompassing permits for both water abstraction and wastewater discharge (Carrera-Hernandez, 2017). By 2000, around 320,000 abstraction permits had been issued to users, documented in the Public Register of Water Rights (REPDA) (Carrera-Hernandez, 2017). This number increased to approximately 450,280 by 2006 (Carrera-Hernandez, 2017). The allocation of extraction volumes occurred without thorough water availability assessments, resulting in over-concessioned extraction capacities (Carrera-Hernandez, 2017). Water users had authorization to withdraw more surface water than was available within their respective watersheds, or to extract more groundwater than could be naturally replenished through groundwater recharge processes (Carrera-Hernandez, 2017). The REPDA database is laden with inaccuracies and unreliability, with instances of extraction wells mistakenly located in the Gulf of Mexico or the Pacific Ocean (Carrera-Hernandez, 2017). Additionally, uncertainty surrounds actual groundwater withdrawals, especially among agricultural users, as water meters do not always exist to measure and monitor extraction rates (Carrera-Hernandez, 2017). Of the agricultural tubewell users that do have installed meters, a large number of them do not actually function properly. In turn, control over extracted water volume is not possible (Hoogisteger & Wester, 2017). To compound this issue, the state of Guanajuato does not have the human capacity to implement regulations. With only 4 inspectors in 2003 and 10 inspectors in 2016 within Guanajuato and widespread bribery practices, as well as more extreme cases of abduction of field inspectors by angry farmers, the number of tube wells has increased from 2000 in 1960 to over 17,300 in 2015 (Hoogisteger & Wester, 2017). According to Hoogisteger and Wester, it is clear that although viable regulatory frameworks have been established, there are legal and administrative inconsistencies contributing to the uncontrolled extraction of groundwater and overexploitation of aquifers in Guanajuato (Hoogisteger & Wester, 2017). While the control of the National Water Authority on the industrial and domestic sectors has been strict, the legal system's effectiveness on the agricultural sector has not been successful (Hoogisteger & Wester, 2017).

Issues of equity have started to surface within Guanajuato as wells go dry from aquifer drawdown. Small farmers have been the first group eager to sell part or all of their water concession, as they do not have the resources to replace or deepen their wells. Those who can afford to replace or deepen their wells are benefiting, and in turn, contributing to the sustained overexploitation of groundwater (Hoogisteger & Wester, 2017).

Chapter 5: Causes and Conditions

5.1: An Overview

Water systems consist of large interconnected networks that operate simultaneously across multiple domains (natural, societal, political), multiple scales (spatial, temporal, jurisdictional, institutional), and different levels (e.g. local, regional, global) (Islam & Susskind, 2013). When we approach water management problems for a given domain, scale, level, findings and insights cannot simply be transferred to other scales, domains, or levels (Islam & Susskind, 2013)

When looking at a complex water system like the case of Guanajuato, we must take into account the idea of emergence. The concept of emergence aids our comprehension of why a specific approach aimed at attaining a particular water management goal might yield unanticipated consequences, even if that approach has proven effective in different situations. We must not presume that a collective response to one water management challenge will replicate itself elsewhere until we grasp the intricacies of regional and contextual distinctions, along with comprehending the probable effects that local interactions and variations are poised to bring about.

Guanajuato is one of the thirty-two states of the Federal Entities of Mexico (Instituto Nacional de Estadística, Geografía e Informática), and it includes three basins. The Lerma-Chapala basin serves as an important shared resource and continues to be put under pressure due to competing demand amongst states. Guanajuato competes with Mexico City for abstraction of groundwater in the upper section of the

Lerma-Chapala Basin and with Guadalajara downstream for the conservation of Lake Chapala (Sandoval, 2004). The interconnectedness of water resources has led to transboundary water issues and contention between States. Furthermore, the southern part of the state is considered as part of the Bajio region, a culturally and economically significant hub of agriculture in the center of Mexico.

Furthermore, the water issues within the state of Guanajuato can be looked at in terms of local, regional, and global levels. At the local level, certain communities are seeing their wells go dry. Others are experiencing the health effects of drinking water contaminated with high levels of arsenic and fluoride. At a regional level, there is conflict and cooperation between states for use of shared basin resources. At a global level, water problems can be evaluated at a macro scale, with the potential to evaluate export agriculture in terms of water footprint.

5.2: Uncertainty

There is a high degree of uncertainty related to water management in Guanajuato. Issues such as climate change and hydrological variability add to the complexities of providing actionable solutions.

