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Bordering on Water Management:  
Ground and Wastewater in the United States – Mexico Transboundary Santa Cruz Basin

by

Anita Dale Milman

A dissertation submitted in partial satisfaction of the

requirements for the degree of

Doctor of Philosophy

in

Energy and Resources

in the

Graduate Division

of the

University of California, Berkeley

Committee in Charge:

Professor Isha Ray, Chair  
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Professor Nicolas Sitar

Fall 2009

Bordering on Water Management: Ground and Wastewater in the United States – Mexico  
Transboundary Santa Cruz Basin

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by Anita Dale Milman

## Abstract

### Bordering on Water Management:

Ground and Wastewater in the United States – Mexico Transboundary Santa Cruz Basin

By

Anita Dale Milman

Doctor of Philosophy in Energy and Resources

University of California, Berkeley

Professor Isha Ray, Chair

Intensive use of groundwater in internationally shared aquifers and flows of untreated wastewater across international borders not only create negative environmental and economic externalities, they also generate tensions amongst neighboring nations. Although there exists a growing body of literature on cooperation over surface waters, few studies examine the management of transboundary groundwater and cross-border flows of wastewater. Templates from research on cooperation over transboundary rivers are likely not applicable to transboundary ground and wastewaters, as they have different physical and institutional characteristics. Through an investigation of the shared ground and wastewaters in the Upper Santa Cruz River basin (USCRB), located along the US-Mexico border, my research improves understandings of factors that heighten and hinder bi-national cooperation over those transboundary resources.

In the USCRB ground and wastewaters are characterized by a high degree of uncertainty. Contested visions, ill-defined management goals, an inability to quantify water needs, and incommensurability between outcomes cause the utility functions of both the US and Mexico to be poorly defined. Moreover, due to incomplete conceptual models, insufficient data, and subjectivity in interpretation, physical processes are not well understood. As a result, it is unclear what either side of the border stands to gain or lose from implementing transboundary ground and wastewater management activities.

In addition to this uncertainty, institutional arrangements within both the US and Mexico condition the position of each country vis-à-vis its shared waters. Polycentricism in national and sub-national institutional regimes leads to gaps and overlaps in authority while concurrently, the evolving nature of institutional arrangements leads to ambiguity in authority and responsibilities. These gaps, overlaps, and ambiguity limit the capacity of each country to conduct transboundary water management activities.

The combination of this complex institutional environment with considerable uncertainty compels each country to undertake unilateral action based on that country's ethos of water and the immediate incentives it faces. Strengthening the internal capacity of each country, by

addressing structural problems in the institutional realm and improving knowledge in the technical-information realm, will lead to greater awareness of possible synergies from cooperation and will increase its ability to take advantage of those synergies.

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# Chapter 1 : Beneath the Surface – The Challenge of Transboundary Ground and Wastewaters

*“As I travel around the world, people think the only place where there is potential conflict over water is the Middle East, but they are completely wrong. We have the problem all over the world.”*  
-- Kofi Annan (Swanson, 2001)

## 1.1 Introduction

The effective management internationally shared waters is an issue of critical concern, as more than 263 international river basins and an unknown number of aquifers span an international border (A. Wolf, 1997). Relative to our understanding of shared surface waters (Bernauer, 2002; Conca, 2006; Dinar & Dinar, 2003; A. Wolf & Giordano, 2002), we know remarkably little about the management of shared groundwater or cross-border flows of waste water. The management of these resources is understudied, in part because there is not as robust a history of collaboration. For example, even though the United States of America (US) and Mexico entered into a treaty<sup>1</sup> over shared surface waters in 1944 (IBWC 1944), a comprehensive agreement over groundwater has yet to be reached (R. Hall, 2004; Hardberger, 2004; S. Mumme, 2005). Yet reliance on groundwater resources has increased, as has the export of wastewaters across international borders.

In light of the paucity of agreements, it is tempting to apply templates from research on shared river basins to transboundary ground and wastewaters; however, such findings may not be transferrable, as ground and waste water resources have distinct physical characteristics and are governed quite differently from surface water resources.<sup>2</sup> For example, surface water infrastructure is invariably in the public domain (funded and operated by governmental agencies), larger in scale (fewness applies) and therefore more subject to "management", and in the transboundary context, to agreements. Additionally, surface water is more apparently subtractable resulting from identifiable (visible) use points, which raises the need for allocation decisions. By contrast, groundwater is more commonly privately developed, dispersed, smaller-scale, and difficult to physically control (fugitive) and therefore more difficult to regulate, let alone make the subject of international treaties. Wastewater is more privately produced, and is a dual nature resource, the demand for which is highly dependent upon the available supply and the degree of treatment (contingent commodity). These differences suggests that national governments may have more difficulty internally regulating and managing their ground and waste water resources and, as a corollary, that national and sub-national institutions may be of greater salience in transboundary management.

Through an analysis of the management of surface, ground, and waste waters in the Upper Santa Cruz River Basin (USCRB), located along the US-Mexico border, I aimed to improve understandings of how transboundary ground and waste waters are managed and the factors the heighten or hinder collaborative action over those resources. More specifically, through my

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<sup>1</sup> Treaty between the United States of America and Mexico on the Utilization of Waters the Colorado and Tijuana Rivers, and the Rio Grande (hereafter 1944 Treaty).

<sup>2</sup> For a detailed comparison of the physical and institutional characteristics of surface, ground, and waste waters see Appendix A.

research, I sought to determine how the US and Mexico could benefit from jointly managing the shared water resources in the USCRB and to understand why formal arrangements had not been reached. I theorized both the physical characteristics of ground and waste waters and the national and sub-national institutional arrangements governing those resources significantly impact management processes.

My research reveals a high degree of uncertainty regarding the utility that could be derived from implementing transboundary water management activities in the USCRB. Due to contested visions, both within and across the border, water management objectives are not clearly defined. The value of enacting water management activities is also uncertain, as difficulties in determining current water uses and predicting future conditions hinder quantification of water needs. Valuing is made all the more difficult due to incommensurability between and non-substitutable management goals. Water availability and the impacts of water use are similarly uncertain, as knowledge of hydrologic processes is incomplete due to the physical complexity of flow through the aquifer, the interdependence of groundwater supply with demand, scarce data, and equivocal conceptual models. Lastly, institutional factors related to data collection, technical knowledge, and management paradigms serve to mediate knowledge of values and water availability.

In addition to uncertainty, institutional arrangements within both the US and Mexico condition the position of each of the US and Mexico vis-à-vis transboundary ground and wastewaters in the USCRB. Gaps, overlaps, and ambiguity in the authority and responsibilities of national and sub-national institutions constrain the activities each country can undertake. The combination of this complex institutional environment with considerable uncertainty compels each country to undertake water management activities based on that country's ethos of water and the immediate incentives it faces.

Throughout this introduction and in the chapters that follow, I recount the above in more detail. In this introduction, I situate my research in the broader context, present my research objectives and methods, and provide a roadmap of the remainder of the dissertation. I begin with a depiction of globally shared water resources and their importance. I assess the literature on transboundary water management and explain gaps in current understandings of shared ground and waste water resources. Next, I present my research objectives, both academic and personal, and explain the methods I used in conducting this research. I then outline the contents of the remainder of this dissertation. Lastly, I conclude with a summary of the implications of my work.

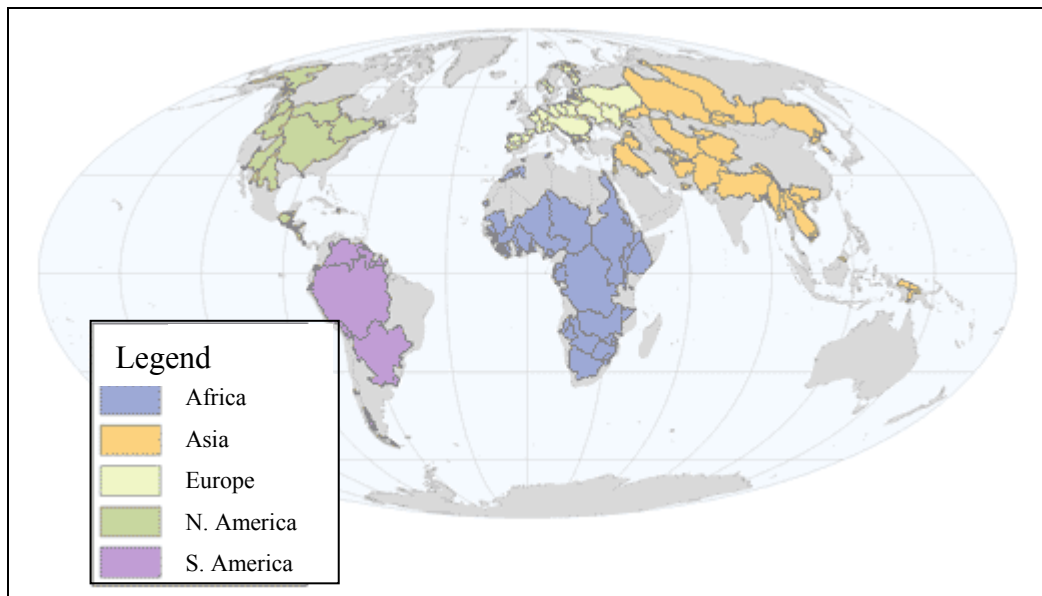
## **1.2 A World of Shared Water Resources**

There is a growing recognition that the world's water is now, or may soon be, in crisis (Gleick, 1993; Biswas, 1999; Rogers, et.al. 2005; United Nations 2006). In 1998, approximately 76% of the world's population lived in a region with low or catastrophically low levels of water supplies (Shiklomanov, 1998). It is estimated that by 2025, approximately 62% of the population will live in countries experiencing water stress (Arnell, 2000). The exact availability of water supplies is uncertain, as climate change will have a dramatic impact on the global hydrologic cycle (Arnell, 2000) and population growth will lead to decreased per capita availability

(Vorosmarty, Green, Salisbury, & Lammers, 2000). Environmental degradation will also take its toll. Already an estimated 12,000 km<sup>3</sup> of water, equivalent to approximately three times annual anthropogenic water use, is considered unfit for use due to pollution caused by wastewater (UNESCO, 2003). The complexity and depth of the problem is compounded by spatial and temporal variations in the distribution of water supplies and demands (Shiklomanov, 2000). Water scarcity in the context of continued growth has led to increased competition over shared water resources. These circumstances highlight the need to increase our understandings of how to best manage the world's transboundary water resources.

Globally, there are 263 international river basins (Figure 1-1), spanning 45.3% of the land surface of the earth (excluding Antarctica) and extending through 145 nations (Aaron Wolf, Natharius, Danielson, Ward, & Pender, 1999). The exact number of transboundary aquifers (Figure 1-2) remains unknown, due to insufficient data and the subjectivity of hydrogeologic interpretation (Feitelson, 2006).<sup>3</sup> However, existing inventories suggest there are sixty-five shared aquifers in the Americas, thirty-eight in Africa, and forty-seven in the Balkans alone (UNESCO, 2006). These numbers are in flux, as political boundaries may change. Regardless of the exact number, the fact is the majority of countries share water resources and as their reliance on these resources increase, cooperative water management strategies must be devised.

**Figure 1-1: International River Basins**

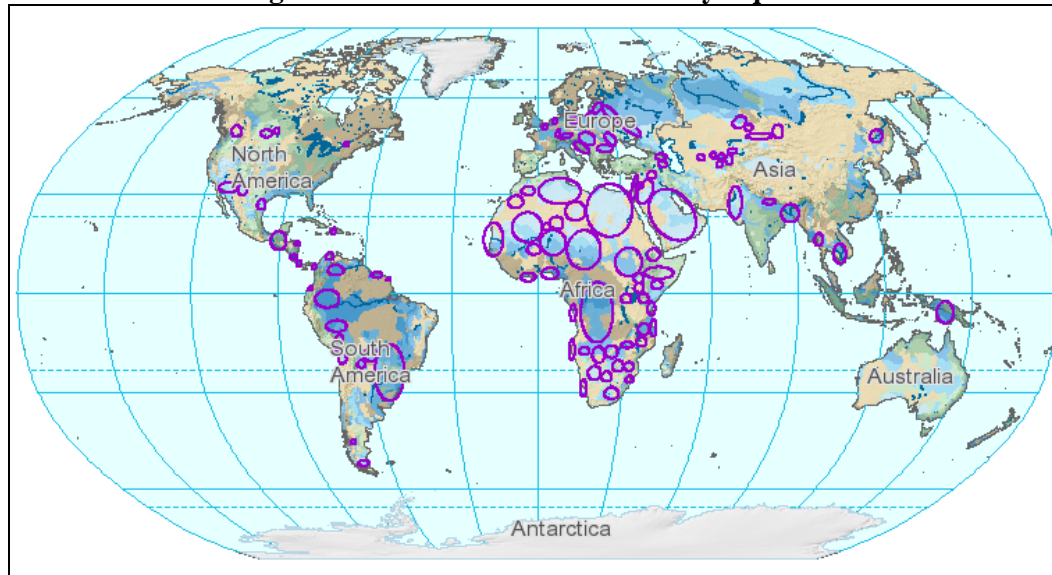


Source: <http://www.transboundarywaters.orst.edu>

<sup>3</sup> For example, the actual number of aquifers crossing the US-Mexico border is unknown. Stephen Mumme (2000) identifies 18; IGRAC (2009) identifies 10; UNESCO and ISRAM (2004) cite 18, 8 and 9 all in the same document; and the Good Neighbor Environmental Board (2005) claims there are between 18-20. This incongruence between expert opinions is identified by Todd Jarvis on his international water log blog <http://internationalwaterlaw.org/blog/?p=10>.

<sup>3</sup> Wells in the Santa Cruz river basin provide 40% of the water supply for the city of Nogale, Sonora (COAPAES, 2005). Other sources of water for Nogales, Sonora include wells in the Los Alisos river basin, located to the southwest of the city, and several lower yield wells located in the Nogales Wash, a tributary to the Santa Cruz which runs through the center of town.

**Figure 1-2: Identified Transboundary Aquifers**



Source: <http://www.whymap.com>

A long history of cooperation exists over internationally shared water resources. Between 805 and 1984 CE more than 3,600 treaties were signed which address international water resources (A. Wolf, 1997). The Transboundary Freshwater Dispute Database includes the text of 145 treaties that address aspects of internationally shared water resources that address issues beyond boundary definition, navigation, and fishing rights (A. Wolf, 1997). Most of these treaties address hydropower (fifty-seven treaties) and water supplies (fifty-three treaties). Industrial water use, navigation, flood control, and pollution are other issues included in the treaties (Beach, et al., 2000; Hamner & Wolf, 1998). The primary focus of these treaties is surface water resources.

Yet as surface freshwater supplies per capita dwindle around the globe, groundwater extraction and flows of wastewater are becoming more important. Excluding polar ice, ninety-seven percent of the world's available freshwater resources is stored as groundwater (Foster, 1999). Water released from aquifers provides base flow to streams and forms approximately 36% of global river runoff (Zektser & Everette, 2006). In industrialized nations, groundwater exploitation increased dramatically between 1950 and 1975, as energy and pumps became readily available. Between 1970 and the present, groundwater use has also increased dramatically in the developing world (UNESCO, 2003). Currently, global abstractions of groundwater are approximately 600-700 billion m<sup>3</sup>/year (Zektser & Everette, 2006). This is equivalent to approximately eight times the annual flow at the Aswan High Dam (Nile River Basin Challenge Program, 2007) or 1.3 times the average total annual flow of the Mississippi River (Shiklomanov, 1999). Groundwater is used to meet 50% of global potable water needs, 20% of the demand from irrigated agriculture, and 40% of the needs of self-supplied industry (UNESCO 2003; Zektser and Everett 2006). Unfortunately, increased groundwater use has its costs. As rates of groundwater use increase, intensive use of groundwater can lead to increased pumping costs, land subsidence, salt-water intrusion, mobilization of natural or human sources of

contamination, and ecosystem deterioration. Some of this degradation is irreversible. Thus cooperative transboundary groundwater management strategies are needed to prevent a tragedy of the commons from occurring, harming both sides of the border.

The role of wastewater is also growing. Shiklomanov estimated that in 1995, more than 1,500 km<sup>3</sup> of wastewater were produced (UNESCO, 2003). This number includes 326 km<sup>3</sup>/year generated in Europe, 431 km<sup>3</sup>/year in North America, 590 km<sup>3</sup>/year in Asia and 55 km<sup>3</sup>/year in Africa (Shiklomanov, 1998). In 1999, only approximately 6% of the wastewater generated in Latin America was properly treated (A. K. Biswas, 1999). Similar problems exist throughout Africa and Asia. Untreated flows of wastewater pollute freshwater resources and are a threat to human and environmental health. Yet increasingly, wastewater is also being seen more positively as a new supply to be taken advantage of in water-scarce regions. Direct reuse or recycling of wastewater and aquifer recharge using wastewater are common practices in the US (CIDWT n.d.; McKenzie, 2004) and multiple other countries such as Pakistan, Ghana, Vietnam and Mexico (Pescod 1992; IWMI, 2003). Where wastewater flows across international borders, questions arise regarding who is responsible for treatment, to what degree wastewater should be treated, and who retains ownership or the right to the water after it has been treated.

There are far fewer agreements over transboundary ground and waste water resources than over shared surface waters. Existing international agreements barely address groundwater or flows of wastewater. Matsumoto (2002) analyzed the text of 400 international water related treaties and found 109 of them include the words well, spring, or groundwater. However, when he analyzed the 62 of these for which he could obtain the full text, Matsumoto determined the majority do not directly address groundwater. Only seventeen mention surface-groundwater relationships and, in those, groundwater is a secondary concern. Six mention groundwater quality and eight mention groundwater quantities but do not make provisions for allocation. Only nine include groundwater management provisions and only one specifically allocates groundwater. Hamner (1998) and Beach et al. (2000) also note the paucity of groundwater related agreements. At the time of their analyses, only three international agreements specifically addressed groundwater supply: the 1910 Convention regarding the water supply of Aden between Great Britain and the Sultan of Abdali; the 1994 of Peace Between the State of Israel and the Hashemite Kingdom of Jordan; and the 1995 Israeli-Palestinian Interim Agreement on the West Bank and the Gaza Strip (Beach, et al., 2000; Hamner & Wolf, 1998). Agreements over cross-border flows of wastewater are even fewer, although wastewater is included in the Israeli-Jordan 1994 Peace Treaty and as Minutes amended to the US-Mexico 1994 Treaty for the Utilization of Waters of the Colorado and Tijuana Rivers and of the Rio Grande.

### **1.3 Research on Transboundary Surface, Ground, and Waste Waters**

Research on transboundary waters aims to provide insights regarding how countries manage their shared water resources and factors leading to conflict or cooperation. The literature consists primarily of studies of internationally shared river basins; yet, conclusions drawn from studies of river basins may not be applicable to transboundary ground and waste waters. This is because conflating these three types of water resources obfuscates differences in the physical and institutional characteristics of each resource. These characteristics influence both the knowledge a country has regarding the utility of enacting water management strategies and the capacity a country has to undertake such activities. My research in the USCRB contributes to the literature



on transboundary water management by demonstrating how the physical and institutional characteristics of transboundary ground and wastewaters serve to increase uncertainty and decrease management capacity, thus impacting processes for collaboration and cooperation<sup>4</sup> over shared waters.

The literature on transboundary waters is dominated by case studies of individual river basins; however, theoretical and comparative studies are becoming more commonplace (Dinar & Dinar, 2003). Normative studies prescribe mechanisms for allocating shared waters or addressing pollution (Draper, 1997; Rowland, 2005; Wang, Fang, & Hipel, 2003; Wouters, 2004). Such mechanisms are based variously on the doctrines of absolute sovereignty, territorial integrity, reasonable and equitable use, polluter pays, victim pays, and benefit sharing (Barrett, 1994; Giordano, Giordano, & Wolf, 2002; Grey & Sadoff, 2003; Hardberger, 2004; Rogers, 1993; A. Wolf, 1997). Positivist studies attempt to explain factors influencing regime formation and regime behavior. Most of these use econometric analysis to look at the roles played by geography, hegemony, and cultural or economic integration (Espey & Towfique, 2004; Giordano, et al., 2002; Song & Whittington, 2004; Yoffe, et al., 2004). Yet some positivist studies use mathematical models to analyze the possibilities for achieving cooperation. These models assume a negotiation mechanism and use either game theory or optimization analysis to predict whether or not a cooperative solution exists. They also analyze how linkages, side payments, enforcement mechanisms, and third party involvement mediate negotiation outcomes (Barrett, 1994; Frisvold & Caswell, 2000; Küçükmehtemoglu & Guldmann, 2005). Lastly, best practice studies rely on historical and political analyses and make recommendations for formulating sustainable and effective regimes (Bernauer, 2002; Waterbury, 1997; A. Wolf, 1997) usually via participation, enforcement, and flexibility mechanisms (Barrett, 1994; Milich & Varady, 1998).

The above mentioned research all concern transboundary rivers. Increasingly, attention has been directed at shared aquifers, while there remains little discussion on cross-border flows of wastewater. The few works that address groundwater are either descriptive case studies (Arias, 2000; Chavez, 2000; Froukh, 2003), theoretical bargaining scenarios (Just & Netanyahu, 2004; Netanyahu, Just, & Horowitz, 1998), or critiques of how international law either omits groundwater (Dellapenna, 2000; Mechlem, 2003; Utton, 1982) or misrepresents the physical realities of it (Jarvis, Giordano, Puri, Matsumoto, & Wolf, 2005). Studies that address wastewater do so under the general context of pollution prevention and abatement and do not focus explicitly on wastewater as a positive resource. Where groundwater and wastewater are not specifically addressed, it is implicitly assumed that the theories and findings related to surface water apply to all transboundary waters. The significance of the different physical and institutional characteristics of transboundary surface, ground, and waste waters is best understood through an examination of the assumptions embedded in studies of transboundary water management. Through such an analysis it becomes apparent how, assumptions commonly made in the transboundary water literature may not hold true for those resources.