For example, in the Lerma-Chapala basin, IWRM was applied to combat water issues between the years of 1989 and 2004. While some scholars have portrayed the case study as successful, others have countered that the policies implemented were not appropriate. The controversy stems from uncertainties regarding volume of surface and groundwater used, efficiency by agriculture upstream Lake Chapala, volume of water supplied to the main urban settlements and industries within and outside of the basin, growth of water demand from various sectors, effects of different water allocations, water availability, average renewable water in the basin, and the relationship between surface and groundwater (Godinez-Madrigal, 2019).

5.2.1: Climate Change

Looking back at the history of the natural domain in Guanajuato, there were years of extremes on both ends of the spectrum. From extreme drought that destroyed crops, to devastating floods that drowned entire communities, the region is not immune to the perils of not enough – or too much – water. Although there has always been unpredictability in the region when it comes to climate, there is no doubt an extra layer of uncertainty related to changing precipitation patterns, droughts, and extreme weather events, which in turn are impacting water availability and demand at a temporal scale. Uncertainty in the prediction and modeling of future climate conditions and their effects on water resources makes it increasingly difficult to determine long-term planning.

Semi-arid regions are particularly vulnerable to high interannual rainfall variability and freshwater scarcity, often experiencing extended periods of drought and flooding. Guanajuato has historically faced periods of devastating drought, followed by intense seasonal rainfall and afternoon thunderstorms between the months of May and October (Deng, 2020).

Over the past decade, Mexico's Central Highlands are experiencing a decline in precipitation, increasing temperatures, and decreasing lake levels (Orozco-Ramírez & Astier, 2017). Climate models from the end of the 19th century predict an increase in the frequency and severity of drought events, particularly in water-stressed regions like northern Guanajuato (Deng, 2020). In the northern section of Lerma-Chapala, a basin primarily situated in the northern section of the state, climate change projections predict increasing temperatures and declining annual precipitation will lead to more frequent droughts and a reduction of the surface water runoff by as much as 29% by the year 2100 (Acosta & Martínez, 2014). This prediction was estimated using the variation of future precipitation from 23 atmosphere-ocean general circulation models and the utilization of the reliability ensemble averaging method.

A 2019 Soil and Water Assessment Tool (SWAT) analysis of Guanajuato's Independencia basin looking at the effects of climate and land management on hydrological processes, sediment loading, and pollutant transport, ultimately projected that the state may actually see higher precipitation and temperature under all emissions scenarios compared to the baseline condition (Deng, 2020). Under RCP 8.5 (the highest baseline emissions scenario) where global temperatures would increase by 4.3 degrees celsius by 2100 (ClimateNexus), SWAT shows mean annual surface runoff and deep aquifer recharge increasing more rapidly than a RCP 4.5 scenario (Deng, 2020). Under emission scenario RCP 4.5, which is considered a moderate scenario by the Intergovernmental Panel on Climate Change (cal-adapt), increasing rates of surface runoff and deep aquifer recharge will slow towards the end of the century (Deng, 2020). However, as the population and demand for dwindling water resources in the region grows, over exploitation of the groundwater for irrigated agriculture would counter the increased recharge. Small-scale rural farmers that have historically relied on rain-fed agriculture will be most vulnerable to the changes likely to come in the foreseeable future (Bee, 2016).

5.2.2: Hydrological Variability

The western and central sections of Guanajuato have a semi-arid monsoon climate, with 90% of the 600 mm annual precipitation falling in the rainy season that stretches from May to October (García, 2004). Variability in precipitation within the State follows the topography, separating Guanajuato into three distinct regions: the Sierra Madre Oriental in the northeast, the Mesa del Centro in the central region, and Eje Neovolcánico to the southwest. The Sierra Madre Oriental accounts for the lowest elevation, with the sharpest vales and most varied topography. The Mesa del Centro is known for its plateaus and escarpments, with elevation ranging from 2000 to 2500 meters. The Eje Neovolcánico is flatter, with most of the region's elevation around 1,500 meters.