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<sup>4</sup> Here, and throughout, I distinguish between cooperation as formal and collaboration as informal.

Research on transboundary water management relies, with some exception,<sup>5</sup> on economic rationalism and rationalist theories of international relations as its underpinnings.<sup>6</sup> By economic rationalism, I refer to the fact that studies of transboundary water represent countries as rational, utility-maximizing actors with, if not perfect, at least reasonable, estimates of the impact transboundary water management activities will have both themselves and the country(s) with which they shares water resources. Assumptions of economic rationalism are clearly manifest in game theoretic, optimization, and benefit sharing analyses.<sup>7</sup> By rationalist theories of international relations, I refer to the tendency of the literature to take a country (nation-state) as the unit of analysis and to explain transboundary water management outcomes based on the collective action dilemma that arises from the lack of a higher authority in the international realm. The literature's reliance on rationalist international relations frameworks is apparent, as the focus of many studies is on power dynamics (geographic, economic, military), relative and absolute gains from cooperation, international legal doctrines, and regime formation (treaties and river basin organizations).<sup>8</sup> Yet, my research in the USCRB indicates the assumptions embedded in economic rationalism and rationalist theories of international relations do not well represent how transboundary ground and waste waters are managed in practice.

Studies of transboundary waters tend to assume each country knows the quantity of water physically available to it, as well as the impact possible water management activities will have on hydrologic processes. Studies also presuppose countries have well defined water management goals and knowledge of the costs and benefits of different management activities to both themselves and the countries with whom they share water resources (Frey, 1993). However, transboundary water resources, and particularly transboundary groundwaters,<sup>9</sup> are characterized by a high degree of analytic uncertainty; in other words, information regarding hydrologic processes, needs, benefits, and costs is incomplete. This analytic uncertainty is compounded by strategic uncertainty,<sup>10</sup> as not only is there incomplete knowledge, but countries may also hold disparate values and management paradigms.

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<sup>5</sup> For example, Blatter and Ingram (2001) use the case studies in their edited book to support their claim that we need to move beyond modern rationalist approaches to transboundary waters, which have focused on the nation-state, and instead adopt an approach that considers values, histories, networks, and culture.

<sup>6</sup> Although only presented briefly here, these theories and their salience in the transboundary literature is covered more in depth in the following chapters. In Chapters 2 and 3, I address theories on economic rationalism, whereas in Chapter 5, I speak to international relations theories.

<sup>7</sup> See for examples of game theory (Barrett, 1994; Dombrowsky, 2007; Fernandez, 2006; Frisvold & Caswell, 2000; Just & Netanyahu, 2004); of optimization (Küçükmehtemoglu & Guldmann, 2004; Rogers, 1993; Whittington, Wu, & Sadoff, 2005), and of benefit sharing (Jagerskog & Lundqvist, 2006; Phillips, Daoudy, Ojendal, McCaffrey, & Turton, 2006; Sadoff & Grey, 2005).

<sup>8</sup> See for examples of power dynamics (Dinar, 2000; Frey, 1993; Yoffe, et al., 2004; Zeitoun & Warner, 2006), of relative and absolute gains from cooperation (Rogers, 1993), of international legal doctrines, (Draper, 1997; Wang, et al., 2003; A. Wolf, 1997) and of regime formation (Bernauer, 2002; Espey & Towfique, 2004; Song & Whittington, 2004).

<sup>9</sup> Uncertainty is more pronounced for groundwater than for surface waters for a number of reasons, as discussed in Appendix A. Uncertainty regarding the availability of water and the impacts of use is greater because while surface water availability depends primarily on meteorological variability, groundwater availability is also determined by geological heterogeneity and the groundwater abstraction regime. Uncertainty regarding costs and values is also greater, as depth to water changes with use, and as definitions of sustainable use are contested, and because the value of groundwater also depends on the availability of other water resources.

<sup>10</sup> See (Iida, 1993) for a description of analytic and strategic uncertainty.

The role uncertainty plays in negotiations and water management strategies is not accounted for in rationalist approaches to transboundary waters, and thus is noticeably absent from the literature. Even the few studies that incorporate an explicit recognition of uncertainty continue to perform analyses by assuming fixed values for water supplies and benefits. For instance, in their game theory analyses of the Israeli-Palestinian Mountain Aquifer, Just and Netanyahu (2004) explain they do not have enough empirical information to assess payoffs and therefore must make assumptions. They then proceed to conduct a game theory analysis using singular benefit and cost functions. The same is true with Whittington, et al. (2005), who describe in some detail how the economic value of water is dynamic over time and differs by user and location, yet then create an optimization model of the Nile River Basin which maximizes economic benefits described by prices and per unit values held constant over time.

Uncertainty features prominently in the management of ground and waste waters in the USCRB. By showing how assumptions of complete information, well-defined utility functions, and commensurability do not hold true in the USCRB, I demonstrate that neither the US nor Mexico can be characterized as rational utility maximizing actors, and thus challenge framings based on economic rationalism. Recognition of the uncertainty inherent in transboundary ground and waste waters is important, because, as Lemarquand (1976) theorizes, when the consequences of a transboundary water management strategy are not fully understood or cannot be adequately assessed, countries may be reluctant or unwilling to reach an agreement.

Not only has my research in the USCRB led me to critique rational economic approaches to transboundary waters, it has also led me to question the centrality of rationalist international relations theories in studies of transboundary ground and waste waters. Specifically, I interrogate the adoption of a state-as-container approach and the assumption that structural factors<sup>11</sup> in the international realm are the main determinants of a country's actions. The primary actor in the majority of the literature on transboundary waters is the nation-state, which is treated as a monolithic unit (Du Plessis, 2000).<sup>12</sup> The presumption is that the nation-state, as a sovereign unit, has the capacity to make decisions regarding and to implement transboundary water management strategies, should it so choose. These decisions are thought to be driven primarily by the relationships between countries, what each stands to lose or gain, and international norms and expectations.

The effectiveness of international environmental regimes is contingent upon both the willingness and the capacity of a country to participate (Levy, Young, & Zurn, 1995). Yet, my research in the USCRB shows that a country may not be endowed with this presupposed capacity to manage

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<sup>11</sup> In rationalist theories of international relations, the international system (i.e., the world) is modeled as sovereign states operating in an anarchical environment. Thus 'structural' or 'systemic' factors refer to the characteristics of such an environment that influence the interactions between nation-states. For example, Dinar (2000, pp380) uses the term systemic variable to refer to "the anarchical nature of the international system, the number of major powers in the system, the distribution of military and economic power among them, patterns of military alliances and international trade, and other factors that constitute the external environment common to all states."

<sup>12</sup> Although the nation-state is the unit of analyses for the majority of transboundary water studies, non-state actors are not fully disregarded. The role of transnational networks and supra-national entities (Barrett, 1994; A. Biswas, 1999; Conca, 2006; Elhance, 2000; Frisvold & Caswell, 2000; Gerlak, 2007) and the influence of domestic interest groups has not been ignored (Feitelson, 2006; Frey, 1993; Furlong, 2006; LeMarquand, 1976; Sneddon & Fox, 2006; Trollaldalen, 1992; Turan & Kut, 1997).

its transboundary waters. I contend that a country's capacity to conduct transboundary water management activities is mediated by the national and sub-national institutions governing water within that country. While the importance of institutions in influencing behavior is recognized with respect to international river treaties and international river basin-regimes, the role of institutions internal to the nation-state has been almost completely overlooked in studies of transboundary water management.<sup>13</sup> Only a very few studies make brief mention of difficulties arising from the configuration of national water management agencies (Hayton, 1978; LeMarquand, 1976; Matthews, 2005; A. T. Wolf, 2007), and of these, only one looks in detail at how governance structures can create barriers to cooperation (Norman & Bakker, 2005).<sup>14</sup>

My research demonstrates that neither the US nor Mexico are well characterized by a state-as-container model, and as such, an approach to analyzing them that relies on this assumption overlooks how the institutional environment within each country impacts its capacity to enact transboundary water management strategies. Rather than a monolithic unit, each country is better described as having a polycentric and evolving institutional structure for water management. By poly-centric,<sup>15</sup> I refer to the distribution of authority for policy and decision-making, implementation, and enforcement to multiple entities at different scales of governance. By evolving, I refer to the fact that the institutional environment for water management is in a constant state of flux, as jurisdiction, laws, and regulatory authority change. The polycentric and evolving nature of the institutional structure within each country creates gaps, overlaps, and ambiguity in the authority of national and sub-national institutions. Consequently, responsibility for decision making, implementation, and enforcement is not be clearly defined and procedures allowing for certain water management activities to occur are not in place. As a result, both countries' capacity to undertake transboundary water management is limited.

Gaps, overlaps, and ambiguity in the authority of national and sub-national institutions are especially pronounced in the case of ground and waste waters. Until recently most countries did not regulate groundwater use; rather the right to use it lay with the overlying property owner and was subject to the right of capture (Shah 2002; Hodgeson, 2006). Wastewater reuse too, often remains within the private domain. Moreover, particularly in federations, responsibility for water management is frequently shared between national and sub-national levels of governance. Furthermore, as Shah (2002) demonstrates for India, governments may lack the political capital

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<sup>13</sup> Although left out of the literature on transboundary waters, the importance of the institutional environment within a country is well documented in studies of public choice, federalism, and collective action (P. Hall & Taylor, 1996; Hooghe & Marks, 2003; E. Ostrom, 1990)

<sup>14</sup> The tie between international decisions and domestic politics has, albeit infrequently, been incorporated into analyses of transboundary waters, primarily through application of Putnam's (1988) two-level games. According to this model, a country's position in international negotiations is the outcome of the interaction between national politics, which constrain the acceptability of policy decisions at the domestic level, with international negotiations, during which national governments seek to maximize domestic support while minimizing adverse consequences in the foreign realm.

<sup>15</sup> Ostrom et al. (1961) use the term polycentric to refer to "many centers of decision-making which are formally independent of each other." In my use of the term, I broaden this term to also account for the fact that there also may exist centers of decision making that have inter-dependencies. An example of this would be the relationship between the US Environmental Protection Agency and the Arizona Department of Environmental Quality.

necessary to create new regulations.<sup>16</sup> Thus a national government may not have the authority to necessary to control the ground and wastewater management activities of its own constituency.

If, as I assert, due to both the high degree of uncertainty characterizing and the structure of national and subnational water management institutions governing ground and waste waters, economic rationalist and rationalist international relations theories approaches to transboundary waters do not well represent actual practice, then we are left to ask how can the actions countries take to manage those waters best be understood.

Research on transboundary rivers has shown extra scientific factors such as equity, sovereignty, prestige, and cultural ideologies influence the water management strategies countries adopt (Bernauer, 2002; Frey, 1993; Rogers, 1993; A. Wolf, 1997). In the USCRB, concerns regarding equity and sovereignty are present; yet the most salient factor appears to be the water management paradigm each country holds, and in particular what it views as best management practices. In addition, financial incentives from outside entities, such as the Border Environmental Cooperation Commission, has encouraged unilateral decision making, as water management agencies on both sides of the border endeavor to take advantage of funding opportunities. Taking the roles of a country's water ethos and immediate incentives into consideration, I posit transboundary ground and wastewater management might be best viewed less an exercise in utility maximization and more as a series of unsystematic steps expected to provide some improvements to water management problems. This representation echoes Lindholm's (1959) description of public administration as a practice of 'muddling through.' The usefulness of this representation is that it forces recognition of the information, coordination, and implementation challenges that create real impediments to the management of transboundary ground and waste waters, and thus pushes both scholars and practitioners to seek and suggest solutions to overcome these barriers.

#### **1.4 Research Objectives**

In designing and conducting my dissertation research, I hoped to achieve both theoretical-topical and personal goals. My overarching motivation was to improve understandings of transboundary waters, so as to increase possibilities for collaboration and cooperation. I hypothesized the impetus for and the impediments to management of transboundary ground and waste waters differ from those of transboundary surface waters. I selected the US-Mexico border region as the focus my research because the two countries have a strong history of cooperation over shared surface waters, yet, with the exception of one agreement to limit groundwater pumping in a specific location,<sup>17</sup> there have been no formal agreements between the two countries regarding the management of their shared aquifers (S. Mumme, 2004). The two countries have cooperated over the treatment of wastewater in Ambos Nogales and in Tijuana/San Diego; however,

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<sup>16</sup> The link between groundwater and property ownership makes implementation of new regulations all the more difficult (Utton, 1982). Individuals within a country may reject groundwater regulations, claiming it infringes upon their private property. Similarly, a country may be hesitant to enter into an international agreement that restricts pumping or regulates land use (due to its impact on groundwater) because such an agreement would be seen as ceding sovereignty over its own natural resources.

<sup>17</sup> In 1973, the US and Mexico approved Minute 242 to the 1944 US-Mexico water treaty, through which both countries agreed to restrictions on pumping near San Luis (IBWC, 1973).

wastewater has not to date been jointly managed as a positive resource for reuse or aquifer recharge.

I arrived at the Upper Santa Cruz River Basin through a series of discussions and interviews with employees at the US Environmental Protection Agency, the International Boundary and Waters Commission, and the Arizona Department of Environmental Quality. The USCRB was an ideal location for my research for two reasons: i) concerns over how to best address problems related to flows of waste waters across the border and pumping of ground waters persist in the region, and ii) the size of the region (both geographic expanse and the human-sociologic structures in place) make it easily accessible for an individual researcher. Shortly after I began my research, the USCRB was designated as a priority aquifer as part of the Transboundary Aquifer Assessment Act (United States Senate, 2005).

Narrowing my research focus, I was lead to ask the following three questions, specifically as they relate to the USCRB:

- What are the water management objectives within each of the US and Mexico and how are those affected by the other country?
- How might transboundary ground and waste water management activities benefit each country?
- What drives decision making?

To answer the first question, I sought to determine the water needs and management goals within each country; the quantity of water available to meet those objectives; the impacts of using that water; the costs, benefits, and tradeoffs in meeting those objectives; and the impact of water use on one side of the border across the border. The second question called for identifying possible water management strategies and evaluating the costs and benefits of each. The third question required investigating barriers and incentives to the water management strategies identified in question two; and more specifically, how the physical characteristics of water and the institutional arrangements governing the use and management of those waters influence management decisions. I theorized that answers to these three questions, in concert, would lead to insights into the key economic, institutional, and political factors mediating the management of transboundary waters in the region.

Beyond my topic-specific interests, my research was also driven by personal aims and principles. I wanted my dissertation research to contribute not only to academic theories, but also to provide information directly useful to the people and entities I was studying. Thus my research was designed to have an applied component, and in particular, to undertake an analysis that would be useful to stakeholders but which, due to resource and mobility constraints, otherwise might not have been accomplished. Hence I collected, consolidated, and verified data from the Mexican portion of the basin, I analyzed hydro-geologic conceptualizations of the border, and I identified sources of uncertainty. Copies of this work, including my groundwater simulation models and model results, were given to water management agencies on both sides of the border, along with recommendations on how to reduce uncertainty. I have no pretense that I managed to accomplish these tasks as well as or to the extent I desired, but I made what I hope was an admirable effort. As progress on the Transboundary Aquifer Assessment Act continues, my efforts have at minimum saved officials on both sides of the border valuable time and resources,

as mining for and evaluating historic data is a lengthy and intensive. Beyond my efforts related to groundwater analysis, I also offered my assistance to the Arizona Department of Environmental Quality (ADEQ) and translated the City of Phoenix pretreatment manual into Spanish. This manual is currently being used as the basis for a wastewater pretreatment program ADEQ is assisting the Mexican water utility to develop and implement.

I also wanted to ensure my research was empirically grounded, and in particular was cross-validated by an extensive field work component and by individuals and entities within the study region. One of my academic preoccupations is with the abstraction of theory from the real world, necessitated by the need to simplify in order to describe and understand complex processes. The act of generalizing and thereby choosing what to include and what to leave out of our theoretical constructs, can lead key details or factors that in fact act as incentives, barriers, and constraints in real-life to be overlooked. It is my opinion that grounding research in practical realities is essential if we hope academic theorizing will lead to effective or applicable solutions. I have no illusions that my research in the USCRB represents a conceptual breakthrough that will immediately resolve our transboundary resource management dilemmas. I recognize my work is indeed more a critique of theoretical framings than a normative statement and it does not emphasize constructive policies. None-the-less, I deem the attention I draw to the need to account for both uncertainty and the nature of national and sub-national resource management institutions is quite important, as recognizing these frequently overlooked factors is essential if we wish to devise effective strategies for managing transboundary ground and wastewaters.

Lastly, in my research, I wanted to bridge disciplinary boundaries. Our disciplinary trainings, including their implicit methods and epistemic perspectives, become the lenses which filter and focus our perceptions, which at times causes us, albeit inadvertently, to not see the entire picture. I am alternately bothered by both technocratic society and the post-positivist response to it. I do not fully align myself with one side of this debate or the other. I do believe the dominant paradigm of today emphasizes technocratic and rationalist perspectives, and as such, overlooks some truths from cognitive and constructivist perspectives. This viewpoint is reflected in my discussion of commensurability across borders and of how decisions are influenced by the ‘ethos’ of water a country holds. Yet I concurrently recognize that physical (in this case, hydrologic) and economic constraints are real and technology, infrastructure, and money are important in resolving our environmental problems and conflicts. While conducting my research and writing this dissertation, I struggled to ensure the account I give is a truth. I cannot claim to have fully overcome disciplinary trainings, nor do I claim this dissertation reflects the entire spectrum of what is occurring in the USCRB. There are many ways to categorize and understand what is happening in the region. Power, equity, hegemony, economic optimization – all of these exist to some extent. Yet, my observations, conversations, and analysis have led me to see perspective written in this thesis as the dominant, overarching story.

## **1.5 Research Methods**

My research was based on an iterative process of empirical data collection, theory development and fitting, and additional data collection. The research began in 2005 with a series of conversations with officials from the U.S. Environmental Protection Agency during which they described several of the issues they were encountering along the border overall, and in Nogales more specifically. I then visited the Upper Santa Cruz River Basin for two months in June and

July of 2005. I returned for July and August of 2006 and for September and October of 2007. In between periods of more extended field research, I also made several shorter visits to the region and attended planning and stakeholder meetings, including visits related to bi-national meetings of the Transboundary Aquifer Assessment Act in each of January, April, and June of 2008. After each round of field research, I analyzed my findings to determine where they fit in with the literatures on transboundary water management and where they diverged.

In conducting my research, I adopted a multi-dimensional approach. Starting with a utilitarian analysis, I analyzed water management objectives and the costs and benefits of water management strategies for each side of the border. I then shifted to a water resources perspective, investigating hydrologic processes and to determine the availability of water and the impacts of water use. My investigation of the aquifer included development of groundwater simulation models using MODFLOW. Lastly, I assumed an institutional perspective, mapping the institutional environment to understand how governance structures influence water management activities.

My analysis is based on information garnered from key informant interviews, participant observation, data collection, and document review. I conducted 63 formal interviews with employees at governmental agencies, large water rights holders, advisory board members, and other stakeholders. In addition, I attended numerous public meetings on both sides of the border. I also collected and analyzed primary and secondary data including, among others, reports from water rights holders; official and internal water utility reports and documents; population, economic, and agricultural censuses; water use logs; hydro-geologic test results; stream gauge measurements; satellite images, and academic publications. Overlap exists between these multiple sources of information, which proved useful in triangulating my analysis and verifying consistency throughout.

## **1.6 Overview of Dissertation Chapters**

The details of my research are presented in the following chapters. I begin in **Chapter 2**, by presenting the study area. I describe the Upper Santa Cruz River Basin in depth, including information on water management challenges and proposed strategies for addressing transboundary ground and wastewaters in the region.

Following the introduction to the study region, in Chapters 3-6, I describe the high degree of uncertainty in the USCRB with respect to each country's overall objectives, the costs and benefits of alternate water management strategies, and the physical flows of water in the region. In **Chapter 3**, "Contested Visions, Unknown Values and Needs," I demonstrate that neither the US nor Mexico has a complete understanding of what it stands to gain or lose through the implementation of transboundary ground and waste water management activities. To do so, I first delineate the diverging views of water management objectives both within and across the border. Then, using empirical data,<sup>18</sup> I reveal how water needs in the USCRB are made uncertain not only by these contested visions, but also by insufficient data, difficulty in predicting future conditions, the challenge of estimating water needs for non-consumptive uses, and institutional arrangements. I draw from the literature on economic valuation (see for example, Hanemann, 2006) to make apparent how valuing water is complex as benefits are

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<sup>18</sup>Additional details on the calculations used in the analysis in Chapter 3 are included in Appendix B.



frequently non-substitutable and incommensurate. Throughout this chapter, I illustrate how uncertainty is particularly salient in the case of ground and waste waters due to the interconnection between supply and demand, the dual nature of wastewater as a resource, and trade-offs between characteristics of the water itself (reliability, timing, quality, cost).