Guanajuato is located in a transition between key climate zones due to the effects of the El Niño-Southern Oscillation. Despite minimal variation in total summer precipitation, extreme precipitation events do occur in the form of both heavy rainfall and drought (Méndez-Pérez, 2005). Recently, local government spearheading efforts in water resource management have had increasing concern on the shortterm and longterm variability of precipitation. With unsustainable irrigation practices, groundwater levels are declining up to 3 meters per year in parts of Guanajuato (Cortés et al, 2007). During the summer, daily evaporation averages 1.5mm per day in eastern Guanajuato and 2mm per day in western Guanajuato (Sheffield et al, 2010). Potential evaporation averages 1,500 mm per year. With average precipitation averaging 600 mm per year, agricultural and urban demand for water and annual evaporation exceed annual precipitation, resulting in a net water deficit and recurring low reservoir storage levels (Scott et al, 2000). The number of days in a row with under 1 mm of rainfall has gone up (Aguilar et al, 2005). There are concerns with daytime minimum and maximum temperatures in short term planning since preliminary evidence suggests an increase in the number of days with temperatures in the 90th percentile. Long term planning concerts focus on rainfall and potable water storage (Barrett & Longoria, 2013).

Although concerns are prevalent in the state, there is a lack of true understanding of the precipitation and temperature climatology. Large scale studies have been completed to look at the variability of precipitation, temperature, evaporation, and potential evaporation. However, more studies are needed to evaluate what is happening within the state itself.

Natural variability in river flows, groundwater recharge, and aquifer levels can be challenging to predict accurately. Fluctuations in water availability from year to year and the availability of accurate models can affect water allocation decisions. According to Astrid Hernández-Cruz, there is a lack of comprehensive hydrological data, especially in the characterization of aquifers and groundwater throughout Mexico. Water quality data is scarce as well, due in part to lack of financial resources (Hernández-Cruz, 2022).

5.3 Scale and Levels

In the context of water management in Guanajuato, Mexico, there are several issues related to scale that pose challenges and complexities for effective and sustainable water resource management. Scales, in this context, refers to “the spatial, temporal, quantitative, or analytical dimensions used to measure and study any phenomenon” (Islam & Susskind, 2013). Level refers to “the units of analysis located at different positions of each scale (e.g., levels refer to seconds, days, seasons, decades, etc. for temporal scales)” (Islam & Susskind, 2013). Water policies that are implemented at a regional scale will affect and be affected by whatever is occuring at other scales and levels. An appropriate solution at a regional level may not be a great solution at a local or global level (Islam & Susskind, 2013).

Connecting issues of scale and level across both natural and societal domains is crucial for advancing current water management practices. Currently, theories and practices in the natural domain emphasize adaptability and spatial-temporal data related to water quantity, quality, and ecosystem functions. In the societal domain, water management centers on levels and scales of institutional behavior and temporal considerations. The political domain requires navigating interactions between various scales and levels in obtaining effective water management. The misalignment between the societal domain (e.g., water governance scale) and the natural domain (e.g., water allocation at different scales) gives rise to significant scaling challenges in water management (Islam & Susskind, 2013).

Guanajuato is located within three main hydraulic-geographical basins: the Lerma-Chapala basin, the Pánuco river basin, and the Santiago river basin (Reynoso, 2000). The Lerma-Chapala-Santiago Basin is the most significant in terms of land cover and transboundary uses, encompassing 77% of the state's territory (Reynoso, 2000) and playing a crucial role in water management and resource allocation within Guanajuato.

Since water management is transboundary, the solution space must not simply look within a watershed, but within the problem-shed. According to Griffin, a problem-shed is defined as a “geographic area that is large enough to encompass management issues, but small enough to make implementation feasible” (Griffin 1999).