In **Chapter 4**, “Hydrologic Uncertainty: Water Availability and Impacts of Use,” I build on the central thesis of Chapter 3 to show how uncertainty stems not only from questions related to objectives and values, but also from the complexity of hydrologic processes. I demonstrate that groundwater flows in the region are poorly understood, conceptualizations of the aquifer are incomplete, and the role of treated effluent in aquifer recharge is not fully known. This uncertainty is exacerbated by institutional factors that mediate knowledge, such as legal definitions, unmonitored water use, and data and technical capacity constraints. The combination of analytic uncertainty with differing paradigms for water management lead the US and Mexico to hold diverging beliefs about the availability of water and the impacts of water use, and thus to differentially interpret the importance and usefulness of adopting transboundary water management strategies.

**Chapters 5 and 6**, “Knowledge of Aquifer Behavior in the USCRB,” serve to both support, quantitatively, claims regarding the inherent uncertainty associated with groundwater, and to provide information useful to groundwater managers in the region as they seek to reduce uncertainty. Chapter 5 discusses the uncertainty which arises from data constraints, measurement error, and technical limitations, and demonstrates how the incomplete conceptual model of the aquifer on the Mexican side of the border proves to be particularly problematic with respect to determining aquifer behavior. The chapter presents eighteen groundwater simulation models, each representing a different conceptual model of the aquifer, which were developed and calibrated to measured water table levels in 1997. The models illustrate how analytic uncertainty can create room for subjective interpretation of the available information. The models also provide useful information regarding where additional data could be collected or hydrogeologic testing performed so as to reduce uncertainty and improve understandings of aquifer behavior. Chapter 6, which is structured as a groundwater modeling report, provides supporting data and information regarding the groundwater simulation results discussed in Chapter 5.

In **Chapter 7**, “Polycentric and Evolving Institutions - Gaps, Overlaps, and Ambiguity,” I transition from an analysis of uncertainty regarding costs and benefits of water management to uncertainty in the authority and responsibility for water management. Here I demonstrate that a country’s approach to its transboundary ground and wastewaters is conditioned not only by the physical characteristics of the resources but also by national and sub-national institutional arrangements. The polycentric and evolving nature of the institutional environment for water management within both the US and Mexico leads to gaps, overlaps, and ambiguity in authority and responsibility. Through an analysis of four water management strategies proposed in the region (signing of a forbearance lease, recharge of the aquifer, the transfer of potable water across the border, and restrictions on groundwater abstractions), I trace the gaps, overlaps, and ambiguity in institutional arrangements, describing how they impede the capacity of each country to adopt transboundary water management strategies.

Lastly, in **Chapter 8**, “Transboundary Ground and Wastewater Management in Practice” I show how, in the context of uncertainty and complex institutional arrangements governing the management of ground and waste waters, a country’s ethos of water and the immediate incentives it faces become key determinants of the decisions it will make. Neither the US nor Mexico is attempting to maximize total benefits accrued in the basin nor the utility accrued to itself. Rather each country is making decisions based on its ‘ethos’ of water management in conjunction with the immediate incentives it faces. I conclude by theorizing about the implications of my findings more globally, as countries move to more decentralized management of water resources and heavier reliance on ground and waste water flows.

My research suggests cooperation over transboundary ground and waste waters is contingent upon overcoming knowledge and institutional barriers. Due to the high degree of uncertainty, effective management strategies will need to incorporate the flexibility to adapt to improving knowledge, changing needs and evolving circumstances. Cooperation will also require changes that bridge gaps, unify overlaps, and clarify ambiguities in the institutional environment.

The implications of my research extend beyond the Upper Santa Cruz River Basin, as there is reason to believe my findings may be representative of other transboundary ground and wastewaters. In most countries there exists a high degree of uncertainty regarding the availability of, the utility which can be derived from, and the management goals related to ground and waste water resources. We can also expect to find a polycentric and evolving institutional environment, as ground and waste waters are usually governed at local, regional, and national levels. Moreover, institutions for the management of water within a country are changing due to shifting in paradigms for water governance (Easter & Hearne, 1995; Saleth & Dinar, 2000; Tortajada, 2001). Although institutional arrangements within any country will not mirror exactly those of the US or Mexico, it is likely that this evolving process will entail at least momentary ambiguity, and perhaps more long-lasting gaps and overlaps in authority. Thus as we seek to promote the effective management transboundary ground and wastewaters, we need to bring to the forefront the role of the intra-national in international cooperation. Key to international cooperation is strengthening of the internal capacity of a country; both by addressing structural problems at the institutional realm and knowledge gaps in the technical and planning realm.

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## Chapter 2 : The Upper Santa Cruz River Basin

### 2.1 Introduction

The United States – Mexico border region is beleaguered by problems related to economic poverty and environmental degradation. More than 13 million people live along the border and that number is growing at a rate more than double the national average of either country (Van Schoik, Brown, Lelea, & Conner, 2004). Water supply and sanitation are primary concerns. “In 1999, 12% of the border population did not have access to potable water, 30% lacked access to wastewater treatment facilities and 25% needed access to solid waste disposal facilities... [Moreover,] on the Mexican side of the border only 34% of wastewater is treated” (U.S. General Accounting Office, 2000). A combination of water scarcity, water contamination, and a lack of infrastructure creates enormous public health risks to the border population (GAO 2000). Water is essential both to the economy of the region, which depends on agriculture and industrial manufacturing, and to the border region’s rich eco-systems, which provide habitat for a variety of species and migrating birds

The 2000 mile-long border crosses the political boundaries of two countries, ten states, thirty-five Mexican municipalities, twenty-five US counties, twenty-five Tribal Nations, and fourteen sister city pairs. The three largest river basins include the Colorado River, the Rio Grande, and the Tijuana Rivers. However, thirteen other rivers<sup>19</sup> (EPA 1998) and seventeen groundwater aquifers (Hall, 2004) cross the border. My research focuses one of these rivers and its associated aquifer: the Upper Santa Cruz River Basin (USCRB).

The Upper Santa Cruz River Basin is located in both Arizona and Sonora (Figure 2-1). The headwaters to the river begin near San Rafael, Arizona. The river then flows south, crossing into Mexico and making a 55-kilometer “U” turn, returning to the US just east of Nogales Arizona (Figure 2-2). The USCRB lies within the Sonoran Desert. Precipitation ranges between 280 – 440 mm per year and the area is susceptible to drought (Liverman, Merideth, & Holdsworth, 1997; Morehouse, Carter, & Sprouse, 2000).

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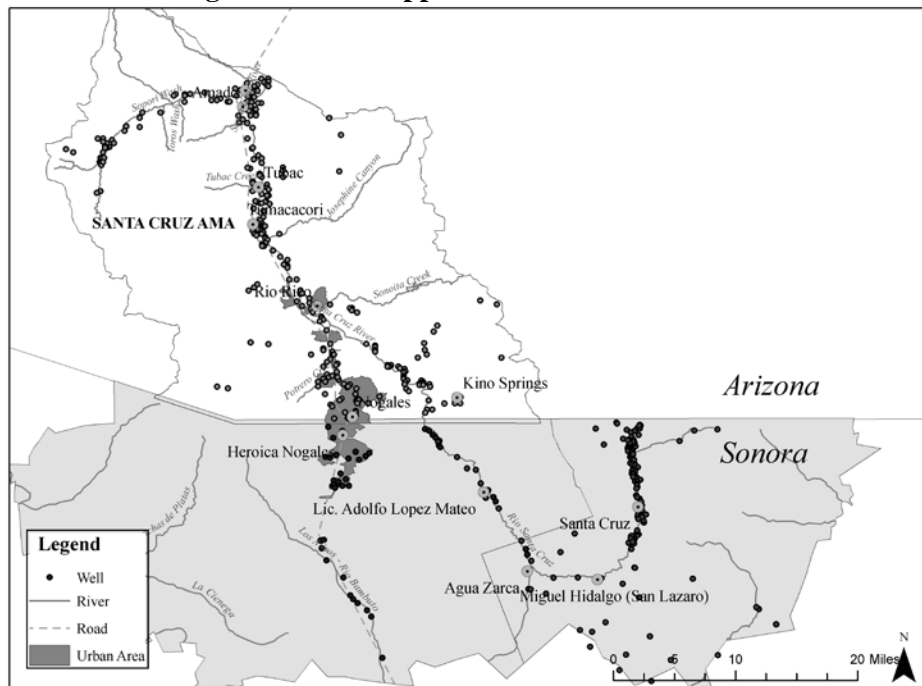
<sup>19</sup> These thirteen rivers include: the New River, the Alamo River, the Gila River, the Santa Cruz River, the San Pedro River, the Rio Yaqui, the Rio Casa Grande, the Rio Conchos, the Pecos River, El Diablo River, the Rio Salado, and the Rio San Juan



**Figure 2-1: Location of the Upper Santa Cruz River Basin**



**Figure 2-2: The Upper Santa Cruz River Basin**



**2.2 Santa Cruz Active Management Area**

I use the Santa Cruz Active Management Area (SCAMA) as my unit of analysis for the Arizona side of the border. The SCAMA was created by the Arizona legislature (Senate Bill 1380) in 1994 as a distinct water management district in an effort to more effectively address the unique

water management concerns of the area (ADWR, 1997). The region encompasses 716 square miles, extending 45 miles north from the border with Mexico, where the river flows north into Arizona, up to the Continental gauging station, just north of the Santa Cruz and Pima County boundary (ADWR, 1999). The SCAMA was selected as the study region both because it is the political boundary for water management activities and because it represents a hydro-geologically distinct region.

The Santa Cruz River Valley traverses the SCAMA, with the Tumacacori Mountains to the west, the San Cayetano and Santa Rita Mountains to the east, Huachuca Mountains to the Southeast, and the Atascosa Mountains to the Southwest. The Santa Cruz River Basin is considered one of the most diverse riparian regions in the Southwestern U.S. (EPA, 1999). At higher elevations, the region is primarily comprised of sage, creosote bush, and greasewood shrubs (Brady, Gray, Castaneda, Bultman, & Bolm, 2002), yet within the riparian corridor there is an array of cottonwoods, willows, and mesquite (EPA, 1999). Wildlife includes a myriad of species of birds, reptiles, and small mammals (T. W. Sprouse, 2005), including seventeen listed and three candidate endangered species (EPA, 1999). The region is also a key migratory corridor for over 400 species of migrating birds (Mabry, 2005)

The first ‘urbanization’ in the region occurred when Padre Kino established a mission in Tumacacori during the late 1600’s. In 1752, the Tubac Presidio was established and soon after Spanish land grants were allocated, encouraging further settlement. Cattle ranching emerged as the main economic enterprise. In 1853, the region became part of the USA through the Gadsden Purchase/Treaty of Mesilla.(Holub, 2001; Mabry, 2005) Since then, the valley has been an important byway for trade between the US and Mexico. In 1882, a railway was completed allowing rapid passage of goods between Hermosillo and Tucson. The train still runs daily, yet trucking has taken over as the main mechanism for transporting goods, with approximately 250,000 trucks crossing the border daily (Federal Motor Carrier Safety Administration, 2001). Sixty percent of all winter produce consumed in the US and Canada pass through the Port of Nogales and is processed and distributed by warehouses in Nogales, Arizona (Santa Cruz County, 2007). Agricultural production within the SCAMA has dramatically declined since the 1970’s, and less than half the acreage previously planted remains in use (ADWR, 1999; Liverman et al., 1997). Primarily forage crops are grown (Liverman et al., 1997; National Agricultural Statistics Service, 2004), as these support the cattle ranching that remains a key element of the region’s economy (Consulate of the United States, n.d.). Growth in the SCAMA has also been sparked by tourism, retirees, and growth in the nearby city of Tucson.

Today the four main population centers within the SCAMA include the City of Nogales, Rio Rico, Tubac, and Amado, and each has its own distinct character. The City of Nogales is the county seat, and the main industrial and commercial center of the SCAMA. Although Nogales, Arizona is home to only approximately 20-25,000 residents, an estimated 30,000 people cross the border everyday for work, shopping, or recreational purposes (ADWR, 1999). Rio Rico encompasses a larger yet more rural residential region. Rio Rico extends approximately 79 miles (ADWR, 1999) and currently contains approximately 6000 housing units. Tubac is a smaller more upscale area, home to approximately 1000 persons, many of whom are retirees and artists. Tubac is located along the most lush part of the riparian corridor and contains houses with larger

yards and fuller landscaping. Amado is the smallest and most rural area and home to only approximately 300 residents.

### 2.2.1 Water Management Concerns in the SCAMA

Water used in the SCAMA is obtained primarily from the Santa Cruz River, its tributaries, and its associated aquifer. The river itself can be characterized as intermittent, yet it maintains several perennial reaches, including the region immediately downstream from the Nogales International Wastewater Treatment Plant (NIWTP). Major tributaries to the river include the Nogales Wash, Potrero Creek, Sonoita Creek, and the Sopor Wash, as well as Peck, Agua Fria, and Josephine Canyons (ADWR, 1999). There is a strong interaction between surface and ground water in the region. The boundary of the SCAMA delineates a change in hydrogeology, as north of the SCAMA boundary, the younger alluvium both broadens and deepens, allowing for greater storage. As the portion of the aquifer within the SCAMA is shallow and relatively narrow, coordinated management of ground and surface waters is needed (ADWR, 1997). More details on the hydrogeology of the region are included in Chapter 6.

Water management concerns in the region include issues related to water supply availability; environmental protection; and water quality. Growth during the past decade has led to questions of how fast and to what extent the population in the SCAMA will increase and whether or not there is sufficient water to meet growing demands. Worries about insufficient supply have increased, as the region experienced a sustained drought between 1996 and 2004 (Goodrich & Ellis, 2006) and scientists are expecting climate change will make the US southwest hotter and drier (Kaufman, 2007). Growth on the Mexican side of the border has sparked fears about the impact Mexican water use will have on Arizona. Water resources evaluations suggest increased pumping from Mexican well fields will negatively impact Arizona water availability, as it will induce recharge from the river on the Mexican side of the border and reduce baseflow across into Arizona. Baseflows are important to sustaining the riparian vegetation and recharging the aquifer on the US side of the border during periods in between floods (ADWR, 1995)

Beyond concerns about the quantity of water available, there are also questions about what the impact of water use will be. The official water management goals of the SCAMA include maintaining safe-yield and preventing local water tables from experiencing long term decline (ADWR, 1997). The intention is to both ensure sustainable water management and to avoid negative localized impacts. Declining water levels could lead to increased pumping costs, land subsidence, damage to the riparian ecosystem, and reduced stream flows. Many residents are also worried about protecting the vibrant riparian corridor, which has recently experienced a large-scale tree die-off (McCoy, 2008). The corridor also provides key habitat to several endangered species, including the gila top minnow, the southwest fly catcher, and the yellow cuckoo (USFWS, Personal Communication, October 12, 2007), which may be at risk if stream flow decreases or vegetative cover declines.

Water quality is another salient issue, as maintaining adequate conveyance and treatment of wastewater has proven challenging.<sup>20</sup> Wastewater from both sides of the border is treated at the

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<sup>20</sup>Groundwater pollution is another issue of concern, as several wells in the Nogales Wash (T. W. Sprouse, 2005) and Potrero and Valle Verde well fields (ADEQ, 2007) have tested positive for tetrachloroethylene. This problem is

Nogales International Wastewater Treatment Plant, located in Rio Rico, Arizona. More than 14 MGD of wastewater crosses the border in a 30” (76 cm) diameter pipe, called the international outfall interceptor (IOI), which is located just below the Nogales Wash, a major tributary to the Santa Cruz River. The IOI is in poor condition and infiltration of storm water combined with sewage flows, exceed the pipe’s capacity. There are frequently small leaks and heavy monsoon floods threaten to rupture the pipe (McCombs, 2007), which would result in a large-scale spill. Spills from the transportation of raw sewage to the treatment plant are only one aspect of water quality concerns of the SCAMA. Peak flows to the NIWTP often exceed its treatment capacity, and when they do, untreated wastewater is forced to by-pass the plant. Even water treated and released as effluent does not meet EPA standards for ammonia concentrations and presents a risk to fish and wildlife downstream from the plant. (T. W. Sprouse, 2005). After the Sierra Club filed a suit against the NIWTP for Clean Water Act violations in March 2000, a court decree required the plant comply with water quality standards by 2004 or face fines (Gelt, 2006). Additional penalties could be imposed by the Arizona Department of Environmental Quality (ADEQ) if the NIWTP fails to comply with standards as part of the Aquifer Protection Permitting Program (T.W. Sprouse & Villalba Atondo, 2004).

### **2.3 The Mexican Portion of the Basin**

The unit of analysis for the Mexican portion of the basin includes the portion of the municipalities of Heroica Nogales (here after referred to as Nogales, Sonora or Nogales, SO) and Santa Cruz that fall within the Santa Cruz River Basin. I include in the analysis the entire urban center of Nogales, SO (here after referred to as the city of Heroica Nogales, to distinguish it from the City of Nogales, Arizona and from when I refer to the entire municipality of Nogales, SO). This area is designated by the Mexican National Water Commission (CONAGUA) as part of the “Region II: Northwest” (Commission Nacional del Agua, n.d.; Padilla, 2005) and also forms part of the CONAGUA’s Colorado River Basin management region. Geographically, not all of the city of Heroica Nogales falls within the Santa Cruz River Basin; nonetheless, the entire city is included in the analysis because the city is the largest, most influential, and fastest growing consumer of water in the basin. Moreover, the entire city has an impact on transboundary flows of water, as water planning occurs at the municipal level, and as all wastewater generated in the city, regardless of its source, currently flows across the border to be treated at the NIWTP.

The “U” of the Santa Cruz River Valley as it passes through Mexico, begins north of the municipality of Santa Cruz, and then passes between the San Antonio and Chivato mountain ranges, and crossing west into the municipality of Nogales, and then heads north between the Pinito and San Antonio mountains. Vegetation and fauna are similar to SCAMA, although as can be seen through personal observation as well as satellite and aerial images (USGS, 2008) the region is noticeably dustier and has less vegetation.

The history and development of Nogales and Santa Cruz, Sonora, diverges from SCAMA following the Gadsden Purchase (U.S. Department of State, n.d.) . While within the US, the industrial revolution, western migration and settlement were occurring, Mexico experienced political instabilities and a series of revolutions (Suarez Barnett, n.d.) . Despite this, trade

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related to the dumping of industrial chemicals and solvents and, as it is only indirectly related to water quantity concerns, is beyond the scope of my analysis.

continued to increase between Sonora and Arizona. In the mid-1930's, as part of Cardenista land reforms, ejidos (cooperative land holdings) were established in Santa Cruz and Nogales. The 1960's sparked a period of rapid industrialization along the Mexican border, including the formation of maquiladoras. Today the region retains both its ranching roots and this industrial focus. Agriculture in both the municipalities of Nogales and Santa Cruz is dominated by cattle ranching, although in Santa Cruz, half the agricultural land pertains to small proprietors and ejidatarios, who grow vegetables, beans, and corn. Santa Cruz has little to no industry and limited commercial enterprises, however; maquiladoras (industrial manufacturing and assembly plants that produce goods for export) drive the Nogales economy. In 2007, there were 92 maquiladoras in Nogales, SO (Gobierno del Estado de Sonora, n.d.). Basic goods and services, and cross border tourism (primarily night clubs and crafts sales) also contribute to the economy. Another key element, often not officially discussed, is the presence of "guests", or persons in transit while planning to attempt an illegal border crossing or who have been deported from Arizona and not yet left the city.

The main population centers include the city of Heroica Nogales, the town of Santa Cruz, and several ejidos. As mentioned previously, the city of Heroica Nogales is the largest urban center in the region. The 2000 official census cited the population as 156,854, although as will be discussed in the section on water needs, the true number is expected to be much higher. The city is urban and growing rapidly, as more housing, industry, strip malls, and businesses are established. Conversely, the town of Santa Cruz is quite small, containing no more than six local stores. The 2000 census reported the official population of Santa Cruz as 911 persons. There are 6 ejidos in Nogales, SO and 8 in Santa Cruz, SO, with populations ranging from 20 to 100 persons each (SAGARPA, 2006)<sup>21</sup>

### 2.3.1 Water Management Concerns in Mexico

The Santa Cruz River crosses into Mexico's municipality of Santa Cruz, Sonora, just south of the USGS Lochiel Stream Gage in San Rafael, Arizona. The river then flows south, between the San Antonio and El Chivato mountain ranges, passing by the town of Santa Cruz. It bends west near Miguel de Hidalgo/Cañada de Arizpe and then turns northwards near Agua Zarca. The river crosses into Arizona at the Buena Vista Ranch, east of the City of Nogales, Arizona. The CONAGUA classifies the river as a perennial; however, with the exception of the reach that runs through Parque Mascareñas, which continuously has water, the river bed is frequently dry. There are no major tributaries to the river, yet a number of ephemeral streams are formed in canyons leading to the river.<sup>22</sup>

The Santa Cruz River and its associated aquifer are the primary source of water for the town of Santa Cruz and the ejidos, and supply a large percentage (40% in 2006)<sup>23</sup> of the water used by the city of Heroica Nogales (COAPAES, 2005). Water is extracted from both shallow and deep

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<sup>21</sup> Ejidos in the municipality of Nogales include Cibuta, La Arizona, F.M. Cardenas Valdez, Mascarenas, Centauro de la Frontera, and Adolfo Lopez Mateos. Ejidos in the municipality of Santa Cruz include Miguel Hidalgo, Quitovaca, San Fernando, San Antonio, Zorrilla, El Desahije, El Burro, El Cajoncito.

<sup>22</sup> These include: Zorrilla, La tinaja, La Parrilla, Agua Zarca, Las La Callera, Las Jacalomes, El Pilar, La Escondida, La Avispas, La Galera, La Capilla, San Luis.