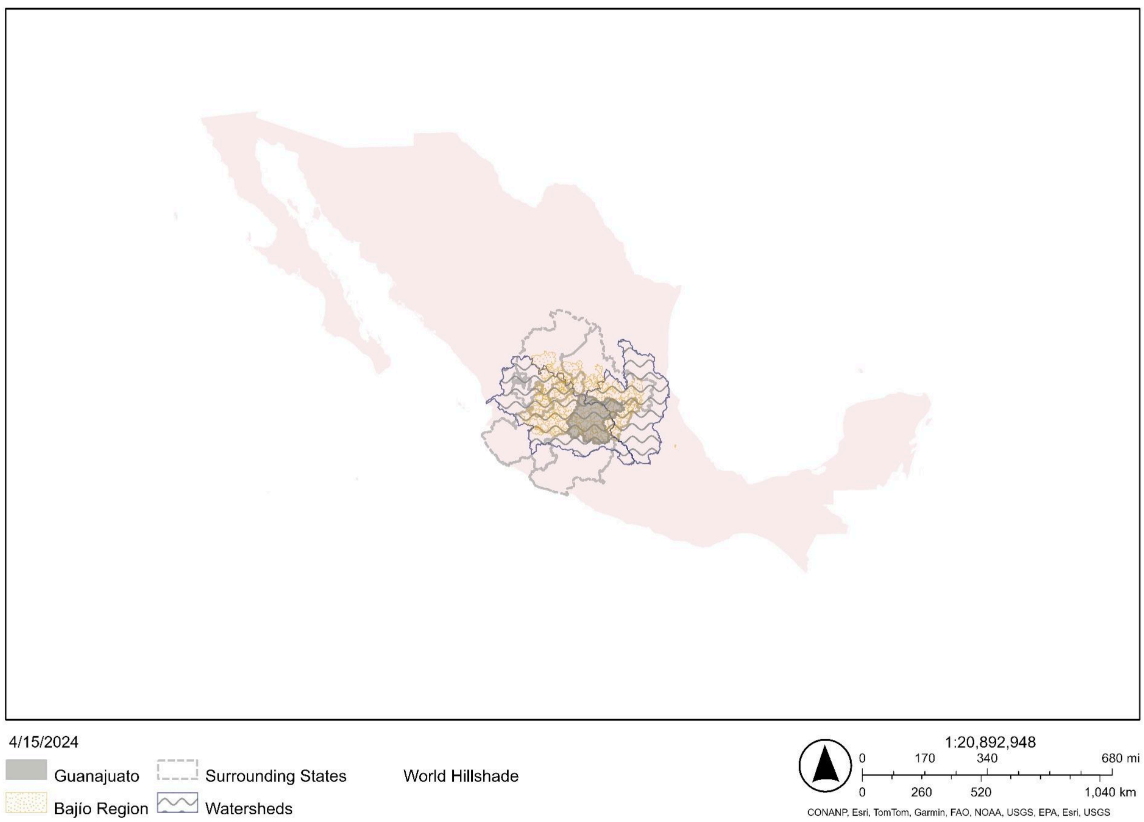

Figure 4. *This map shows the different spatial levels used to evaluate the problem-shed: state, regional, and basin-level*

5.3.1 Spatial

Located in central Mexico, Guanajuato is bordered by the states of Jalisco to the west, Querétaro to the east, San Luis Potosí to the north, Zacatecas to the northwest, and Michoacán to the south.

In Mexico, the spatial distribution of water availability and demand do not align. The majority of the country's population is concentrated in its northern regions, even though the southern region experiences higher levels of precipitation (Carrera-Hernandez, 2017). Situated in the central region of Mexico, the Lerma-Chapala Basin originates close to Toluca and flows into Lake Chapala. Encompassing five states—Querétaro, Guanajuato, Michoacán, Jalisco, and the State of Mexico—this basin has become the country’s largest water consumer.

The contamination status of the Lerma-Chapala basin shifts from 'strongly contaminated' prior to reaching Salamanca, Guanajuato to 'very strongly contaminated' after passing through the city. This contamination can be attributed to the presence of industry within the Lerma-Chapala basin, including petrochemical facilities in Toluca, tanneries in León, and the world's fifth-largest oil refinery in Salamanca (Carrera-Hernandez, 2017). Spanning an extent of 52,000 km^2 (excluding the enclosed basins of Lakes Cuitzeo and Pátzcuaro), the Lerma-Chapala basin covers a significant area. Close to the city of Toluca, the Lerma River stretches over a length of approximately 700 km before ending in Lake Chapala, Mexico's largest lake. This river is fed by several principal tributaries, namely the Queretaro River within the confines of the State of Queretaro, the Laja, Turbio, and Guanajuato Rivers in Guanajuato, and the Duero River in Michoacan. Within the expanse of the Lerma Basin, there are 750,000 hectares of irrigated land—representing one-eighth of the irrigated hectares across Mexico. Despite hosting significant urban centers and industries, irrigation dominates the water utilization landscape in this basin, claiming an estimated 80% of the total water consumption (J. Carrera-Hernandez, 2017).

The Panuco river basin and Santiago river basin account for the remaining 18% and 5% of Guanajuato's land cover (Reynoso, 2000). Flowing towards the Pacific Ocean, the waters of the Lerma and Santiago river basins account for approximately 83% of Guanajuato's territory and over 90% of total water volume for Guanajuato in terms of surface waters and aquifer recharge (Reynoso, 2000). The Panuco river basin sees little usage from the state as it flows towards the Gulf of Mexico (Reynoso, 2000).

Within the three hydrological basins, there are two hydrological regions: the Lerma-Santiago (belonging to hydrological region No. 12) and the Santa María and Extroaz basin (belonging to the High Panuco river basin). Within these two regions, there are 1,500 groundwater storage areas, including the two largest in Guanajuato – the Solis dam and Ignacio Allende dam (Reynoso, 2000).

The Bajío region constitutes the central area of Mexico north west of Mexico City and east of Guadalajara. The region includes the majority of Guanajuato, parts of Querétaro, Michoacán, Jalisco, and San Luis Potosí. Due to its fertile soul, it has historically been the principal agricultural region of the Lerma-Chapala Basin (Wester, 2008).

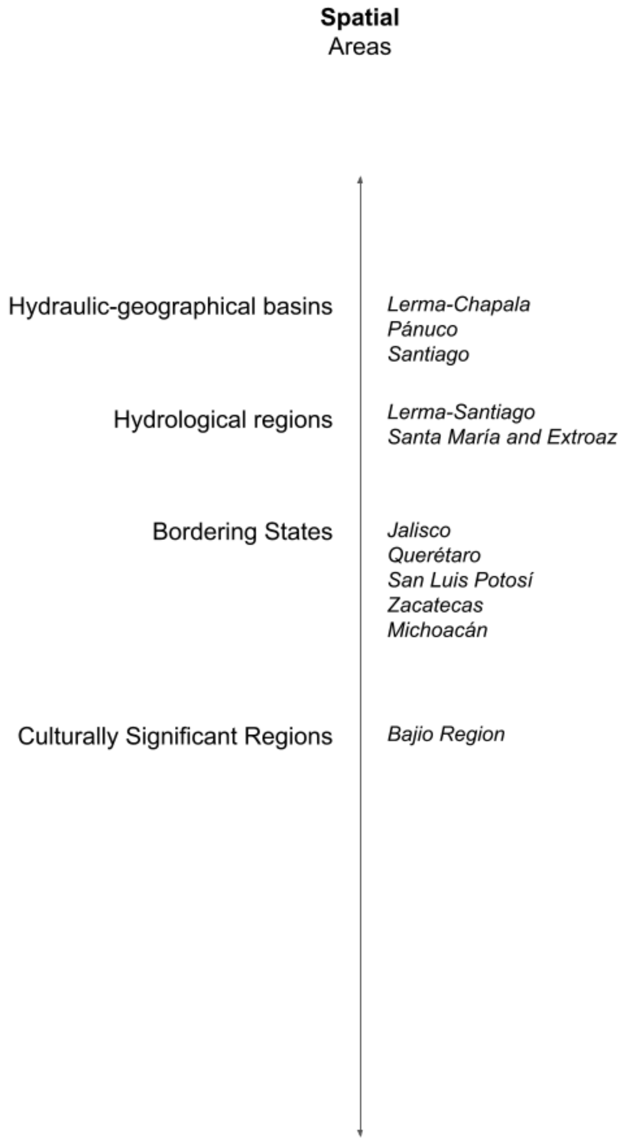

Figure 5. A diagram of the different spatial criteria related to the water management problem in Guanajuato, Mexico

5.3.2 Jurisdictional

Within Mexico, water management is administered by various governmental entities at the federal, state, and municipal levels. At the national level, the Water Commission (Comisión Nacional del Agua, CONAGUA) acts as the federal agency responsible for water resources management, water quality, and sanitation. The administrative body oversees water policy, planning, and regulation, and plays a significant role in managing Mexico's water resources. Another national-level agency, the Ministry of Environment and Natural Resources (Secretaría de Medio Ambiente y Recursos Naturales, SEMARNAT), is responsible for environmental policy, including aspects related to water quality, conservation, and ecosystem protection. The Secretariat of Agriculture and Rural Development (Secretaría de Agricultura y Desarrollo Rural, SADER) is a national agency that plays a role in agricultural water management and irrigation, focusing on promoting sustainable agricultural practices and efficient water use. The Ministry of Health (Secretaría de Salud) is involved at the national level in ensuring the quality and safety of drinking water and sanitation systems to protect public health.

At the state level, there are State Water Commissions (Comisiones Estatales del Agua, CEAs) that handle issues related to water distribution, infrastructure development, and resource management within each individual state. In 1997, the Technical Committees for Groundwater (Comités Técnicos de Aguas Subterráneas, COTAS) was established to improve groundwater management across Mexico. The first two COTAS in the country were established in the state of Guanajuato, for the Celaya and the *Laguna Seca* aquifers, and were developed because the top-down regulatory approach did not succeed in dealing with problems associated with large groundwater extraction. The COTAS were established as local water management organizations and were created to help the federal government in the administration of water-rights. COTAS also implements groundwater management plans, acting on behalf of water users, and works towards elevating local awareness through communication campaigns and formal agreements with the education system of each municipality (Carrera-Hernandez, 2017).