<sup>23</sup> Other sources of water for the city of Heroica Nogales include the Los Alisos river basin, located to the southwest of the city, and several lower yield wells located in the Nogales Wash, a tributary to the Santa Cruz which runs through the center of town.

wells and from an infiltration gallery located along riverbed. During the summer dry season, wells can run dry, and throughout the year, the city of Heroica Nogales has difficulty supplying its citizens with water. The municipal run water utility for Heroica Nogales, the Organismo Operador Municipal de Agua Potable, Alcantarillado, y Saneamiento (OOMAPAS) reported that in 2007, only 87% of the urban population had access to piped water ( OOMAPAS, Personal Communication, October 4, 2007), this includes two colonias that do not have potable water or sewerage connections. Of those with piped water, 5% receive service 24 hrs/day, 60% receive service 12 hrs per day, 30% receive service 4-5 hrs per day, and the remaining 5% receive water every other day. The city expects it will need at least 600 lps more to meet current water needs and provide daily (but not 24-hr) water service to all of its residents (OOMAPAS, Personal Communication, July 14, 2005). As the city is growing at a rate of 4.3% per year (Ayuntamiento de Nogales, Personal Communication, October 2007), more water will be required to accommodate expected future growth.

Ensuring water quality<sup>24</sup>, and especially the conveyance and treatment of wastewater, is another water management challenge faced by the city of Heroica Nogales. The existing wastewater collection system, which in 2006, only served 80.2% of the city's population (BECC, 2004, n.d.; BECC/COCEF, 2006), is aging and in need of major repairs. Existing pipes have outlived their useful service life and often contain holes or cracks which allow for infiltration of rain and ground water. The pipe network simultaneously serves as a pluvial and sewage drainage system. The combination of infiltration, rainwater, and wastewater frequently exceeds the capacity of the pipes. Sediment build-up and other blockages exacerbate the situation, causing pipes to break and raw sewage to spills throughout the city and, in particular, into the Nogales Wash, which flows into Arizona.

In addition to wastewater conveyance problems, Mexico's capacity to treat the wastewater generated is limited. Due to primarily to infiltration of rain and groundwater into the sewer conveyance pipes, but also urban growth, flows of wastewater often exceed Mexico's allotted treatment at the NIWTP. When the combined peak flows from the SCAMA and Mexico exceed the treatment plant's capacity, a portion of the raw wastewater by-passes the plant and is released directly into the river. Growth is expected to continue, especially towards the south of the city, thus in order to extend wastewater collection and treatment services to the entire city, additional wastewater treatment capacity will be needed.

Lastly, flooding during the monsoon season is also a major concern for water managers in the city of Heroica Nogales. The city is located on steep terrain and many streets were constructed along natural run-off channels and arroyos. Development, including paving and cementing walkways and roads, has served to decrease natural infiltration processes. As a result, heavy monsoon rains frequently cause landslides and flooding, damaging houses and businesses, impeding transportation, and at time resulting in human deaths (USGS, 2007). Beyond direct damage to the city and its residents, flooding also threatens to destroy the IOI, which would

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<sup>24</sup> Bacteriological pollution associated with deficiencies in the municipal sewerage system and chemical pollution related to industrial discharges and illegal dumping are water quality problems the city of Heroica Nogales. High contaminant levels of tetrachloroethylene and other toxics have been found in some wells (Sanchez, 1995). Although these are salient issues, I do not address them in my analysis, as currently they do not have an impact on water quantity concerns in the region.

dump thousands of gallons of sewage into the Nogales Wash (Coppola, 2008; McCombs, 2007; Swedlund, 2008). The city has contracted with the US Corps of Engineers to conduct feasibility studies for retention dams which it hopes could help prevent future flooding (Ayuntamiento de Nogales, Personal Communication, October 2007).

## 2.4 **Transboundary Water Management Strategies**

A variety of activities might be undertaken by either or both sides of the border in order to address the three primary water concerns of the region: treatment of wastewater, supply availability, and non-consumptive water uses.<sup>25</sup> These three issues are inter-related<sup>26</sup> and solutions to these problems need to take into consideration their connections. Four possible strategies, based on scenarios presented in the Ambos Nogales Facility Plan (Camp Dresser & McGee, 1997), articles written about the region (Holub, 2001; T. W. Sprouse, 2003), and key informant interviews, are listed in Table 2-1. I selected these four strategies for analysis based on their salience in discussions in the region and their usefulness in examining how the physical and institutional environment impacts the each country’s approach to its transboundary ground and waste waters. The strategies do not represent the full possible range of water management activities and this discussion is not meant to be a normative statement regarding what strategies should be implemented in the region.

**Table 2-1: Four Possible Water Management Strategies**

Activity	Potential Benefits
Mexican wastewater used to recharge aquifer in the US	increase available supply, maintain instream flows, maintain water table levels
Mexican wastewater used to recharge aquifer in Mexico	increase available supply, maintain instream flows, maintain water table levels
Potable water provided from US wells to Mexico	reduce need for Mexican groundwater abstractions
Restrictions on groundwater abstractions	prevent drawdown of water table, maintain instream flows

### 2.4.1 Wastewater Treatment and Aquifer Recharge

The first two scenarios refer to using treated wastewater to recharge the aquifer. Due to the hydrology of the region, other renewable water sources are not available; thus wastewater is seen as the most accessible opportunity to augment water supply. As mentioned previously, wastewater from both sides of the border is currently treated at the Nogales International Wastewater Treatment Plant (NIWTP), located in Rio Rico, Arizona.<sup>27</sup> The plant is jointly owned by the City of Nogales, Arizona and the International Boundary and Waters Commission

<sup>25</sup> Flood prevention and water quality concerns are also important, yet a discussion of these is beyond the scope of this analysis.

<sup>26</sup> Released effluent (treated wastewater) can be used directly to meet water needs (as instream flows or directly applied as irrigation water, for example at golf courses) or indirectly as a source of recharge to the aquifer (providing water for future abstraction and maintaining water table levels). Moreover, water abstractions impact the water table level, and thus influence pumping costs, instream flows, and riparian vegetation.

<sup>27</sup> The NIWTP, built in 1951 but since upgraded, was constructed in Arizona because locating the plant in Arizona was more cost effective (the topography of the region is such that Arizona is located downhill) (T.W. Sprouse & Villalba Atondo, 2004)

(IBWC).<sup>28</sup> The treatment capacity of the plant is 17.2 MGD, of which 9.9 MGD capacity is allocated to Mexico (as per Minute 276 of the 1944 Treaty)<sup>29</sup> and 7.3 MGD is allocated to the City of Nogales, Arizona (IBWC, Personal Communication, June 14, 2006; IBWC, 1988).<sup>30</sup>

Currently, treated wastewater (effluent) from the NIWTP is released into the Santa Cruz River, near Rio Rico, Arizona. Flows of wastewater from Mexico often exceeded Mexico's allotted capacity,<sup>31</sup> and, when the combined peak flows from the SCAMA and Mexico exceed the total plant capacity, untreated wastewater must by-pass the plant and enters the river untreated.<sup>32</sup> Complicating the issue is that effluent released from the NIWTP does not comply with EPA water quality standards for nitrate and ammonia (EPA, 2008), and thus the plant is out of compliance with both the Clean Water Act and with ADEQ Aquifer Protection Program. As a result, two problems need to be addressed simultaneously: the capacity to treat wastewater in the region needs to be increased and, in order to meet US standards, the degree to which wastewater is treated needs to be augmented.

Several plans<sup>33</sup> have been proposed to address jointly the issue of treatment capacity and effluent quality including various combinations of upgrading the existing NIWTP, expanding the capacity of the existing NIWTP, and building a separate wastewater treatment plant to be located in Mexico.<sup>34</sup> Not only have proposals included plans for construction of wastewater treatment infrastructure, they also included schemes that would shift rights, responsibilities, and control over the treated wastewater. A diagram of the possible uses of the effluent to is included in Figure 2-3.

Mexico has the right to reclaim its portion of the treated water or to stop sending wastewater across the border at any time (IBWC, 1967). However, the SCAMA would benefit from continued flow of Mexican wastewater. The quantity of wastewater that originates in Mexico is substantial, equivalent to 58% of SCAMA municipal, industrial and agricultural demands (ADWR, 1999) or 38% of the renewable supplies in the SCAMA (T.W. Sprouse & Villalba Atondo, 2004). Without recharge from Mexican effluent, demand for water in Nogales, AZ would exceed supply by 7000 acre-feet per year (Sprouse 2003). As the tenure of Mexican effluent from the plant is insecure, Arizona law (A.R.S. § 45-576) limits the use of Mexico's portion of the effluent (T.W. Sprouse & Villalba Atondo, 2004). Additionally, the released

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<sup>28</sup> The City of Nogales owns 42.5% of the NIWTP and the USIBWC owns the remaining 57.5% (Holub, 2001)

<sup>29</sup> As is discussed in more detail in Chapter 5, water management along the US-Mexico border is governed by the 1944 Treaty on the Waters of the Colorado, Rio Grande and Tijuana Rivers. Addendums (in the form of Minutes) to treaty extend the responsibilities and commitments of both countries to issues beyond those originally included in the treaty. See [www.ibwc.state.gov](http://www.ibwc.state.gov) for more information.

<sup>30</sup> As the City of Nogales, Arizona does not currently occupy its entire treatment allotment, it currently rents part of its treatment capacity to Rio Rico.

<sup>31</sup> Between 2000 and 2007, flows of wastewater to the NIWTP originating in Mexico exceeded treaty limits in 2000, 2003, 2005, and 2006 ( IBWC, Personal Communication, December 17, 2007).

<sup>32</sup> Although the NIWTP capacity is rated at 17.2 MGD, during storm events, discharge to the treatment plant can reach 30 MGD ( IBWC, Personal Communication, June 14, 2006).

<sup>33</sup> For a comprehensive discussion on many of these proposals refer to (Camp Dresser & McGee, 1997; Holub, 2001; T. W. Sprouse, 2003; T.W. Sprouse & Villalba Atondo, 2004).

<sup>34</sup> These options represent the proposals that received the most attention. Other proposals have been made, including using the NIWTP to treat only Mexican wastewater and to build a separate treatment plant in Arizona for Arizona wastewater (Camp Dresser & McGee, 1997).



effluent forms part of a vibrant riparian corridor in Arizona, which provides habitat to a number of endangered species (T.W. Sprouse & Villalba Atondo, 2004).

One proposal that would allow the effluent to be used in SCAMA would be if Mexico signed a forbearance lease with the US,<sup>35</sup> through which the US would pay a monetary fee in exchange for a secure right to use the effluent for a specified amount of time. Another proposal suggests a portion of the Mexican effluent could be used for cooling in a power plant, which would be built in Arizona yet provide the electricity to Mexico (at a fee). If this were to occur, the power plant would pay the costs associated with treating the portion of Mexican wastewater it uses (Holub, 2001; T.W. Sprouse & Villalba Atondo, 2004). Yet other proposals suggest use of the effluent for aquifer recharge, either in Arizona or in Mexico (Camp Dresser & McGee, 1997; T. W. Sprouse, 2005). If the wastewater is used to recharge the aquifer in the southern end of the SCAMA, some portion of the recovered water might be piped across the border to Mexico, which may be a more effective mechanism for Mexico to make use of its effluent than piping treated or untreated wastewater back to Mexico for aquifer recharge.

Alternatively, Mexico may instead choose to directly reclaim its share of the treated wastewater or to stop sending wastewater across the border for treatment. Since 2006, Mexico has been in the process of designing a new treatment plant, in the Los Alisos Basin (PTAR Los Alisos). This new treatment plant is being designed to treat waste water originating from the southern end of the municipality of Heroica Nogales, which falls in the Los Alisos Basin, but also to treat wastewater flows in excess of the capacity allocated to Mexico. PTAR Los Alisos could also be used to treat part of the 9.9 MGD of Mexican origin wastewater that is currently treated to the NIWTP. Mexican authorities are considering either selling the effluent released from PTAR Los Alisos for use in nearby greenhouses or using the effluent to recharge the aquifer near well fields in Los Alisos (OOMAPAS, Personal Communication, September 22, 2007).<sup>36</sup> The benefit to Mexico of such a scenario is it would increase the availability of supplies in Mexico; the benefit to Arizona is it might reduce the quantity of water Mexico extracts in the Santa Cruz Aquifer.

When I began my preliminary field research in 2005, a plan for addressing wastewater treatment and aquifer recharge in the region had not been settled on. Although options had been discussed since pre-1995 (Camp Dresser & McGee, 1997), talks had stalled, mostly due to disagreements related to funding (both O&M and capital costs),<sup>37</sup> plant capacity,<sup>38</sup> treatment standards,<sup>39</sup> and

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<sup>35</sup> The possibility of signing a forbearance lease is alternately on and off the agenda. Sprouse (2005), Holub (2001) and Pranschke & MacNish (2002), along with officials from ADWR and all mention the possibility. I was told that during the summer of 2005, Mexico was in the process of setting a price for this forbearance ( CILA, Personal Communication, July 2005); yet more recent interviews (CEAS, Personal Communication, October 8, 2007; ADWR, Personal Communication, October 3, 2007) indicate it is not currently under consideration.

<sup>36</sup> During an interview with an upper level manager at OOMAPAS, I was told that water released from PTAR Los Alisos would recharge the Nogales Wash aquifer. Although this comment does not seem to match hydrogeologic data (see Chapter 5), it does serve to indicate the high degree of uncertainty within OOMAPAS about flows of water in the region.

<sup>37</sup> Although capital costs will be paid out of the EPA Border Environmental Infrastructure fund, there were concerns about who would pay the increased operations costs associated with any upgrade to the NIWTP (Gelt, 2006) .

<sup>38</sup> Mexico is concerned that expanding the capacity of the NIWTP would enable the US to take more of Mexico's wastewater, whereas building a plant in Mexico allows Mexico to keep water in Mexico. Arizona feared that if

use of the treated effluent (Gelt, 2006). However, in 2006, a plan was settled upon, which included upgrading the existing NIWTP to meet EPA water quality standards. The upgraded treatment plant will have the capacity to treat 14.7 MGD.<sup>40</sup> A second treatment plant, with the capacity to treat 434 lps (9.9 MGD),<sup>41</sup> will be constructed in the Los Alisos Basin<sup>42</sup> in Mexico (the above mentioned PTAR Los Alisos)<sup>43</sup> (OOMAPAS, Personal Communication, May 30, 2006). Doubts remain as to how long it will take to construct the treatment plant in Mexico, if the infrastructure will be constructed adequately enough to lift the wastewater over the topographic divide into the Los Alisos Basin, and how much of the wastewater will actually be conveyed to Mexico.

Although, actions are being taken to address the wastewater management problems in the basin, these actions will not fully address all aspects of the problem. As PTAR Los Alisos is still being designed, it is unclear what its treatment capacity will be and if this will be sufficient to meet treatment needs.<sup>44</sup> The current plans for upgrading the NIWTP and building PTAR Los Alisos also do not address the issue of increasing demands for water in Mexico, possibilities for reuse of treated wastewaters, and the impact of Mexico's water management strategies on Arizona. Part of the rationale for building PTAR Los Alisos is to keep water in Mexico so that it can be used by Nogales, Sonora (CILA, Personal Communication, June 6, 2007; OOMAPAS, June 28, 2006; OOMAPAS, Personal Communication, June 1, 2006; CEAS, Personal Communication, October

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treatment capacity is not increased but flows of Mexican wastewater exceed the allocated limits, Arizona itself will lose its allotted treatment capacity. (Gelt, 2006)

<sup>39</sup> Wastewater treatment standards are more stringent in the United States than in Mexico. Thus Mexico was unwilling to pay the costs of treating the water beyond Mexican standards.

<sup>40</sup> Although nominally the plant's capacity is 14.7 MGD, in actuality it will be capable of treating up to 15.2 MGD (NADBANK, Personal Communication, May 31, 2006). Allocation is 9.9 mgd to Mexico, 4.1 mgd to the City of Nogales .74 mgd (740,000 gallons per day) to Rio Rico Utilities (Coppola, 2006). "The project includes decommissioning of the existing detritors and their replacement with vortex grit tanks, 6 millimeter screens downstream of the existing 25 millimeter coarse screens, biofilters for plant wide odor control, and three secondary process trains for nitrification and denitrification. (Stantec, 2008).

<sup>41</sup> Separate documents and interviews cite different planned capacities for the Los Alisos wastewater treatment plant. The head of wastewater planning at OOMAPAS (Personal Communication, May 30, 2006), said they planned to build a plant of modular design, so that capacity could be added over time. He said they are planning for 5 modules capable of treating 125 lps each, which would reach a total maximum capacity of 625 lps. However, a powerpoint presentation that included information on the expected production of wastewater in the city, given in May 2006, stipulates that the treatment plant capacity will be 434 lps. A separate presentation, in October 2006, regarding the costs of the wastewater treatment system (including lift stations etc) states the initial capacity of the plant with be 320 lps. I cite the 434 lps value, as that is the combined capacity of the two lift stations that have been designed to convey wastewater to new treatment plant in the Los Alisos basin.

<sup>42</sup> The Los Alisos river basin is located to the South of the City of Nogales. As mentioned previously, Heroica Nogales obtains approximately 40% of its water supply from this basin. Although the river extends into the municipality of Magdalena, the Heroica Nogales well field is and the new wastewater treatment plant will be located within the boundaries of the municipality of Heroica Nogales.

<sup>43</sup> PTAR stands for Planta de Tratamiento de Aguas Residuales, which is Spanish for wastewater treatment plant.

<sup>44</sup> As is discussed in the Chapter 3 section on 'water needs', engineering designs in Mexico are required to use official statistics for design purposes. Given uncertainty regarding the true population in Nogales, Sonora, the treatment plant may not have the capacity to meet the full needs of the population. Moreover, as the current plan is to divert all wastewaters produced south of a specific point in the city, if growth occurs in different pattern than planned, they may be unable to capture the wastewater from this zone and send it to the new treatment plant in Los Alisos. This issue is especially important, due to the topography of the region, a great deal of pumping is required to capture wastewater flows and send them to the Los Alisos basin.

8, 2007). Yet studies on the recharge capacity of the area have not been conducted<sup>45</sup> and thus it may not be physically possible for the Nogales, Sonora to reclaim or reuse this water. Furthermore, there is some indication PTAR Los Alisos might be built with a greater than current excess flows to the NIWTP.<sup>46</sup> Thus, once built, Mexico may choose to decrease the quantity of wastewater it sends to the NIWTP, decreasing the amount of effluent available in Arizona. In Chapter 8, I analyze in greater detail factors influencing the decision to upgrade the existing NIWTP without increasing its capacity and to build a new wastewater treatment plant in Mexico.

#### 2.4.2 Water Diversions and Abstractions

Both sides of the border are concerned about their ability to meet growing demands, in what is in reality, a resource limited environment.<sup>47</sup> The interconnections between both sides of the border, create possibilities for both sides to gain through cooperation. Due to the hydrogeology of the aquifer, pumping restrictions in the SCAMA would be unlikely to impact water availability and flows in Mexico; however, it is thought that groundwater abstractions in Mexico impact the availability of water in Arizona.<sup>48</sup> None-the-less, there is likely some synergy to be found in collaborative management as Mexican well fields tend to dry more frequently than those in the SCAMA while underflow and stream flow into Arizona is closely tied to water usage in Mexico.

Collaborative planning of groundwater abstractions or surface water diversions in the region are not currently on the agenda.<sup>49</sup> Rather, each side is acting unilaterally to manage its own surface

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<sup>45</sup> The Ambos Nogales Facility Plan (Camp Dresser & McGee, 1997), a study was developed for the IBWC which considers options for wastewater treatment and recharge in both Arizona and Sonora, is the only study to date that explores possibilities for recharge in the Los Alisos region. Neither the CONAGUA nor OOMAPAS have conducted their own studies (OOMAPAS, Personal Communication, June 1, 2006; CILA, June 16, 2006; OOMAPAS, Personal Communication, September 21, 2007). Furthermore, even the Facility Plan itself includes the caveat that it is based on literature reviews and does not include sufficient empirical data to be considered a complete recharge study (Camp Dresser & McGee, 1997).

<sup>46</sup> Refer to footnote 41.

<sup>47</sup> On average, approximately 392 Mm<sup>3</sup> precipitation for the Mexican portion of the basin, given the high evapotranspiration rate, it is expected that only 3-8% of precipitation (12-31Mm<sup>3</sup>) reaches the aquifer as recharge (see Chapter 6). Assuming each person uses 173 liters per day (see Appendix B) this would provide enough water for between 186,000 and 457,000 persons. Given the population of the city of Heroica Nogales, Sonora is already expected to be between 195,000 and 350,000 (see Chapter 3), this indicates that Nogales, Sonora already faces water restrictions and must draw from other water sources.

<sup>48</sup> For more information, see Chapter 4. As the river crosses into Arizona from Mexico, outcrops of the Nogales Formation or bedrock constrictions have formed into pockets known as microbasins, which act as mini-storage basins. These microbasins have limited hydraulic conductivity, and at their edges, force groundwater to the surface *Erwin, 2007* (Geologist, Personal Communication, October 13, 2007). The microbasin formations at the southern end of are thought to be barriers to underflow between the Arizona and Mexico. None-the-less, pumping in Mexico can reduce streamflow, which is key to recharge of the micro-basins on the Arizona side of the border (ADWR, 1995). Moreover, there is a high degree of uncertainty regarding fractures within in Nogales formation and little information on the presence of vertical flow/gradients.