At a local jurisdictional scale, there are Municipal Water and Sanitation Utilities. At the municipal level, these jurisdictional bodies oversee water supply, distribution, wastewater treatment, and sanitation services. At the local community scale, there exist coalitions, such as Agua Vida and Hermandad de la Cuenca, and civil society such as Caminos de Agua and Salvemos el Río Laja. They are not administrative bodies, however they are organizations that have the capacity to influence decisions within different scales.

At an inter-governmental level, there exists Basin Councils (Consejos de Cuenca), which are decentralized entities responsible for managing water resources within specific river basins. They promote participatory water management, bringing together stakeholders from different sectors to collaborate on water-related issues.

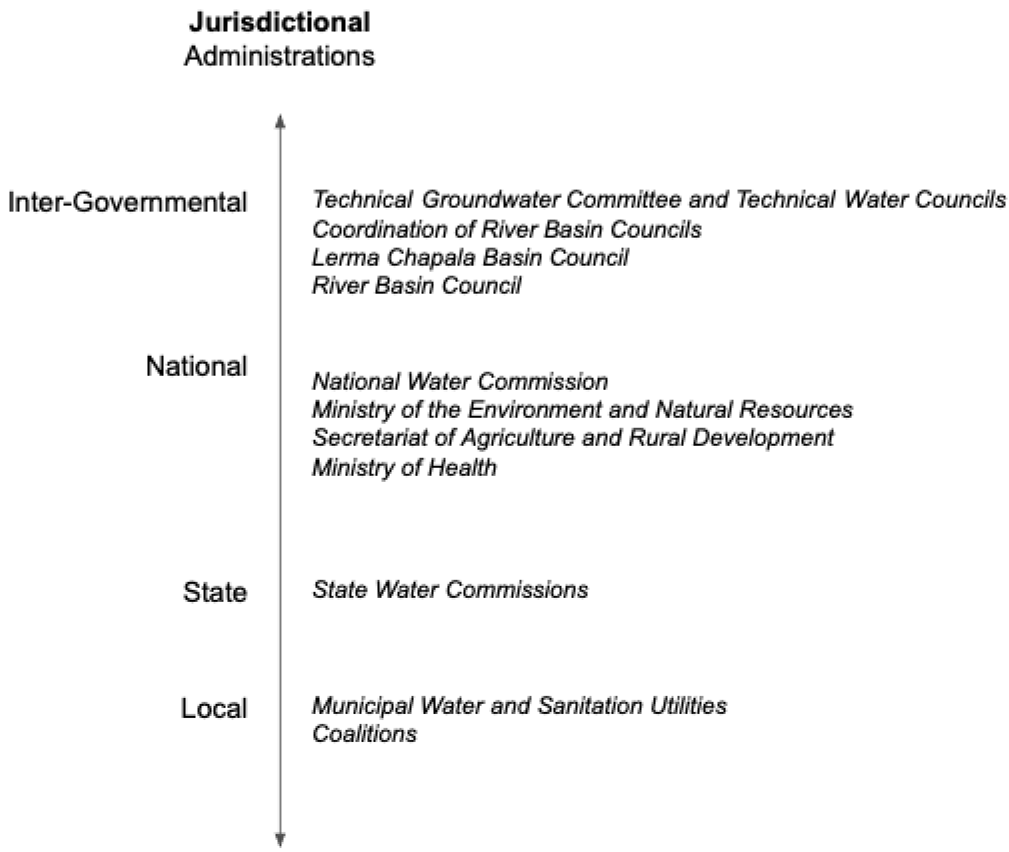

Figure 6. A diagram of some of the different jurisdictional administrations related to the water management problem in Guanajuato, Mexico. This list is not comprehensive.

In addressing these issues of scale, a holistic and integrated approach to water management is crucial. This involves fostering collaboration among stakeholders at various levels, implementing adaptive management strategies, and incorporating local knowledge alongside regional and national policies to ensure the sustainable and equitable use of water resources in Guanajuato, Mexico.

5.3.3 Institutional

Article 27 of the Constitution of the United Mexican States notes that "the property of all land and water within national territory is originally owned by the Nation, who has the right to transfer this ownership to particulars. Hence, private property is a privilege created by the Nation" (Camacho-Garza et al., 2022). Over the decades, the Constitution has seen additions made to Article 27. In February 2012, Article 4 was reformed to include language on the Human Right to Water (Wilder et al., 2020).