<sup>49</sup> Informal cooperation (i.e., actions that are not officially sanctioned by the federal government) already exists between the City of Nogales, Arizona and the City of Heroica Nogales, Sonora. During periods of drought, Arizona has historically supplied water across the border to Sonora via tankers, pipes, and hoses (H Ayuntamiento de Nogales Sonora, 2005; T. W. Sprouse, 2005). However, these are short-term arrangements to address emergencies, which are not officially recognized by the national government of either country, and thus they are not long-term or permanent agreements.

and groundwater resources.<sup>50</sup> Currently both sides of the border already restrict groundwater use; however, those restrictions are not designed to reduce cross-border impacts of water use and those restrictions are not absolute.<sup>51</sup> None-the-less, an informal agreement has been reached such that Nogales, Sonora will notify Nogales, Arizona if plans to drill additional wells in the Santa Cruz aquifer (CILA, Personal Communication, October 2, 2007).

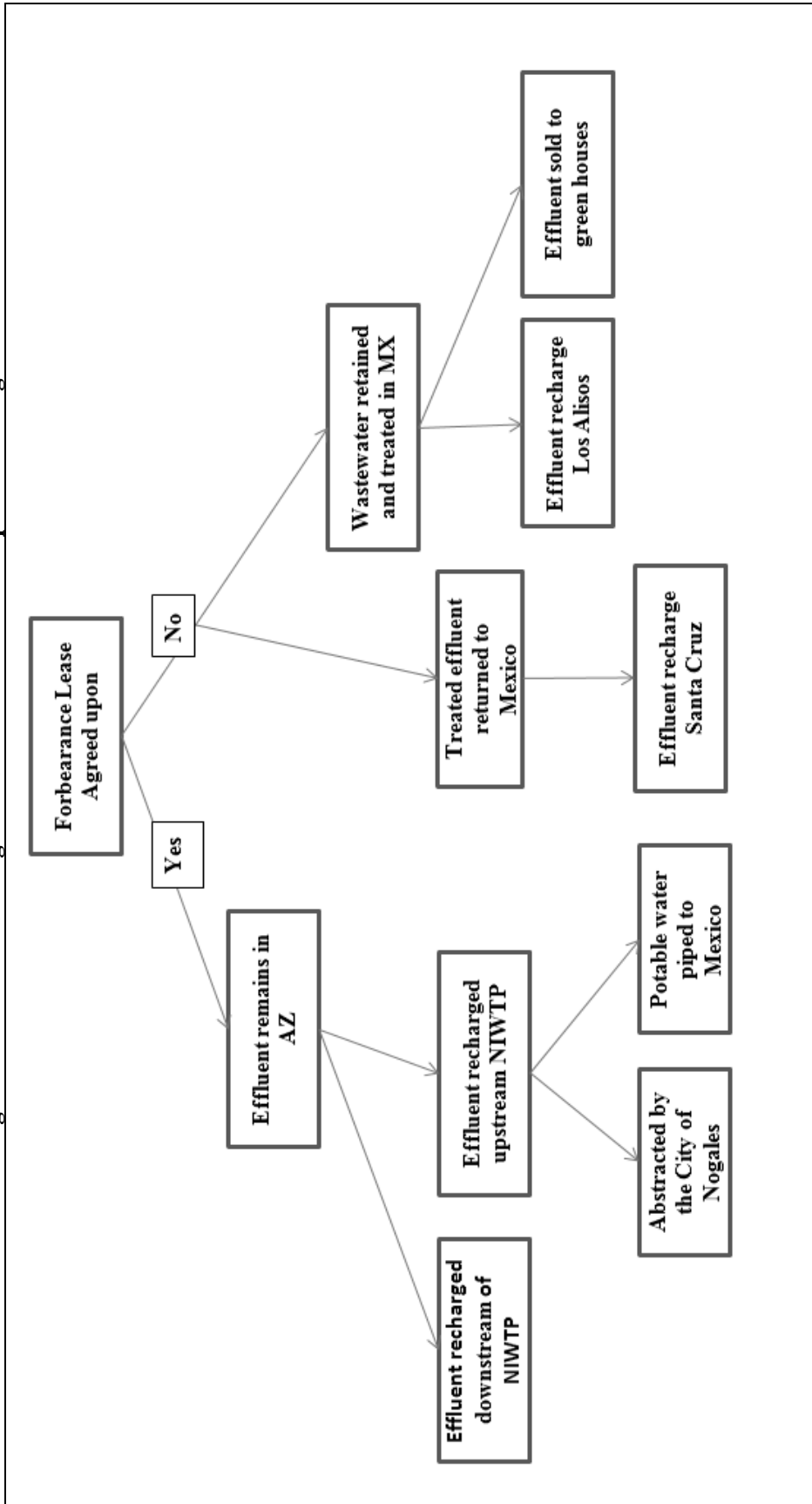
Discussions on cooperative planning or management of the aquifer and surface water resources are not part of the discourse in part, as is discussed in Chapter 4, because each side of the border holds diverging views regarding the availability of water and the impact of water use, and in part, as is discussed in Chapter 8, because each side of the border holds a different ‘ethos’ of water.

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<sup>50</sup> In Arizona, the SCAMA continues to define its management goals and to refine definitions of safe yield and stable water levels. Progress is also being made in efforts to adjudicate surface water rights ( lawyer, Personal Communication October 19, 2006; Mark Larkin, lawyer and water rights owner, Personal Communication October 5, 2008; ADWR, Personal Communication October 5, 2008) and studies seeking additional water supply have been implemented (Pranschke & MacNish, 2002; ADWR, Personal Communication, September 21, 2006). Concurrently in Sonora, plans are in place to increase both groundwater abstractions and surface water diversions. OOMAPAS plans to drill 12-14 new wells along the Santa Cruz River and to construct an infiltration gallery in Canyon Mariposa ( OOMAPAS, Personal Communication, June 1, 2006)

<sup>51</sup> Groundwater abstractions in the SCAMA are regulated by the Arizona Groundwater Code, which includes a controlled system of water rights, restrictions on the issuance of new water rights, and conservation requirements. On the Mexican side of the border, the “zona de veda” designation is designed to allow the CONAGUA to protect the aquifer from over-exploitation by controlling the volume of water concessioned.

Figure 2-3: Possible Strategies to Use the Effluent for Aquifer Recharge



## 2.5 Synthesis

In summary, both sides of the border are concerned about water availability and the treatment of wastewater. A number of water management strategies could be used to address these concerns, some of which might take advantage of synergies in the water supply and treatment needs of both countries. Currently, discussions over joint management strategies to improve supply availability are not on the agenda. However, plans are being made to upgrade the NIWTP and to construct an additional wastewater treatment plant in the Los Alisos basin, in Nogales, Sonora.

Given management decisions are already in process, the goal of my work is not to influence the decision making process. Rather, using the above described water management concerns and possible water management activities as a backdrop, I look to understand how the US and Mexico might evaluate management strategies and factors that influence which approach each adopts. The next three chapters present my analysis of how well each side of the border knows what utility it will derive from adopting a given water management strategy and how uncertainty regarding the costs and benefits of policies impacts the decision making process.

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## Chapter 3 : Contested Visions, Unknown Needs and Values

### 3.1 Introduction

Scholars of conflict and cooperation over transboundary waters usually make the assumption that countries negotiating over internationally shared waters have a clear picture of what is at stake. In other words, there exists the implicit assumption that each country has well defined objectives and knows the utility that can be derived from possible water management strategies. This assumption is evidenced in the widespread endorsement of economic principles such as the adoption of a pareto optimal management strategy or the use of benefit sharing as mechanisms for promoting cooperation over shared water resources (Dombrowsky, 2007; Ganoulis, Duckstein, Literathy, & Bogardi, 1996; Jarvis, 2008; Phillips & Jagerskog, 2006; P. Rogers, 1993; Peter Rogers, 1997; Sadoff & Grey, 2005; Wolf, 2007). It is also a primary assumption of most game-theoretic analyses.<sup>52</sup> Yet my research in the USCRB leads me to challenge this assumption, because, as I will make clear throughout the next several chapters (3, 4, 5, & 6), neither the US nor Mexico has a complete understanding of what it stands to gain or lose through cooperation or non-cooperation. Rather, a high degree of uncertainty exists with respect to the availability of water, the costs and benefits of alternate water management strategies, and each country's overall objectives.

Water resources issues are frequently characterized by uncertainty (Dewulf, Craps, Bouwen, Taillieu, & Pahl-Wostl, 2005; Lund, 1991; Raadgever, Mostert, Kranz, Interwies, & Timmerman, 2008; Warner, Wester, & Bolding, 2008); and I shall subsequently argue that, because ground and waste water resources have very different physical characteristics and are governed quite differently from surface water resources, this uncertainty is even greater for those resources. Few, if any studies, explicitly address the role of uncertainty in the joint management of transboundary waters.<sup>53</sup> Uncertainty related to the inherent variability and incomplete knowledge of water availability, ill-defined management objectives, complex utility functions, or

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<sup>52</sup> In general, game theoretic studies of transboundary waters use either attempt to determine if a cooperative solution (Nash equilibrium, core, Shapley Value) exists (Eleftheriadou & Mylopoulos, 2008; Fernandez, 2006; Frey, 1993; Küçükmehtemoglu & Guldmann, 2005; Netanyahu, Just, & Horowitz, 1998) or analyze how the structure of the bargaining influence negotiations (Barrett, 1994; Dombrowsky, 2007; Frisvold & Caswell, 2000). Game theoretic approaches to international negotiations over water are critiqued because they assume countries have perfect knowledge of both their own payoffs and those of their co-riparian (Frey, 1993; Jonsson, 1983). The role of strategic and analytic uncertainty has been incorporated into game theoretic studies of international negotiations (Iida, 1993); studies of transboundary waters overlook these uncertainties. Yet, as Just and Netanyahu (2004) explain, in most cases there is not enough empirical analysis to assess payoffs, especially where problems are highly political and the available estimates are subject to controversy. Consequently, with the exception of Küçükmehtemoglu (2005) and Eleftheriadou (2008) who use linear programming and consider only benefits from productive sectors such as agriculture, hydroelectric power, and either fisheries or municipal use, most game theoretic studies of transboundary waters assume illustrative payoff matrices rather than using actual values of costs and benefits.

<sup>53</sup> When uncertainty is considered in the transboundary water management literature, it is mainly addressed in the context of ambiguity in agreements (I. Fischhendler, 2008) or climate change (Draper & Kundell, 2007; Itay Fischhendler, 2004). Carraro (2007, pp 345) concludes that "what is still missing in the literature is a negotiation model that considers incomplete information over the resource itself. Water resources are intrinsically unpredictable, and wide fluctuations in water availability are likely to become even more severe over the years." I argue, that not only has water resources uncertainty been left out of the literature, but uncertainty regarding water management goals, water demands, and preferences also has yet to be considered.

jurisdictional authority is left out of analyses. Yet these uncertainties are key characteristics of transboundary waters, especially ground and waste waters, and my research shows they impede the formation of joint water management strategies. My findings are supported by LeMarquand (1976, pp 901) who explains that countries lacking a complete understanding of the outcomes of water management alternatives may be reluctant to enter an agreement and by Underdal (1983) who discusses how uncertainty, in any realm, not just water resources, can lead to negotiation failure.

Throughout the next several chapters, I explain in more detail the nature and causes of uncertainty in transboundary water management in the USCRB and the implications of it for cooperative management of transboundary aquifers and flows of wastewater. My goal is to make explicit that, in the USCRB, management decisions are being made without a full understanding of the costs and benefits at stake. Through my analysis I contribute to the literature on transboundary waters by re-grounding it in the realities of water management and by calling to attention the features of ground and waste waters which serve to increase uncertainty, thus making it especially important to decision making processes.

Surface, ground, and waste water resources have distinct physical and management characteristics, differences, an in-depth comparison of which is included in Appendix A. To summarize briefly, the availability of and impact of use of ground waters is more uncertain than that of surface water, in part because groundwater flows are multi-directional and responses to stresses on the system (withdrawals or recharge) are non-linear. The physically decentralized nature of access and control of groundwater adds to these uncertainties, as it inhibits monitoring and enforcement of management policies. Wastewaters too, contain an added level of complexity, in that they result from the use of other water resources. Thus until the availability of, demands for, and use of other water resources are well understood, flows and characteristics of wastewaters will remain ill-defined. Lastly, the management framework for ground and wastewaters is both less well developed and more fragmented than that of surface waters, adding a layer of uncertainty in terms of policy formation

In the USCRB, uncertainty has three roots. First, contested visions, within and across the border, result in a lack of clearly defined water objectives. The absence of an entity in the United States or Arizona with the authority to prioritize competing goals or to control water use contributes to this uncertainty. Second, even were water objectives to be well defined, determining water 'needs' is complex and full of unknowns due to difficulties in predicting future conditions; the physical complexity of flows of water and the interdependence of supply with demand; and institutional factors that mediate supply, demand, and knowledge. Lastly, incommensurability between management goals & objectives makes it difficult to estimate or to value the true stakes each country faces. The result is that neither country has complete knowledge of what it stands to gain or lose by adopting alternate water management strategies.

The three factors I find to be root causes of uncertainty in the USCRB exist to some degree for all shared waters, regardless of location or type of water resource. However, I argue these factors are more salient in transboundary ground and waste waters for a number of reasons. Contested visions and ill-defined management goals are more likely in the case of ground and waste waters because the definition of 'safe-yield' in groundwater is subjective (Kalf & Woolley,

2005); because it is difficult to identify competing and synergistic uses of these resources; and because wastewater is a dual nature resource that is seen both positively as an additional supply source and as a negative externality. 'Water needs' and availability are indeterminate, due to the complexity of groundwater flows and the fact that the production of and demand for wastewater is closely tied to availability and use of other water supplies. And lastly, commensurability becomes less feasible, because trade-offs between the characteristics of the water itself (reliability, timing, quality, cost) must also be taken into consideration.

That water resource management decisions are rarely made in the context of complete information is well known (Tracey, 2008). The logical extension of this is that countries cannot and thus do not make decisions to maximize utility. Rather, policy formation is more a process of 'muddling through' (Lindblom, 1959). If our goal as researchers is to develop better understandings of what leads to increased cooperation, improved welfare, and sustainability, it is important the models we develop accurately capture the decision making processes that occur on the ground. In highlighting the fallacy of assumptions of complete information and well-defined utility functions, my research points to limitations in the effectiveness of mechanisms commonly promoted as means to increase cooperation such as 'benefit sharing' or the 'basket of goods approach.' If countries do not have a clear picture of what they stand to gain or lose, and if they view benefits as incommensurate, determining acceptable trade-offs is made impracticable. My work is especially important, in that by underscoring the distinction between surface, ground, and waste waters, I demonstrate that these resources cannot be conflated. Rather, decision making and possibilities for cooperation differ depending on the characteristics of the specific water resource of concern.

The focus of this chapter is on what might be considered the 'demands' side of uncertainty. I focus on the water management objectives for the region, the quantity of water needed to meet those objectives, and utility gained through them. Chapters 4, 5, & 6 continue my discussion on uncertainty though a focus on the 'supply' side; i.e., through an analysis of water availability and the impact of withdraws on supply, water levels, and instream flows. Data used for this chapter was collected from a variety of sources. I conducted key informant interviews with representatives from each of the governmental agencies connected with water management in the USCRB as well as citizens involved in stakeholder groups or with large water rights claims. I also attended a number of public meetings held by the International Boundary Waters Commission, the Arizona Department of Water Resources, and Santa Cruz County. In addition, I collected data on water use, water tariffs, agricultural production, population growth, land use and zoning, and other information important for estimating water needs and values from a number of primary and secondary sources.

To begin this chapter, I depict the contested visions for the basin, explaining how within the US there exist competing water management objectives and diverging views of how water use should be prioritized and that these objectives may be incompatible with those of Mexico. Then, through a water 'requirements' analysis, I make evident that neither the US nor Mexico knows how much water is needed to meet their respective water management objectives. I reveal the uncertainty which exists and explain the implications of this for water planning. Lastly, I discuss challenges in valuing the benefits of water management objectives and how incommensurability between water uses and goals obviates comparisons and makes some tradeoffs unacceptable.

### **3.2 Evaluating Water Management Strategies: Objectives, Needs and Benefits**

If, for the present, we assume that countries are rational utility maximizing actors, an assumption common throughout the literature on transboundary water management,<sup>54</sup> then logically it would ensue that both the US and Mexico would adopt water management strategies accordingly. However, I argue neither the US nor Mexico can act as a rational utility maximizing actor, because water management objectives are not fully defined and because knowledge of water needs and the utility that will result from the adoption of any given water management strategy is incomplete.

A clear picture of what a country hopes to achieve is important for understanding the usefulness or evaluating the effectiveness of water management strategies. A country likely holds multiple and simultaneous water management objectives; some of which will be completely independent and others of which will be interdependent (either synergistic or competing). Within the USCRB, as I explain in the section on Contested Visions below, there exist multiple and competing objectives. Where competing objectives exist and have not been prioritized, evaluating the utility of alternate water management strategies becomes impracticable, as values and preferences are not well defined.

The issue of prioritizing competing objectives is closely tied to questions of what tradeoffs exist between objectives and what utility is derived from meeting them. In the USCRB, I find that not only do competing visions exist, but there is also incomplete knowledge of the tradeoffs between objectives due to a high degree of uncertainty in the amount of water needed for each objective and uncertainty regarding the flows of water in the region. Moreover, I claim that each country cannot determine the utility it might derive from alternate water management activities because the costs of adopting each strategy are not fully determined and because valuing the benefits is complicated by incommensurability.

### **3.3 Contested Visions**

#### **3.3.1 Debates Within the US**

Visions for the future of the SCAMA are contested, as water management objectives are closely tied to questions related to growth, the economy, culture, and the environment. While these questions remain unresolved, it remains unclear how much water is needed or desired when, where, and for what. As will be discussed in Chapter 7, this uncertainty regarding the future of the basin, is due in part to the institutional framework through which water is managed on the US side of the border, and inhibits the negotiation process. The combination of a lack of a basin water management authority, decentralized property rights to water, and federal and state mandates make it such that there is no entity with the authority or responsibility to prioritize water management objectives, to control use, or to manage recharge in the region.

Discussions in SCAMA regarding how much growth should be permitted to occur invoke passionate responses. Only 38% of the land in Santa Cruz County is privately held, yet growth in that land has been occurring rapidly and much more is expected to occur (Santa Cruz County,

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<sup>54</sup> The assumption that countries are rational utility maximizing actors can be seen through the literature on benefit sharing, see (Sadoff & Grey, 2005; UNDP, 2006) to name a few, and game theory, see (Barrett, 1994; Dombrowsky, 2007) to name a few. Furlong (2006) explains how the literature on transboundary waters has traditionally taken a rationalist approach, although both she, Frey (1993), and others critique this approach.

Personal Communication, June 15, 2006). The housing boom of the late 1990's and early 2000's prompted developers and large landholders hoping to subdivide and develop their land to request changes to the county's comprehensive land-use plan, as they hope to take advantage of growth in the region and increasing property values. Although many in the county would like to see continued growth occur (Coppola, 2007; Davis, 2007), others disagree. In the Tubac sub-region alone, more than new 11,000 homes have been proposed. Many residents are against such development (Davis, 2007), believing the development will have a negative impact on their surroundings and their quality of life.

The primary concern about development is related to the impact it will have on the character of the community, and much of the debate centers around the Northwest County/Tubac sub-region. The County Comprehensive Plan explicitly states "The vision of development in the Northwest County is for slow, deliberate growth with the aim of preserving and maintaining the area's historic, cultural, ranching and agricultural heritage" (Santa Cruz County, 2004, pp9). Interviews with residents and their comments at public planning meetings indicate they are worried about the impact development will have on the aesthetics, the lifestyle of the community, and the riparian ecosystem. The possible adverse affects of development on ranching is of particular concern, as sub-divisions and growth threaten to destroy the traditional way of life and change the character of the community. Water that is used by new housing developments will likely come from water rights holders who currently use the water for ranching and agriculture, and there are fears that shifts in water usage will lead to lowered groundwater levels and reduced stream flow, impacting both pumping costs and the riparian corridor.

Riparian vegetation is currently the largest consumer of water in the SCAMA (ADWR, 1999). The riparian corridor has grown considerably since the construction of the NIWTP in 1951, and the size of the corridor that should be maintained or protected is yet another contentious subject. Those in favor of protecting the existing extent of the corridor claim its importance both in providing essential ecosystems services (such as providing further treatment of the released wastewater), its importance as habitat to migrating birds and several endangered species, and its value to residents and in attracting tourists for recreation, hiking, and birding. Yet others see the riparian corridor as an unnecessary sink of precious water resources. One resident even claims the "riparian area is on steroids," (Roy Ross, Personal Communication, June 18, 2006), stating his belief that the area had grown unnaturally large due to the high nutrient loads in waters released from the NIWTP and this unnatural growth should be cut-back. At a number of ADWR Groundwater Users Advisory Council meetings, several residents argued that most of the water scarcity problems in the SCAMA could be resolved if part of the riparian corridor were removed or allowed to decline.

Each of the above visions for the future calls for a different type of water management strategy. If a large amount of residential growth is expected to occur, the water management strategy adopted would need to account for the fact that residential water use is both more constant throughout the year and less elastic than agricultural water use. A shift away from agricultural would also change the amount of incidental recharge, the amount of runoff, and the location and timing of withdrawals. A future which maintains the extent of the riparian corridor, would require planning for maintaining stable water levels and instream flows. This type of water

management is quite different than a water availability analysis, because it requires more careful analysis of physical processes and more localized management of water abstractions.

### 3.3.2 Debates Between Mexico and the US

As will be discussed in detail in Chapter 5, the institutional environment in Mexico differs greatly from that of the SCAMA. Water is more centrally managed; as is the development process. Thus, even though there may exist different visions for the basin, the resulting management objectives are more coherent. Nogales, Sonora's main objective is to meet the needs of its growing population as best as possible, prioritizing water use for economic growth (OOMAPAS, Personal Communication May 30, 2006; OOMAPAS, Personal Communication, October 4, 2007). The CONAGUA supports this goal, by prioritizing water for municipal use (CONAGUA, Personal Communication, October 7, 2007).

Here, contested visions exist not within a country, but across the border. While within the SCAMA, there exist debates about prioritizing the environment and development, Mexico is explicitly willing to tradeoff riparian vegetation and instream flows (SeismoControl, 1996) in exchange for meeting human needs and economic development. A country's water management objectives, priorities, and its ethos of water (the role of which is addressed in more depth in chapter 5) are key determinants of the way that country values water management strategies. Differing water management objectives, priorities and valuing of the benefits from water will impact cooperation. In bargaining, a country may view certain water uses as incommensurate, and be unwilling to make tradeoffs. For example, if Mexico prioritizes human needs over the environment, its willingness to enter into an agreement with the SCAMA which requires it gives up some of its available water in order to protect the ecosystems in Arizona will be reduced while Mexican citizens have insufficient supplies.

Although the role of interest groups in transboundary water management has been addressed in several articles (Feitelson, 2006; LeMarquand, 1976; Sneddon & Fox, 2006), both these studies and studies which treat the state as a monolithic unit do not consider how, given a lack of clear water management goals, a country cannot act to maximize its utility, because it does not know what it hopes to achieve.

Contested visions (such as the above debates regarding growth, land use, and ecosystems conservation) create uncertainty with respect to future objectives. As will be explained in Chapter 7, this situation is exacerbated when, as in the SCAMA, there is no singular entity with the authority to plan and enact water management strategies for the region.

Through the discussion so far, I have established there are a number of water resources concerns in the USCRB that need to be addressed and these concerns are closely tied to ideas about development and the environment. Moreover, within and across the border, there are different views about how these issues can best be addressed and how water resources use and management should be prioritized. As a result, determining the utility that can be derived from any given water management strategy is problematic; as there exists no agreement upon the terms of what is being evaluation.

### **3.4 Water Needs and Demands**

The contested visions mentioned above represent a major challenge in determining the utility derived through the adoption of a water management strategy, because they result in lack of clarity regarding objectives and prioritization of goals. As a result, it is difficult to quantify the amount of water required in order to achieve those goals or the benefits derived from meeting them. Without this information, a country is operating under the veil of uncertainty while making decisions or negotiating cooperative management strategies.

Recent additions to the literature on transboundary waters (primarily stemming from the liberal political philosophy) recommend moving from a ‘rights’ to a ‘needs’ and eventually to an ‘interests’ approach to negotiations over shared waters (Jarvis, 2008; Sadoff & Grey, 2005; Wolf, 2007). The premise behind this recommendation is an ‘interests’ approach increase possibilities for cooperation as it will allow countries to discover their shared interests and efficiencies that can be gained through cooperation. Never-the-less, ‘interests’ still need to be translated into practicable policies; which means countries need to have objectives that are sufficiently well-defined and prioritized to make informed decisions regarding how actions will contribute to meeting their ‘interests.’ In other words, countries still need to identify how much water it needs in order to meet its water-related objectives, the tradeoffs that exist between objectives, and the costs and benefits associated with meeting objectives.

I have discussed how, in the USCRB, contested visions make it so ‘interests’ in the region are not well defined. Although a country may have unclear and non-prioritized management objectives, a rudimentary estimate of ‘water needs’ can be developed based on the general (yet un-prioritized) water management objectives, existing water uses, expected future conditions. Yet, as I demonstrate below, often that estimate too is fraught with uncertainty.

A number of general management goals can be clearly identified for each side of the border. In the SCAMA, these goals range from ensuring the overall well-being of residents to environmental protection. In the Mexican portion of the basin, the main focus is on extending and improving the quality of water services and economic development. Table 3-1 includes a summary of those objectives and the uses of water that would help to achieve those objectives. I use this summary of the general goals as a framework for estimating the ‘water needs’ of each side of the border.

My use of the term ‘needs’ is a misnomer. There is no set answer to how much water each side of the border needs; need implies requirement, and defining the requirements of each side of the border is a subjective issue. Additionally, the objectives are not necessarily all-or-nothing goals; rather the objectives can be partially fulfilled. The objectives may also be unbounded, in that there may be no upper limit on how much water could be used to reach the goal or there may be no upper limit on the extent to which the goal can be achieved. Some of the goals in fact may not even require water at all, rather water is an intermediate good used to achieve the objective, and other goods or policies could be substituted for water while still allowing that goal to be reached. Furthermore, some of the objectives are synergistic and others are competing objectives. Thus the amount of water needed to meet the objectives is dependent upon prioritization of goals. As I discussed in the section on contested visions, this prioritization and setting of the water management agenda for each side of the border has not yet occurred.

**Table 3-1: Water Management Objectives and Water Use**

	<b>Vision</b>	<b>Goals/Objectives</b>	<b>Water Use</b>
<b>Arizona</b>	General well-being of residents	Maintain health, economy, and services	Residential, commercial, industrial, and governmental use
	Economic growth and urbanization	Subdivide, develop, and sell land	Residential water use and landscape irrigation
	Preserve way of life/historic ranching lifestyle	Continue agricultural practices	Stock watering and irrigation for fodder crops
	Preserve the character of the community	Maintain open space and aesthetic of the community	As instrumental in controlling the structure of the environment (preventing development)
	Maintain aesthetic environment and protect ecosystems	Protect riparian ecosystem	Maintain instream flows and water table levels
<b>Sonora</b>	General well-being of residents, economic development	Extend and improve quality of existing water and wastewater services, economic development	Residential, commercial, industrial, and governmental use

In estimating ‘water needs,’ I do not attempt to calculate the amount of water that would be required to fully achieve each of the above objectives, primarily due to the complexity and amount of understandings and data that would be required to do so. Rather, I adopt a pragmatic approach that uses these goals to identify ways in which water has been used for in the past and how water might be used to in the future. For example, it is possible to determine how much water was used for domestic purposes and how much might be needed to meet increased demands due to expected residential growth. Through my assessment, I show the range of quantities of water that might be used by each side of the border. I also indicate the management objectives for which the amount of water necessary cannot currently be quantified. This analysis shows the uncertainty each country is faced with regarding the quantity of water it would need to fulfill each separate water management goal, regardless of synergies or competition among water uses and management goals.

My analysis of water needs for each side of the border considers five categories: residential, non-residential municipal (commercial and governmental) industrial, agricultural, environmental. For each category, I estimate the amount of water used in 2006 and the amount of water that might be needed to accommodate growth for the year 2025, 2050, and later. My estimates of future needs are based on growth rates projected by local governmental agencies and do not account for the possibility of a dramatic shift in growth trends or water use that might be caused by technologic change or other major events (such as the current US mortgage crisis). As the estimates are based on current use plus expected growth; they do not incorporate the responsiveness of the amount of water desired to price or supply availability. Thus the estimates do not adequately incorporate any consideration of value or costs. Furthermore, as will be discussed below, the amount of water needed to achieve some management goals is not always quantifiable.



### 3.4.1 SCAMA

The SCAMA was formed as a result of the Arizona Groundwater Management Act, which was designed to provide more effective management of the state's scarce water resources. Consequently, ADWR collects and maintains detailed information on water use in the region.<sup>55</sup> Current water use, in and of itself does not represent the 'water needs' in the region; however, the information on what water was used for serves as a starting point for determining water needs in the region. My estimates of the water needs for SCAMA, which are summarized in Table 3-2,<sup>56</sup> are based on a per capital rate for municipal water use and a continuation of current industrial, agricultural and environmental water use. I adopted a 'water requirements' approach<sup>57</sup> rather than use the extraction data for two reasons: because the amount of water pumped is not necessarily the same as water needed (due to inefficiencies in application or use of water) and because the data available does not include surface water diversions,<sup>58</sup> none-the-less, data on 2005 water abstractions were useful in corroborating my estimates.

Although approximating the amount of water needed to meet current municipal (including residential) and industrial uses is fairly straightforward, estimating future needs is highly uncertain as is determining both current and future water needs for environmental purposes. The uncertainty which exists in estimating 'water needs' for the SCAMA is, with the exception of environmental needs, not related to an inability to estimate the amount of water currently used to meet given objectives or demands. Rather, it is related to questions of predicting future trends including the extent and rate at which development will occur, shifts in water use patterns, and the impact of climate change on water needs.

Determining environmental water needs is complicated not just by questions regarding future changes, but also by the difficulty in quantifying the amount of water necessary to meet environmental objectives. The quantity of water fish species and other flora and fauna need to survive is not well known, and even if they were, translating that information into a quantity of water needed to maintain stable water levels and instream flows is problematic. Water levels and instream flows are not a water quantity, rather they are characteristics of a desired state of flows of water through the system. Moreover, the best way to characterize them would be by looking at how much water can be withdrawn from the system while maintaining this state, rather than

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<sup>55</sup> All non-exempt well users in the SCAMA (exempt refers to users who withdraw from wells with a pumping capacity of less than 35 gpm for non-irrigation purposes) are required to provide annual reports to ADWR that include an estimate of the amount of water extracted from wells during that year (see <http://www.azwater.gov/dwr/WaterManagement/Content/AMAs/default.htm> for additional details).

As a result, the amount of water extracted from wells currently used to meet residential/municipal, industrial and commercial water needs in SCAMA is relatively straight forward to estimate. However, data on surface water diversions is more difficult to determine, as water rights holders that divert surface water are not subject to the same reporting requirements.

<sup>56</sup> More details on the calculations are included in Appendix B.

<sup>57</sup> To clarify, what I refer to as a 'water requirements approach' encompasses determining existing water uses and projects how those might change into the future. This differs from a framework that estimates water needs based on priority planning objectives or goals.

<sup>58</sup> Moreover, the amount of surface water diverted does not necessarily represent the amount of that water that is "needed" as surface water rights in Arizona are subject to a "use or lose" policy, and consequently water rights holders in the SCAMA must make use of their full allocation of surface water every five years in order to maintain possession of their right, regardless of if that water is put to productive use (ADWR, Personal Communication, July 15, 2005; ADWR, 1999).

how much water needs to be left in or added to the system in order to achieve this state. The relationship between water levels and instream flows and water withdraws and recharge is complex, and, given the lack of understanding of the behavior of the aquifer in the USCRB (See Chapter 5 and 6 for details), determining how to manage water in order to meet environmental water needs may be near quite difficult.

**Table 3-2: Estimates of Water Needs within the SCAMA**

in Acre-Feet-per-Year	Current Use Scenario (2006)		ADWR Third Management Plan (2025)		Medium Development Scenario (2050)		Full Development Scenario (2114)	
	AFA	Mmy3/yr	AFA	Mm3/yr	AFA	Mm3/yr	AFA	Mm3/yr
<b>Estimated Population</b>	42,123		58,481		102,606		372,983	
<b>Residential Scenarios</b>								
Current Housing Stocky	8493	10.5			8493	10.5	8493	10.5
New Houses In addition to current					12440	15.3	66955	82.6
Total Residential Demand	8493	10.5	11400	14.1	20933	25.8	75448	93.1
<b>Non-Residential Municipal</b> (Commercial, Services, Government)								
			all municipal included in residential		all municipal included in residential		all municipal included in residential	
<b>Agriculture</b>								
Livestock	318	0.4			318		318	0.4
Crops	7251	8.9			7251	8.9	7251	8.9
Total Agricultural Demand	7569	9.3	10300	12.7	7569	9.3	7569	9.3
<b>Industrial</b>	1490	1.8	2400	3.0	1490	1.8	1490	1.8
<b>Riparian</b>	25800	31.8	25800	31.8	25800	31.8	25800	31.8
<b>Exempt wells</b>	included in residential & agriculture		1000	1.2	included in residential & agriculture		included in residential & agriculture	
<b>Environmental -- Non-consumptive Demand</b>								
Maintain Stable Water Table Levels	unknown		not considered		unknown		unknown	
Maintain Instream Flows								
<b>Total water demands for SCAMA</b>	43352	53.5	50900	62.8	55792	68.8	110307	136.1

The 'water needs' presented in Table 3-2 were calculated using a 'water requirements' approach (W. M. Hanemann, 1994) and therefore do not take into consideration the interactions between supply and demand. Yet the interaction between supply and demand influences water needs. I would argue is especially important in the case of ground water and waste waters, because for these resources, supply and demand curves are often not independent. This dependence arises from three factors: i) water is a contingent commodity, ii) groundwater availability is dependent on water use and recharge, and iii) demands for ground and waste waters are often residual demands. By contingent commodity, I refer to the fact that the value and the demand for water depends on the environment in which it is made available. An example of this would be that the amount of water needed for agriculture or landscaping depends on how much water was available throughout the year (e.g. soil moisture content); yet this will also be closely tied to the amount of aquifer recharge and runoff that occurred. By groundwater dependence, I refer to the fact that availability of groundwater changes with abstraction and recharge; stresses on the system influence gradients and the flow regime, altering the amount available for abstraction at any location and time. Lastly, by residual demand, I refer to the fact that the amount of water desired depends on availability of other water sources. Wastewater is frequently viewed as a last choice option, due to the cost and effort of treating it before use.

Although my calculations of water 'needs' are simply based on how much water might be needed for a variety of uses in the SCAMA, and therefore, my calculations do not take into consideration the role of supply, it is important to understand this supply-interaction effect, particularly because supply in the SCAMA is possibly quite closely tied to water use in Mexico. The impact of pumping in Mexico on underflow across the border and on water table levels is one concern, while the threat that Mexico may discontinue the flow of wastewater to the NIWTP is another concern, as the discharge of effluent from the treatment plant may play a pivotal role in maintaining instream flows and recharging the downstream part of the aquifer. Either might influence environmental water needs within the SCAMA, as they change the flows of water in the region.

Beyond supply and demand, the amount of water 'needed' is mediated by factors external to the market or the consumer. Institutional factors can serve to place either upper or lower limits on water needs. In the SCAMA, I show how four institutional factors regulate water needs: the SCAMA management goals, the assured water supply rules, surface water rights requirements, and the Endangered Species Act.

As mentioned previously, the official water management goals of the SCAMA include maintaining safe-yield and preventing local water tables from experiencing long term decline (ADWR, 1997). How to operationalize these goals is still being worked out; yet these rules influence 'water needs' in the SCAMA in that they will be instrumental in defining the level at which the water table should be maintained (even if that level incorporates a degree of variability) and they will influence the quantity of water considered available for withdrawal. In other words, these rules, which are not necessarily being developed only for environmental reasons, will place constraints on what I have lumped into the 'environmental needs' category.

The Assured Water Supply (AWS)<sup>59</sup> rules accompanying the AZ Groundwater Management Code, also serve to define water needs in the SCAMA. The AWS rules dictate that in order for a developer to subdivide and sell lands, the developer must demonstrate a 100-yr assured water supply. This regulation, in effect, puts a lower limit on residential water needs, in that a certain amount of water must be available per lot, in order for that lot to be developed. At the same time, ADWR has imposed conservation requirements (municipal, industrial and agricultural) that place upper limits on the amount of water that can be used for specific uses (ADWR, 1999, n.d.).

The Arizona Surface Water Rights system also imposes an additional ‘water need’ in that surface water rights are subject to a “use or lose” framework. Thus in order to maintain possession of a water right, rights holders must use their full allotment at least once every five years, regardless of if that water is put to productive use ( ADWR, Personal Communication, July 15, 2005; ADWR, 1999). Although this might not be considered a ‘water need’ per say, it influences the total water needed, because in order for surface rights holders to use their full allotment at least once every five years, there needs to be enough water physically available to meet other needs as well as to be “used” by surface water rights holders attempting to maintain their water rights.

Lastly, environmental regulations play a role in determining ‘water needs’ in the SCAMA. For example, the Endangered Species Act (ESA) (USFWS, n.d.) mandates protection of critical habitat, including requiring maintenance of specific instream flows. Although the ESA has not yet been invoked for the USCRB, potentially, it could be a determinant of future water needs in the basin.

### 3.4.2 Mexico

Estimating existing water use for the Mexican side of the border is more complex than for Arizona, as less data and information are available. The CONAGUA is required to maintain and manage a registry of water concessions, the Registro Publico de Derechos de Agua (REPDA)<sup>60</sup>, which contains information on the volume of water allocated. Concession holders are required to pay an annual fee based on the amount of water they use. However, registration in REPDA has been slow, (Hearne & Trava, 1997) and not all water use is recorded. Thus information on current water abstractions is dispersed, i.e., much of it lies only within the hands of the water users themselves.

The OOMAPAS, the water utility for the city of Nogales, Sonora, maintains information on the amount of water it abstracts and distributes for municipal use. However, this does not include information on municipal or industrial use of water extracted from wells not under OOMAPAS control,<sup>61</sup> nor does not include information agricultural water use. Furthermore, water

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<sup>59</sup> “Every developer is required to demonstrate an assured water supply that will be physically, legally, and continuously available for the next 100 years before the developer can record plats or sell parcels. The ADWR will not issue a public report, which allows the developer to sell lots, without a demonstration of an assured water supply.” (ADWR, 2005)

<sup>60</sup> See the (Commission Nacional del Agua, n.d.) The CONAGUA and REPDA were both formed as part of the 1992 Ley de Aguas

<sup>61</sup> A number of private wells supply water to residential, commercial, and industrial users throughout the city. Many of the maquiladoras use water from wells located on their property (OOMAPAS, Personal Communication, October 4, 2007). Additionally, residents and businesses unconnected to the OOMAPAS distribution system or those who are connected yet do not receive water 24 hours per day or experience other technical problems with the water

abstraction by OOMAPAS is not a good proxy for water needs/use due to large losses in the distribution system,<sup>62</sup> uncertainty regarding the true number of connections to the distribution system,<sup>63</sup> a lack of metering,<sup>64</sup> and the fact that customers frequently obtain water from other sources.

In determining the 'water needs' for the Mexican portion of the basin, I adopted a 'water requirements' approach, similar to that used for estimating water needs for the SCAMA. However, given the limitations of the data on water withdrawals, I am unable to use data on water withdrawals to corroborate my estimates. Therefore, a high degree of uncertainty exists in the estimates of both current and future 'water needs' for the Mexican portion of the basin. This uncertainty is primarily related to a lack of information on current water use,<sup>65</sup> but is also related to uncertainty in predicting future conditions.

With respect to determining current domestic water needs, a key problem is addressing the wide variation in estimates of the current population of Nogales, Sonora and determining how much water that population requires. According to various government sources, listed in Table 3-3, the population of the municipality of Nogales, Sonora is somewhere between 192,000 and 350,000 people. One reason for the considerable variation in the expected population size is due to the large number of 'guests' in the city.<sup>66</sup> Given the uncertainty that exists regarding the size of the current (and historical population), the general scope of growth that will occur in a given time frame is perhaps infeasible. Furthermore, even if an estimate of the population could be settled upon, assigning a per capita water allotment is problematic. Water use is lower than in Nogales, Arizona, (Morehouse, Carter, & Sprouse, 2000) and a recent empirical study indicated residents use, on average, 173 lpcd (OOMAPAS, Personal Communication, June 13, 2008).<sup>67</sup> However, given improved service provision, with water available 24 hours a day, residents might use larger amounts of water.

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system frequently obtain water from pipas, i.e., trucks that deliver bulk water (OOMAPAS, Personal Communication, October 7, 2007). Although OOMAPAS will send 'pipas' that obtain water from OOMAPAS wells to its customers on a temporary basis, water from private wells is used to fill non-OOMAPAS pipas. Private wells fall under the regulation of the CONAGUA and water abstractions are to be reported on a regular basis; however as of Summer 2007, several of these wells were not registered with the CONAGUA ("Taking it to the streets," 2007; OOMAPAS, Personal Communication, October 7, 2007), and thus there exists no record of abstractions from those wells.

<sup>62</sup> OOMAPAS estimated 50% of water conveyed through the Heroica Nogales water distribution system is lost, either via seepage, leaks, or theft (OOMAPAS, Personal Communication, June 13, 2008)

<sup>63</sup> Levesque and Ingram (2002) estimate 36% of all connections to the OOMAPAS distribution system are illegal; Morehouse et al (2000) cite a COLEF estimation of 3000 illegal connections; and the municipality of Nogales, Sonora began a program in May 2007 to seek out illegal connections to the system. (H Ayuntamiento de Nogales Sonora)

<sup>64</sup> In 2005, less than 0.7% of residential billing was measured, 74% of commercial billing was measured, and 100% of industrial billing water measured (OOMAPAS, Personal Communication, June 27, 2006)

<sup>65</sup> The one exception is industrial water use, which is well documented via metering and reports to the CONAGUA.

<sup>66</sup> Guests include both legal and illegal immigrants who reside in Nogales for an unspecified amount of time and would not be counted in official statistics.

<sup>67</sup> If per capita water use in Sonora is indeed 173 liters (45.7 gallons) per day, per capita water use in Sonora is only approximately 25% of water use in Arizona.