In Mexico, water management is governed by a range of laws and regulations at the federal and state levels. The National Waters Law (Ley de Aguas Nacionales) is the primary federal law that establishes the legal framework for water resources management at the national level. It outlines the principles for water allocation, use, conservation, and protection. It regulates the process used by the National Water Commission to allocate water supply (World Law Group).

The General Law on Ecological Equilibrium and Environmental Protection (Ley General del Equilibrio Ecológico y la Protección al Ambiente) addresses environmental protection including water quality and ecosystem conservation. It provides the legal basis for regulating water pollution and environmental impact assessments related to water projects (Gobierno de México).

In order to comply with the National Water Law, CONAGUA prepared the National Hydraulic Program – a governing policy document for administering water resources. Objectives for the years 2020-2024 highlighted the guarantee to the human right to water and sanitation, the efficient use of water to contribute to the sustainable development of productive sectors, the reduction of vulnerability of populations prone to floods and drought, the preservation of the integrity of the water cycle to guarantee the hydrological services provided by the basins and aquifers, and the improvement of conditions of water governance to strengthen decision-making and combat corruption (Comisión Nacional del Agua).

Under the National Waters Law, Article 13.1, the Basin Advisors (los Consejos de Cuenca) establish their own general rules of integration, organization, and functioning (Red Mexicana de Cuencas). At the state levels, each state in Mexico has their own water laws and regulations that complement the federal framework. These state laws often address local water management issues and regulations.

The Public Registration of Water Rights (El Registro Publico de Derechos de Agua) provides legal security to users of national waters and their inherent public goods; safeguarding the registered rights and ensuring that every person has the right to be shown the registry entries and obtain proof (Comisión Nacional de Agua).

Figure 7. A diagram of the different institutional rules related to the water management problem in Guanajuato, Mexico. This list is not comprehensive.

5.3.4 Management

The National Water Program (Programa Nacional Hídrico) is a strategic planning document that sets out the objectives, goals, and priorities for water resources management at the national level (Comisión Nacional del Agua). It helps guide water management policies, projects, and actions. The National Water Infrastructure Program (Programa Nacional de Infraestructura Hídrica) focuses on developing and improving water infrastructure, including dams, reservoirs, irrigation systems, and water supply networks, to ensure efficient water distribution and use. The National Program for

Efficient Water Use (Programa Nacional de Uso Eficiente del Agua) initiative aims to promote water conservation and efficient water use practices across sectors. It includes measures to reduce water waste in agriculture, industry, and urban areas.

In Guanajuato, there are water plans that address local water challenges, priorities, and strategies. These plans often focus on issues such as water allocation, infrastructure development, conservation, and sustainable use.

Chapter 6: The Actionable Solution Space

A thorough evaluation of the history of water management in Guanajuato, along with causes and conditions, has revealed that the issues the state is facing are incredibly complex. In the natural domain, there is compromised water quality and water quantity. In the social domain, there are issues of water equity and water access. And in the political domain, there have been the formation of many institutions and policies at different scales that have oftentimes competing values. To understand the problem-shed of water problems for the state of Guanajuato, a macro perspective derived from evaluating basin level policies and transnational agreements is insightful. For example, NAFTA presented unintended consequences, changing the landscape of not only trade, but the environment. The transnational policy was recognized as the first major trade agreement to include environmental provisions, however results have shown coordination of joint land and water resources for arid and semiarid regions like Gunajuato are lacking. What emerged was an increased dependence on food production using unsustainable groundwater resources within the country (Bohn et. al, 2018). In the domestic domain, there are communities in desperate need for clean, accessible drinking water. Smaller scale solutions for localized problems could include rainwater harvesting or a transition to less water-intensive agricultural practices. However, in order to truly address the larger water management issues in the region for generations to come, there needs to be major shifts in water policy, water allocation, and water management within the problem-shed.

Water diplomacy would provide an opportunity for stakeholders to find actionable solutions to the issues being faced. For water diplomacy to lead to an actionable solution, complete stakeholder representation should be formed. Stakeholders in the water management network should include individuals and groups who are currently, or expected to be, affected by water policy, water management, or water allocation decisions. By excluding any particular individual or group relevant to the issues at hand, there will be gaps in localized knowledge and the potential for bottlenecks resulting from push-back from those that feel they were not fairly represented in any decision-making. In the case of Guanajuato, it is important that there are representatives from the administrative bodies at the national level (CONAGUA, SEMARNAT, SADER, Secretaria de Salud), the provincial level (CEA), local level (municipal water and sanitation utilities), and inter-governmental (Lerma Chapala Basin Council, Technical Groundwater Committee, Technical Water Council, etc.). Non-governmental and community organizations such as Caminos de Agua, Salvemos el Rio Laja, and Hermandad de la Cuenca de Independencia and existing networks such as Agua Vida should also be included.