**Table 3-3: Estimated Population of Nogales, Sonora 2005-2006**

Municipal Government <sup>68</sup>	204,458
Municipal Government <sup>69</sup>	270,000
OOMAPAS <sup>70</sup>	350,000
CONAPO <sup>71</sup>	195,340
OOMAPAS <sup>71</sup>	225,851
CFD <sup>71</sup>	238,483
Proyeccion SI + I <sup>71</sup>	192,695
CONAGUA <sup>71</sup>	254,525
IBWC <sup>71</sup>	254,525
INEGI <sup>72</sup>	193,517

Uncertainties also exist regarding non-residential municipal water needs, riparian vegetation water needs, and other non-consumptive environmental water needs. However, despite these uncertainties, I endeavored to provide a coarse estimate of the quantities of water that might be needed in the Mexican portion of the basin. My estimates are provided in Table 3-4 and details on my calculations are included in Appendix B. To summarize, estimates of residential water use are based on a per capita daily water requirement. Non-residential municipal demands are based on the ratio of 1995 residential to non-residential water use. High estimates for both residential and non-residential municipal use are based on the OOMAPAS estimate for the current population and an annual growth rate of 2.6%. Low estimates are based on the CONAPO estimate for the current population and an annual growth rate of 2.1%. Estimates of industrial water use are based on information on OOMAPAS water sales to industry and industrial REPDA inscriptions. Agricultural water use is calculated using data on livestock and crop water requirements and the number of irrigated acres and head of livestock. My estimates of water use by riparian vegetation is quite rudimentary, and is based solely on an assumed geographic expanse of vegetation and evapotranspiration.

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<sup>68</sup> (H Ayuntamiento de Nogales Sonora, 1997)

<sup>69</sup> Calculation based on approximate number of houses and average household size per communication with Claudia Gil

<sup>70</sup> Population based on interviews with OOMAPAS (OOMAPAS, Personal Communication, October 4, 2007). Although this estimate is the highest of any Mexican calculation, the number is corroborated by a number US sources including the web-site of the company hired to make improvements to the NIWTP (<http://www.water-technology.net/projects/nogales>), studies by the US Department of Health and Human Services (<http://www.atsdr.cdc.gov/HAC/pha/NogalesWash/NogalesWashHC082106.pdf>) and the Arizona Department of Environmental Quality (<http://acwi.gov/monitoring/conference/98proceedings/Papers/34-CAST.html>)

<sup>71</sup> (BECC/COCEF, 2006)

<sup>72</sup> (INEGI, 2005)

**Table 3-4: Estimates of Water Needs for the Mexican Portion of the Basin**

	Current Use Scenario (2006)			2026			2050			2100		
	Population <sup>73</sup>	Mm3/year	AFA	Population	Mm3/year	AFA	Population	Mm3/year	AFA	Population	Mm3/year	AFA
<b>Residential Scenarios</b>												
High Estimate	351,728	33.6	27,269	586,919	56.1	45,503	1,085,487	103.8	84,156	3,912,092	374.1	303,299
Low Estimate	197,068	18.8	15,278	298,441	28.5	23,138	491,289	47.0	38,089	1,389,346	132.9	107,714
<b>Non-Residential Urban (Commercial, Services, Government)</b>												
High Estimate		5.0	4,090		8.4	6,825		15.6	12,623		56.1	45,495
Low Estimate		2.8	2,292		4.3	3,471		7.0	5,713		19.9	16,157
<b>Agriculture</b>												
Livestock		0.6	451		0.6	451		0.6	451		0.6	451
Crops		4.3	3,477		4.3	3,477		4.3	3,477		4.3	3,477
<b>Industrial</b>		1.3	1,014		1.8	1,485		2.9	2,350		7.5	6,114
<b>Riparian</b>		6.9	5,612		6.9	5,612		6.9	5,612		6.9	5,612
<b>Environmental – Non-consumptive Demand</b>												
Maintain Stable Water Table Levels		unknown			unknown			unknown			unknown	
Maintain Instream Flows												
<b>Total water demands</b>												
High Estimate		51.7	41,914		78.1	63,355		134.0	108,670		449.5	364,448
Low Estimate		34.7	28,125		46.4	37,634		68.7	55,693		172.1	139,525

<sup>73</sup> Population estimates are combined estimates for the municipalities Nogales, Sonora and Santa Cruz, Sonora; as such, they differ from the estimates included in Table 3-3, which lists the population for Nogales, Sonora alone.



Institutional factors play a role in defining ‘water needs’ in Mexico as well. Federal law dictates norms for planning and design of infrastructure. As a result, OOMAPAS, the water utility is restricted to using official statistics on population and per capita water use when designing infrastructure capacity and planning for the future. However, these numbers may be outdated (as the population may have changed unexpectedly since the last census) or may not be applicable (as national norms are used, yet water use varies immensely due to characteristics of the location and service provider) (CEAS, Personal Communication, October 8, 2007). Although these institutional requirements do not directly mediate water ‘needs’ in the same way Arizona institutions place upper and lower bounds on consumption, they mediate the ability of water managers in the region to meet municipal water needs. In the context of transboundary water management, these institutional requirements may spill over into estimates of ‘water needs,’ thus impacting assessment of the costs and benefits of cooperative water management strategies.

### **3.5 Implication of Water Needs Analysis**

As can be seen from the above analysis, neither side of the border has a complete understanding of the amount of water needed to continue current water uses into the future, let alone to achieve overall water management objectives. If issues related to contested visions are put to the side, it is possible to use a ‘water requirements’ approach and develop a rough estimate of the amount of water needed to continue existing water uses into the future. However, this estimate contains a high degree of uncertainty. For the Mexican portion of the basin, the gap between my high and low ‘water needs’ estimates is greater than expected annual recharge of the aquifer.<sup>74</sup> For the SCAMA, uncertainty is more a question of how much growth will be allowed to occur and when it will occur, as existing water use is better defined and institutional constraints will bound future water use. In the SCAMA, the question of prioritizing competing domestic demands thus becomes all the more important in refining estimates of ‘water needs’.

Beyond the difficulty in predicting future conditions, an issue that is problematic globally not just in the SCAMA and the Mexican portion of the basin, my analysis points to three other factors that hinder the estimation of ‘water needs’. The first is the difficulty in estimating water needs for non-consumptive management objectives such as maintaining instream flows or stable water levels. The second is the interdependence of supply and demand; and the third is the role of institutional factors in mediating ‘water needs’.

Lastly, it is important to note that it is difficult to be consistent in methods used to calculate water needs across the border. Data is collected differently, water is used differently, and perceptions of need may vary. Even a relatively straightforward proxy for need, such as the quantity of water currently used, is problematic. For example, current water use may not represent desired use; rather water use may be constrained by other factors (availability of capital, infrastructure capacity, etc). Per capita municipal water consumption in Mexico is

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<sup>74</sup> Assuming average precipitation over the Mexican portion of the basin is 428 mm (NOAA Satellite and Information Service & National Climatic Data Center, 2007), total annual precipitation is expected to be 392Mm<sup>3</sup>. The difference between the current use high and low scenario is approximately 5% of total precipitation and the difference between the high and low scenario for 2050 scenario is 16% of total precipitation. Yet due to high rates of evapotranspiration, it is thought that only 3-8% of precipitation reaches the aquifer as recharge (see Chapter 4\* for more details). Thus, the difference in the high/low scenario estimates, which could be considered an upper and lower bound, is greater than expected annual recharge.

approximately 25% of that of Arizona. Thus if water ‘needs’ are calculated based on water use, a much larger water need is calculated for Arizona. Yet, much of Arizona municipal water is used for landscaping while many Mexican residents do not have piped water service 24 hours per day. Thus determining ‘needs’ based on use still entails an inherent prioritization of water uses and moreover may be considered contentious from an equity stand point.

### **3.6 Evaluating Utility: Costs, Benefits, Tradeoffs & Incommensurability**

In choosing a water management strategy/policy, a country would take into consideration not only the amount of water it needs to meet its objectives, but also the utility it derives from doing so. In the USCRB, I claim that neither the US nor Mexico has complete understandings of the utility it might derive from alternate water management activities for three reasons: i) the costs of adopting each strategy are not fully determined, b) complexity in valuing water, and iii) incommensurability between benefits.

#### **3.6.1 Costs of Adopting Each Strategy**

In estimating the costs of adopting a given water management strategy, be it a cooperative or non-cooperative strategy, a country must consider both direct economic costs that must be paid upfront as well as associated indirect costs that arise from the specific policy or action. In the case of the USCRB, the direct economic costs that would be incurred through the adoption of alternative water management strategies are unknown, for a large part, because the strategies themselves are not well defined. Moreover, this lack of definition makes estimating the indirect costs<sup>75</sup> associated with them fraught with difficulty; thus I focus my analysis on direct costs and benefits.

In the USCRB, the primary water management activities being considered relate to treatment of wastewater and possible reuse of treated wastewater (either directly or for recharging the aquifer). Thus the direct costs estimates that do exist include the costs of upgrading the NIWTP, repairing the IOI, building a new wastewater treatment plant in Mexico (PTAR Los Alisos), sewage lines associated with these treatment plants, operations and maintenance costs.<sup>76</sup> However, none of these estimates are complete, especially as PTAR Los Alisos has yet to be designed and no plans have been solidified regarding how to make use of treated wastewater.<sup>77</sup>

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<sup>75</sup> Indirect costs might include, for example, the impact of improved wastewater infrastructure on economic development or the impact of untreated wastewater on health.

<sup>76</sup> See for example (BECC, 2004; Caro Camacho, 2006; Pranschke & MacNish, 2002). With respect to funding and project costs, the North American Development Bank estimate for the upgrade to the NIWTP and rehabilitation of the IOI was \$74 million. However, due to restrictions on funding, the project was redesigned to cost approximately \$60 million USD (NADBank, Personal Communication May 31, 2006; International Boundary and Water Commission, n.d.; North American Development Bank, n.d.). Rehabilitation of sewer lines throughout Nogales Sonora is expected to cost \$11 million USD (BECC, 2004), and the lift stations and pressure lines required to convey wastewater to PTAR Los Alisos are expected to cost \$10.2 million USD (Caro Camacho, 2006). The first module of PTAR Los Alisos is expected to have capital costs of between \$4 -8 million in capital costs. O&M costs have yet to be estimated. (Caro Camacho, 2006)

<sup>77</sup> Currently, the question of how to best make use of effluent remains open. Neither side of the border has developed a concrete plan and thus cost estimates remain rough. Some costs estimates have been developed for the City of Nogales to reuse its portion of the treated wastewater from the NIWTP ( ADWR, Personal Communication, September 21, 2006; City of Nogales, Personal Communication July 11, 2006), but I was unable to obtain copies of those estimates. Sprouse and Villalba (2005, pp 9.) cite a Malcolm Pirnie 1997 report that estimates the cost to recapture and pump effluent from the NIWTP outfall to Nogales Sonora as \$184 per acre-foot or \$1,030,000 to

Part of the reason estimates for the direct costs of alternative water management strategies are incomplete is because determining the costs associated with infrastructure projects is an iterative process. Broad order of magnitude estimates are initially developed to help narrow the wide range of possible actions, then using these initial costs estimates in conjunction with other criteria, more specific project plans are formulated and more detailed cost estimates developed. This continues until a final project design is agreed upon. Even then, many cost estimates will remain uncertain until the final infrastructure is in place and the system is operating, as there are likely to be changes in the capital costs due to unforeseen elements during construction, and as operations and maintenance costs are often difficult to predict.<sup>78</sup> Furthermore, cost over-runs during construction are common. The reason it is important to understand this, is it means that in the case of water-related infrastructure, two countries rarely operate with full knowledge of the costs being negotiated. Rather, decisions are made based on a variety of criteria, which may include only partial estimates of costs. In Chapter 7, I discuss the decision making process and the role of criteria other than costs in more depth.

As no other cooperative water management strategies have been discussed (e.g., restricting pumping or surface water diversions, etc), there are no details on what those plans might entail. Developing order of magnitude estimates for the alternate water management strategies, prior to better defining them is impractical. For example, restrictions on groundwater pumping may lead to reduced production (agricultural, industrial etc) but may concurrently lead to higher water table levels and thus reducing pumping costs. Thus the net costs could be positive, negative, or neutral. Moreover, the cost of administering such a policy, and the distribution of those costs, will depend on the mechanisms selected for implementing, monitoring and enforcing it.

### 3.6.2 Complexity in Valuing Water

The utility of a water management strategy is a function not just of the costs (direct and indirect) of implementing such a strategy, but also of the benefits which are achieved through adoption of that policy. Identifying benefits is a question of determining not only the value of a unit of water in a given location at a given time, also the value of that water as it relates to achieving water management objectives, and taking into consideration avoided costs, opportunity costs, and

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pump 8 acre-feet of effluent to the border. The most detailed estimates of the cost of using the effluent for recharge are part of the CDM Ambos Nogales Facility Plan (Camp Dresser & McGee, 1997). However, their study is based on limited empirical information on the aquifer. Moreover, water experts in the region express little confidence in the report (Conversation with government personnel requesting to remain anonymous, June, 2006) and CDM cost estimates appear to be far from (without expanding the capacity) was \$19.2 million USD; yet now that the upgrade has been designed and is under construction, costs are expected to be closer to \$60 million USD.

<sup>78</sup> An example of this might be the construction of a new wastewater treatment plant in Mexico (PTAR Los Alisos). Here, the choice of wastewater treatment technology (activated sludge, aerated lagoons, etc) is a key determinant of the project cost, as is the overall design capacity. However, several costs will not be fully known until the project is operational. This is because not only will the project be connecting new homes and buildings that have not previously been part of the drainage network (and thus the production of wastewater from those connections is unknown) but also because in conjunction with this the city is making improvements to both the sewage lines and the water supply system, and improved water services may lead to increased wastewater production. Moreover, the project will involve lifting the wastewater produced approximately an elevation of 100 meters in order to pump the wastewater from its point of production over topographic divide into the Los Alisos basin. Given this will require a considerable amount of electricity, slight variations in the cost of electricity will have a large impact on operations and maintenance costs.

scarcity rent. Yet determining these is difficult due to the complexity of valuing water and incommensurability of water uses and goals.

Whittington et al. (2005) explain how the value of water depends on the user, the location, and the time. In other words, its value depends upon the environment and context in which it is being used. A variety of the use (and non-use)<sup>79</sup> benefits derived from water in the USCRB are included in Table 3-5. Due to the nature of flows and return flows, some water uses in the region will be synergistic while others may be competing or mutually exclusive. As mentioned above however, there exist a number of contested visions regarding water management goals of the region. In Arizona, a clear water management agenda has not been developed and thus it is not yet known to which management goals will be achieved and what uses of water will be prioritized. In Mexico, even though management objectives are more straightforward, there remains a high degree of uncertainty regarding the amount of water needed and the amount of water available. As a result of both, it is not possible to evaluate the benefits derived from the possible water management strategies discussed above. None-the-less, it is possible to look at the individual water uses on each side of the border to develop an understanding of possible benefits that could be derived.

Hanemann (2006) explains the complexity involved in valuing water as an economic good. In valuing water, it is important to consider the innate characteristics of water as a resource, including its heterogeneity (in terms of location, timing, quality, and variability/uncertainty), its essentialness, its mobility, and its supply characteristics (capital intensive, economies of scale, longevity of capital, expensive to transport, etc). Hanemann also points out three issues commonly overlooked when valuing water: i) water has characteristics of both private and public goods; ii) supply costs do not represent true costs (i.e., they neglect to consider the scarcity value of water), and iii) average and marginal values are likely to be different (i.e., the first, last and all in between units of water will not have the same value). Moreover, one unit of water might serve multiple purposes and one use of water might concurrently lead to multiple benefits. Incorporating all of these aspects into a valuation of the utility derived from water is a complex task, as many of these aspects are not immediately measurable.

Through interviews with key stakeholders and water managers in the region, I developed a list of many of the benefits derived from water in the USCRB (see Table 3-5). The table is not meant to be a complete listing of all the benefits derived from water in the USCRB; rather, my purpose in developing this list is to illustrate the variety of benefits that do exist and the complexity in valuing them. Many of the benefits listed are subjectively experienced and/or are immeasurable. For example, it is difficult to measure the value of improved international relations or of preserving a way of life. Even benefits that might appear relatively straightforward to measure, such as the value of water in agricultural use, has an element of uncertainty associated with it, as input costs and prices received for agricultural goods vary from year to year. For each of the benefits listed in the table, I suggest methods that might be used to estimate the economic value

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<sup>79</sup> By use benefits, I refer to benefits that arise through direct consumption or application of water. However, benefits can also be derived from water even if it is not directly consumed. For example, a non-use benefit of water would be the protection of endangered species through the preservation of habitat or the conservation of environmental aesthetics through the maintenance of a riparian corridor.

of that benefit, along with a few comments on complications that might arise in applying those methods.

Valuing both market and non-market goods is a contentious practice; and almost all methods used are subject to a variety of critiques. Both market and non-market valuation techniques are critiqued as poor reflections of true value, because ‘individuals may have poor information on how specific goals or services impact their well being’ (Champ, Boyle, & Brown, 2003) and thus make their choices without complete information (Champ et al., 2003; Shabman & Stephenson, 2000). The use of market prices is thought to be the least controversial valuation method, as market prices represent revealed choices. In other words, market prices represent the value an individual has actually already paid for a good or service. However, in the case of water and other environmental goods, Shabman and Stephenson (2000) point out that market prices do not reflect the true value of these goods and services because there is limited market exchange of such goods and because options are constantly changing and so preferences will be influx.

Non-market valuation techniques are subject greater critique than valuation based on market values. Zhang and Li (2005) explain that survey techniques, such as contingent valuation methods, are subject to strategic, design, informational, hypothetical, and operational bias (Zhang & Li, 2005). Both Shabman and Stephenson (2000) and Champ et al. (2003) criticizes non-market valuation techniques for their assumption of substitutability; i.e., that goods and services can be taken out of their social or moral context and instead put into the context of exchange for money. Moreover, both sets of authors explain that choices and prices made by people are a reflection not only of value, but of income. Champ et al. (2003) also argue that non-market valuation methods do not take into consideration interdependence of utility functions and fail to recognize that peoples may hold different sets of preferences (private and social). Shabman and Stephenson (2000) reiterate this last point, adding that surveys are not a substitute for actual choices, which require actions that are embedded in issues related to commitment, responsibility, freedom, and morals. There also exist a variety of other critiques of non-market valuation, frequently related to the difficulty in understanding what the respondent is valuing (More, Averill, & Stevens, 1996) and the influence of question structure and anchor prices on results (W. M. Hanemann, 1994; Merrett, 2002).

**Table 3-5: Benefits & Valuing Methods**

	<b>Who Experiences</b>	<b>Method for Measuring</b>	<b>Comments</b>
<b>Use Benefits</b>			
\$ value for housing development			Each developer aims for a different profit margin <sup>80</sup>
\$ from sale of crops or livestock	Ranchers	(Expected) profits from crop or livestock sales	The value of these commodities varies from year to year.
\$ tax shelter	Ranchers	Tax Savings <sup>81</sup>	Savings depends on either:

<sup>80</sup> (Dorn Homes, Personal Communication, September 20, 2007)

<sup>81</sup> There are two possible ways ranches may be used as a tax shelter. The first is that most ranches in southern Arizona are not financially viable; rather ranchers in the region generally also have another source of income. Thus losses from the ranch can be deducted from other earnings for tax purposes. Secondly, property taxes on land zoned agricultural are lower than land zoned for residential use. Some property owners have sub-divided their land to the minimum lot size required to still be considered agricultural (36-acres) and lease the rights to ranchers to run cattle

			i) the losses incurred in a given year, which is related to the national beef market ii) the rate at which property values
\$ consumer surplus residential water use	Residents	Calculation of surplus using demand equations	ADWR regulations include conservation. Mexico does not meter demand or charge based on actual water use. Both inhibit the calculation of consumer surplus.
\$ savings from improved water supply in Mexico	Residents	Averted costs	Multiple benefits are derived from improved water supply (including increased availability, improved water pressure, improved quality, and time savings, among others). Averting behaviors (such as the purchase of water via trucks or bulk bottles) may make up for some of these benefits, but may not incorporate all benefits, and thus the cost of averting behavior may be an underestimate of benefits.
<b><i>Non-Use Benefits</i></b>			
\$ from tourism and recreation in the county	County businesses	Economic activity from tourism	How to separate \$ spent in tourism from other aspects of economy
\$ benefits experienced through recreation, tourism	Tourists	Travel Cost, Contingent Valuation, Input-Output Matrix	Much tourism and recreation piggybacks on trips or outings for other purposes.
\$ increased housing prices from proximity to an environmental amenity (the riparian corridor)	Residents	Hedonic Pricing	The Santa Cruz River is a dual nature resource. <sup>82</sup> This heterogeneity in perception makes some willing to pay more for the amenity and others willing to pay less.
\$ growth potential	City/Municipality County Country	Investment made in other arenas to encourage an equal amount of growth expected to be generated through water	Difficult to estimate how much growth might be due to the availability of water ; also difficult to find information or data on investments to spark growth in other arenas.

on the land. This allows the land to maintain its tax status while still being developed and sold. Other property owners have chosen to maintain agricultural status while they wait for property values to rise, and plan to sell their land to developers at a future date.