When all relevant governmental and non-governmental bodies have been identified and brought into negotiations, there will be the need for joint fact-finding and scenario planning. When modeling different scenarios, there are bound to be uncertainties and complexities that could lead to disagreements. From the start, computer-aided modeling or group decision analysis software should be used to avoid disagreements and make the most informed decisions available. On top of computer-aided modeling, it is crucial to integrate local and indigenous knowledge with expert scientific advice. The process will reveal, yet not eliminate, disagreements – it will show what information is accepted as common knowledge and where and why certain parties interpret results. Some institutions or stakeholders will have their own agendas to maintain based on guidance already embedded within their organizational bodies that will influence their interpretations.

A key step in water diplomacy is value creation, which involves finding more efficient uses of water to meet the needs of multiple, often conflicting, interests as best as possible. Value creation entails finding non-zero-sum outcomes by understanding competing interests of every stakeholder and coming up with creative ways to expand available water supplies through the introduction of innovative technologies and planning. Rather than looking at water as a fixed resource, it is crucial for the stakeholder to look at it as a flexible and expandable resource. Finding common ground will be highly dependent on the building of relationships and trust among the different parties, as well as overcoming differences in culture, education, and politics. A mutual gains approach to negotiation will not lead to a scenario where everyone gets what they want, however the aim is to come up with an agreement where all stakeholders come out of the agreement that meets their interests better than if an agreement never went into effect. A clear example where value creation can be used to contend with conflicts in the inter-basin relations for the Lerma-Chapala Basin Council. Studies such as *“Production of competing water knowledge in the face of water crises: Revisiting the IWRM success story of the Lerma-Chapala Basin, Mexico”* would agree, with specific findings showing the need for scientific transparency, social scrutiny, and evaluation of water knowledge (Godinez-Madrigal et. al, 2019).

A successful outcome will be more likely if informal discussions are tied to formal decision-making processes by government agencies or officials. Therefore, the ongoing water diplomacy process should be convened by one or more agencies with the authority to make decisions. Designated staff members within the agencies should be given the authority to monitor ongoing efforts. Conveners should understand the interests of each key stakeholder, be ready to provide financial support towards fact-finding efforts, and be willing to find and work with a professional mediator rather than facilitate the entire process by themselves.

As the water management problems in Guanajuato are increasingly faced with uncertainties, it is important that management strategies are collaborative and adaptive. Having collaborative adaptive management allows for authoritative agencies to view stakeholders as allies and allows for a cyclical process where it is understood that water network managers will not succeed perfectly on the first try. Efforts will be iterative and results will need reflection - ultimately leading to recalibration of policies, programs, and plans, as well as reconsideration of long term objectives and milestones.

The introduction of the irrigated wheat crop during early Spanish colonial settlement in the Bajío was a turning point in the history of agriculture in the region. At first, the introduction of wheat brought great wealth, albeit to a select few. But the unanticipated emergence of a range of factors, such as urbanization, population growth, industrialization, and climate change, contributed to an increased demand on the limited groundwater resources, ultimately putting a strain on available water supplies. In theory, one idea could involve introducing less water and irrigation-intensive crops to the region. However, in practicality, there are so many complexities that make this seemingly simple solution obsolete.

The Department of Agriculture, small-scale farmers, and larger scale agro-industry players would all need to be at the forefront of negotiations for there to be any chance of a productive actionable solution space. Joint fact-finding would need to involve crop suitability studies and mapping of historic land-use and changes over time. There would need to be agreement on what are the main drivers of land suitability, such as soil, climate, topography, and current land use, and how they are weighted. There would need to be agreement on how uncertainties may affect their modeling, such as the influence of climate change on future crop conditions. Local farmers with a wealth of generational knowledge would be vital in contributing to these scientific efforts.

Once joint fact-finding is complete, the stakeholders must agree on steps forward and see value creation for themselves. The larger scale agro-industry players have long been motivated by the economic incentives of growing certain crops and the export industry has benefited them. They can afford to extract deeper and deeper wells as the aquifers become depleted. Potential economic incentives the State or National government could provide would be one important point of discussion at this stage in the negotiation process.

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