<sup>82</sup> The riparian corridor is considered a benefit to those who appreciate the environment it creates; however; others consider it a cost because it is perceived by some as contaminated. (George Frisvold, professor, Personal Communication, October 5, 2007; Bourne, 2007)

Preservation of water rights for future land sales benefits <sup>83</sup>	Ranchers	Projected future real-estate values minus costs of using water now in order to maintain water rights	Difficulty in forecasting the future value of land.
Preservation of open space  Preservation of riparian corridor  Preservation of the aesthetics of the environment  Maintain the character of the community	Residents Tourists Ranchers Environmentalists	Hedonic pricing, Contingent Valuation, Econometrics	Difficult to distinguish what benefits are actually being measuring when using these techniques.
Psychic of preserving a way of life	Ranchers	Losses sustained from ranching  Cost of moving elsewhere  Contingent valuation	Difficulty in separating psychic value from aesthetic value, perceived future economic gains, and other factors.
Instrumental use in controlling the structure of the environment (i.e., prevention of future growth)	Tubac	Unknown	Need to separate value of water in achieving anti growth goals from other methods used.
Existence value endangered species	Entire world	Contingent Valuation	Determining the value of protecting species from being extinct not just to area residents but also to present and future generations worldwide.  Understanding the importance each species plays in the ecosystem so as to determine full cost of extinction.
Improved Bi-National Relations	Residents Ambos Nogales Arizona & Sonora US & Mexico	Unknown	Unknown

The above mentioned critiques of valuation mechanisms serve to highlight the difficulty countries have in determining the utility that can be derived from various water management strategies. Attempting to place a value on each benefit derived from the use of water in the USCRB is beyond the scope of my research; and in fact, in addition to the difficulty of addressing the many complexities of measurement, the large amount of data, time and resources

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<sup>83</sup> Due to the Assured Water Supply rules in the SCAMA, land is less valuable if it is not associated with a water right.

that would be needed to comprehensively value each type of benefit also serves to support my claim that neither the US nor Mexico has a full understanding of the costs and benefits of possible water management strategies for the region.

Although not all of the benefits that are or can be derived from the use of water in the USCRB can easily be valued, a minimum lower bound on the total value of water used in the basin can be developed based on the tariffs or fees users currently pay for water. Table 3-6 and Table 3-7 show the total fees paid on the Arizona and Sonora sides of the border respectively. A detailed explanation of the calculations is included in Appendix B. These fees represent the value of water for municipal, industrial, and agricultural use in Arizona, but do not include the value of water for agricultural use in Mexico, as agricultural water users in Mexico do not pay concession fees (CONAGUA, Personal Communication, October 8, 2007).



**Table 3-6: Tariffs & Fees Paid for Water in the SCAMA**

	Water – AFA	Water - Mm3	Tariffs Paid (\$US)
Residential Tariffs paid to large providers	5007	62	\$ 4,064,885
Urban-Commercial Tariffs paid to large providers	2819	35	\$ 8,091,464
Non-Utility Regulatory Fee paid to DWR	14238	176	\$ 49,833
Total fees paid for water			\$ 12,206,182

**Table 3-7: Tariffs & Fees Paid for Water in the Mexican Portion of the Basin**

	Low Estimate				High Estimate			
	Water Mm3	\$MX (pesos)	Water AFA	\$US	Water Mm3	\$MX (pesos)	Water AFA	\$US
Tariffs paid to OOMAPAS	18.20	\$ 86,825,295	14753	\$ 8,335,228	18.20	\$ 86,825,295	14753	\$ 8,335,228
Industrial Concession fees paid to CONAGUA	0.77	\$ 5,401,928	626	\$ 518,585	0.77	\$ 5,401,928	626	\$ 518,585
Pipas purchased	0.46	\$ 31,937,500	370	\$ 3,066,000	1.55	\$ 108,587,500	1258	\$ 10,424,400
Garrafones <sup>84</sup> of water purchased	0.03	\$ 33,784,415	26	\$ 3,243,304	0.13	\$ 141,894,542	109	\$ 13,621,876
Total fees paid for water	19.46	\$ 157,949,138	15775	\$ 15,163,117	20.66	\$ 342,709,265	16746	\$ 32,900,089

<sup>84</sup> Garrafones are 19 liter bottles of purified water that can be either purchased in stores or delivered to the home. See Appendix B for more information on the use of garrafones in Mexico.

### 3.6.3 Incommensurability

The above discussion on valuing the benefits derived from water implicitly makes the assumption that the benefits are substitutable; i.e., that the benefit can be compensated for, and that some value can be agreed upon that would be considered an acceptable exchange for the benefit (W Michael Hanemann, 2006). But many of the benefits derived from the use of the water not only do not lend themselves to economic valuation, but they can also be considered non-substitutable. In other words, they are irreplaceable and incommensurate. Waterbury (1997; pp 281) refers to this issue of non-substitutability and incommensurability when he comments that “countries do not share common measures of what constitutes legitimate demand” and that “Riparian claims typically combine incommensurables – human survival, economic growth, national security”

Several of the benefits derived from water in the USCRB fall into these categories. For example, in the USCRB, two non-substitutable uses of benefits stem from the use of water to meet basic human needs and the use of water for protection of endangered species, including the Gila Top Minnow. Not only are these two benefits irreplaceable, but trade-offs between the two cannot be easily imagined. A conversation with an Arizona government official, clearly illustrates this incommensurability. He quotes a Mexican official as having said “You [Arizona] wants water for your fish, but here in Mexico we have people without water to drink. God will punish you.” (Anonymous government official, June 2, 2006). Regardless of how accurately quoted the Mexican official’s words are, the conversation and interpretation of it by the Arizona official demonstrates the existence of different views on how water should be used. If benefits are considered non-substitutable, then not only is valuing those benefits impracticable because making tradeoffs between them will be inconceivable, and thus cooperative agreements may be more difficult to achieve.

Even were benefits to be substitutable, determining commensurability is complicated by the fact that frequently riparian countries are operating in different contexts, and thus the baseline values used for measurement are not equivalent. For example, based on the fees paid per unit of water (in Table 3-6 and Table 3-7 above), it is possible to calculate an average fees paid per unit water for both sides of the border (listed in Table 3-8). From this calculation, it can be seen that the cost per unit of water in Mexico is much higher than that in Arizona. One explanation for this difference might be that water is valued more in Mexico than in Arizona. I used fees paid as a lower bound on the value of water because they represent revealed preferences; they measure how much people actually spent for water, which suggests water was worth at least that much to those people.

Unfortunately, the use of fees paid as a proxy for value neglects to account for differences in the context of water supply. Differences in the supply mechanisms, the billing methods, and the financing mechanisms all influence the fees charged. On the Mexican side of the border, not only is water supplied through the piped municipal network, but it is also supplied via water trucks (pipas) and bulk bottles of water (garrafones). These provision mechanisms lead to higher per unit costs than a piped network because the operations cost (transportation) are higher and because capital costs are amortized over a shorter period of time. Even costs for piped water across the border cannot be directly compared, as in Nogales, Sonora, the piped water network experiences high losses (see footnote 62, on the order of 35-50%) and has a large number of

illegal connections, thus operations costs are averaged over a smaller amount of water than actually provided. Additionally financing mechanisms and subsidies have a large impact on fees charged for water, and thus differences between loans, grants, and regulatory requirements (including restrictions on fees charged) across the border need to be taken into consideration when comparing fees paid.

**Table 3-8: Average Fee Paid Per Unit Water (\$US/Mm3)**

SCAMA	Mexican Study Region
\$44,850	Low Estimate: \$779,289
	High Estimate: \$1,592,813

Moreover, the fees charged do not represent value, because they do not embed that quantity of money in the broader financial context. On average, SCAMA residents spend less than 2% of their income for domestic water use; whereas in Nogales, Sonora, residents spend approximately 10% of their income.<sup>85</sup> This suggests water is even more valuable in Mexico than suggested by a dollar by dollar comparison. Furthermore, one U.S. dollar in the SCAMA does not have the same value as it does in Mexico. This difference arises due to the currency market (exchange rates), and due to differences in both purchasing power and household incomes. Thus a simple comparison of fees, even when those are transformed to the same currency as above, does not convey the relative costs experienced by residents.

Furthermore, the fees charged do not necessarily represent full willingness to pay; rather they represent a minimum value. We can expect residents are willing to pay at least this much for water, as they are already doing so; however, they might place a greater value on water. For example, in Arizona, residents are accustomed to having cheap water service 24 hours per day and of being able to use any quantity of water they desire. Were they to experience a water provision environment similar to that in Mexico, residents might be willing to pay more and the lower bound estimate for water in Arizona might be closer to that of Mexico. Thus my estimate both underestimates the value of water in Mexico and likely also underestimates the value of water in Arizona; yet there is no systematic way for determining the extent to which each is underestimated. Regardless, I do not use this discussion to debunk the use of fees paid as a proxy for the value of water, nor to claim that an economic value cannot be determined for many of the benefits derived from water. Rather, I use it to illustrate the complexity in valuing the benefits derived from value and how efforts to convert benefits to commensurate values are subject to flaws.

The issues of non-substitutability and incommensurability to cooperation over shared waters cannot be avoided when evaluating and comparing the utility of possible cooperative or non-

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<sup>85</sup> Calculation of the percent of income spent for water in the SCAMA is based on average residential water tariffs paid to large providers and median household incomes in Santa Cruz County Arizona. Due to large differences in income and in the sources of water (piped, pipa, garrafone), the percentage of income spent on water in Nogales, Sonora varies widely. Nogales (Subdirector Urban Infrastructure and Public Works, Ayuntamiento de Nogales, Personal Communication, October 16, 2007) estimates that a family, employed in the maquiladoras, spends 10% of their income on water. Calculations using my tariffs paid estimates indicate a family earning 3500 pesos/month (the average income by a maquiladora worker) would spend between 4 and 23% of their income on water, depending on the estimated of the total the population in Nogales used and assumptions about how much water is supplied via pipas and garrafones.

cooperative water management strategies. Preferences for outcomes differ within and across countries, as does willingness to accept tradeoffs. Campbell (2003), in her discussion on intractability in environmental disputes, explains how disputes related to fundamental values and beliefs are more likely to resist resolution. In situations where differences in values and preferences are complementary, this may lead to increased possibilities for cooperation; yet in situations where they are not, cooperation may be all the more difficult to achieve.

### **3.7 Summary**

Throughout this chapter, I have argued that neither the US nor Mexico has a full understanding of the costs and benefits that could be derived from cooperative or non-cooperative water management strategies for the basin. In the section on contested visions, I explained how this uncertainty stems from diverging views of the water management objectives with and across the border. As will be discussed in more detail in Chapter 7, the lack of a clear vision for water management is related to the structure and authority of the water management institutions that govern the region. Next, using a ‘water needs’ approach, I attempted to quantify the amount of water that might be used to meet residential, non-residential municipal, industrial, agricultural, and environmental water demands now and into the future. Through these calculations, I demonstrated that there exists a high degree of uncertainty in any of these estimates due to insufficient current data, difficulty in predicting future conditions, and difficulty in estimating water needs for non-consumptive uses. I also explained how, by regulating water needs and restricting water uses, institutional factors serve to increase these uncertainties. Lastly, I explained how, the aforementioned uncertainties notwithstanding, the utility that might be derived from alternate water management activities remains unknown because the costs of adopting each strategy are not fully determined, valuing water is highly complex and benefits are frequently non-substitutable and incommensurate. As a result of complexity, understandings of the full costs and benefits of any possible water management strategies in the USCRB are incomplete.

The uncertainty created by contested visions, unknown needs, and incommensurability of benefits is not exclusive to the USCRB. Yet, I argue these uncertainties are more prevalent in the case of ground and waste waters. This is because flows of groundwater are difficult to understand and predict and because wastewater is a dual-nature resource. Moreover, as is explained in greater detail in Appendix A and Chapter 7, the authority to control usage of these resources is fragmented and restrictions or controls are difficult to enforce. Consequently, disparate views likely exist over how to best manage, the availability and impact of use of, and the benefits that can be derived from these resources.

The uncertainty analysis in this chapter demonstrates that neither the US nor Mexico has a clear picture of their water management objectives, nor the utility that can be derived from possible water management strategies. This finding leads me to challenge a ‘rationalist’ approach to negotiations over internationally shared waters, and in particular, over shared ground and waste waters. The current paradigm in the literature and promoted by organizations such as the World Bank (Sadoff & Grey, 2005), the Stockholm Water Management Institute (Jagerskog & Lundqvist, 2006), and the UNDP (UNDP, 2006), which states that cooperation can best be achieved through enacting the ‘pareto optimal’ management strategy or by maximizing gains through water sharing or benefit sharing, relies on the premise of rationalism.

Rationalism “draws on microeconomic theories in which political actors seek to maximize their utility within structural constraints, most importantly a lack of information about intentions” (Rathbun, 2007; pp 541) These constraints thus refer to what is considered strategic uncertainty; or rather incomplete information about other actors (Iida, 1993). However, I argue transboundary ground and waste waters are characterized by what Iida (1993) calls analytic uncertainty, i.e., uncertainty regarding the nature of the world. Thus a country negotiating over shared ground and waste waters operates in an environment where it does not know its own payoffs nor those of the other country. Beyond analytic uncertainty, I also argue that rationalism does not account for the differing perspectives commonly held by countries sharing water resources. These perspectives are better described by cognitive and constructivist approaches to international relations.

In the USCRB, I claim, as demonstrated in this chapter, analytic uncertainty manifests in the incomplete knowledge each country has regarding the amount of water desired or needed to meet management objectives and the value of that water. It is also manifest, as is discussed in chapter 4, in the lack of knowledge of the availability of water and the impacts of use on water levels and instream flows. However, strategic uncertainty also exists, due to differences in norms and values across the border. This uncertainty can be seen through the incommensurability in values described in this chapter, through the disparate perceptions of the amount of water available presented in Chapter 4, and through differences in the ‘ethos’ of water held by each country discussed in Chapter 8. The result is both the US and Mexico are not only unable to characterize their own payoffs, they also do not know the other country’s payoffs.

Due to my finding that a rationalist approach poorly captures the features of shared ground and waste waters, I argue we need to move beyond economic approaches to cooperation over those resources. Rather, I argue a more ‘post-normal’ approach is necessary to studies of transboundary water management, that accounts for uncertainties, “unpredictability, incomplete control, and a plurality of legitimate perspectives” (Funtowicz & Ravetz, 1993; pp739). Given the need to make management decisions now, while many uncertainties remain, I argue that rather than search for an ‘optimal’ or even a ‘win-win’ solution, practitioners involved transboundary water management might be better advised to seek incremental solutions that allow for adaptation as water management objectives are defined or shift and as knowledge increases.

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## **Chapter 4 : Hydrologic Uncertainty – Water Availability and Impacts of Use**

### **4.1 Hydrologic Uncertainty in Studies of Transboundary Water Management**

In Chapter 3, I showed how contested visions, unknown needs, and incommensurate values make it such that neither side of the border knows the utility it can derive from the implementation of alternate water management strategies. As a result of my findings, I challenge the application of ‘rationalist’ approaches to studies of transboundary ground and waste waters and argue for the need to examine the role of uncertainty and to adopt non-utilitarian approaches to analyses of shared water management. Here I build upon my claims from Chapter 3 and demonstrate that uncertainty stems not only from questions related to objectives and values, but also from the complexity of hydrology and a lack of knowledge of physical flows of water.

The literature on transboundary waters assumes countries know the quantity of water physically available as well as the impact possible water management strategies will have on hydrologic processes. Variability in flows and uncertainty are not considered.<sup>86</sup> Yet, as discussed in Chapter 3, water resources are characterized by uncertainty. Uncertainty regarding stream flow has already been shown to be a problem with the US-Mexico agreement over the Colorado and Rio Grande (Fischhendler, 2004; Mumme, 1999), as an inaccurate initial estimate of expected annual flows and the impacts of an extended drought have lead disagreements over treaty requirements. Not only can uncertainty and variability undermine the effectiveness of international agreements, even before an agreement is reached, uncertainty can impede negotiation and planning processes.

Transboundary ground and waste waters are characterized by analytic (model) uncertainty<sup>87</sup> because knowledge of the hydrologic system is incomplete. This uncertainty is both aleatory and epistemic. The stochastic nature of hydrologic flows is such that the availability of water changes due to climatic variation from year to year. This inherent variability is intensified by the complexity of flow processes. The movement of groundwater through an aquifer is rarely fully understood, in part due to an inability to completely characterize aquifer properties and their spatial distribution. Furthermore, stresses on the aquifer can have non-linear effects. The recharge of aquifers using wastewater is similarly full of uncertainties, because, in addition to the complexity of groundwater flows, nutrients in wastewater can lead to formation of aquitards or otherwise impede recharge. Moreover, the production and chemical properties of wastewater depend on the use of other waters, which may be uncertain or changing themselves.

In addition to analytic uncertainty, paradigms countries hold for the management of ground and wastewaters may differ, leading to different interpretations of water availability. For example, countries may have different conceptions of what constitutes ‘safe yield’ or other acceptable impacts of water use (for example, reductions in instream flows). They may also hold different

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<sup>86</sup> The one exception is a study by Fischhendler (2004) that analyzes why climatic uncertainty (flow variability) is not included in international water agreements.

<sup>87</sup> Here I use Iida (1993)’s definition of analytic uncertainty, sometimes also called ‘model’ uncertainty. This term refers to the fact that the model of the world being used is not fully determined. In other words, the processes at work are not fully understood.

ideals regarding the degree to which wastewaters should be treated. These differences can lead to disparate views of the quantity of water available for abstraction and use.

In this chapter, I demonstrate how in the USCRB the combination of analytic uncertainty and differing management paradigms leads the US and Mexico to differentially interpret the importance and usefulness of adopting joint water management strategies. I draw on insights gained from interviews and hydrologic studies of the basin to support my claims. To begin, I describe the hydrologic uncertainty<sup>88</sup> in the USCRB, explaining how it arises from incomplete knowledge of hydrologic processes and is exacerbated by institutional factors. I then present water use priorities for both sides of the border. These differing views on the prioritization of water use, combined with hydrologic uncertainty, lead to disparate views on the availability of water, the impacts of pumping, and possibilities for recharge.

## **4.2 Uncertainty of Hydrologic Processes in the USCRB**

As mentioned previously, understandings of hydrologic processes in the USCRB are incomplete. Neither side of the border has full knowledge of how much water is available. The connection between surface water and groundwater is also unknown. The impact of pumping both within and across the border on groundwater levels and instream flows is also uncertain. Similarly, the quantity of effluent released from the NIWTP that recharges the aquifer is unknown, as is the full potential for aquifer recharge in the region. Lastly, there remain many uncertainties regarding the impact climate change will have on water resources in the basin.

### **4.2.1 Groundwater Flows: Availability and Impacts of Use**

With respect to groundwater, the two questions of concern are how much water is available for use and how water use impacts water table levels. Water availability includes not only the quantity of water that can be used but also the location where that water can be obtained and when that water is available. The impact of water use on water levels is important because depth to water is a key determinant of pumping costs, vegetative growth, and river flows.

Oreskes (2003) explains how knowledge of natural systems, and particularly systems in the earth sciences, is often incomplete. Groundwater systems are no exception, and, groundwater flow processes are characterized by uncertainty for a number of reasons. One is that hydrogeologic properties of an aquifer vary spatially and may be quite heterogeneous. Large amounts of data must be collected in order to describe the aquifer, and even then it is not possible to completely determine the properties of the aquifer at all locations. Without sufficient testing and data, key features of the aquifer that impact flows, such as fractures, impermeable regions, and high/low conductivity lenses, may be easily overlooked. Groundwater flows are also complicated to predict because they occur in three-dimensional space and include a temporal component. Not only can flows change direction over time, the impact of stresses on the system, such as water abstractions, may not be evidenced immediately and may have a non-linear impact on flows and water levels. Stresses that cause the groundwater gradient to shift can also induce recharge. This makes estimating groundwater availability even more complex, as it means water use patterns influence water availability.

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<sup>88</sup> For the purposes of this chapter, I use the term ‘hydrologic uncertainty’ to refer in general to uncertainty regarding flows of water and the impact of water use, regardless of the source of that uncertainty.

In the USCRB, knowledge of the portion of the aquifer located in the US side of the border is greater than of the portion located in the Mexican side of the border, as more data is available and more hydro-geologic tests have been performed. Nonetheless, hydrologic processes in Mexico impact the US, and consequently, uncertainties in Mexico lead to uncertainties in the US. In Chapters 4 and 4\*, I explain in great detail the gaps in data and uncertainties in the conceptual model of the aquifer on the Mexican side of the border.

Understandings of groundwater flows in the USCRB are limited, primarily due to the complexity of characterizing the aquifer and a paucity of data. On both sides of the border, multiple microbasins have formed in locations where the aquifer narrows and bedrock rises to the surface. Experts in the region have not yet determined the geometry of these microbasins, nor do they know the geometry of many other sections of the aquifer. Due to insufficient testing and a limited number of piezometric measurements, the hydrogeologic properties of each strata of the aquifer have not been fully determined and it is unclear if vertical flow occurs. Hydrologists in the region speculate fractures in the lower strata and unseen faults may play a large role in conveying water ( ADWR, Personal Communication, September 17, 2007; Geologist, Personal Communication, October 11, 2007); however, the extent to which this occurs is not known. In general, flow processes are not fully understood and the impact of groundwater abstractions on groundwater levels and base flow in the stream is unknown. An expert hydrogeologist in the region, best describes the situation best when he said “[the system] is not all linear, so you can’t immediately tell what is happening.” (Personal Communication, October 11, 2007)

#### 4.2.2 Recharge of Effluent

In the USCRB, uncertainty in groundwater flow processes is directly related to knowledge of wastewater recharge possibilities. Without a clear understanding of the groundwater system, including surface-groundwater interactions, potential recharge of the aquifer using treated wastewater remains unknown. If effluent is released to a streambed, the rate and extent of recharge is governed by streambed properties, aquifer characteristics and conditions, and the chemical properties of the wastewater. High nutrient loads in the effluent can lead to the formation of an aquitard, or semi-impermeable layer, which impedes infiltration of effluent released in a streambed to the aquifer (McCoy, 2008). Direct recharge, through injection, will depend on well properties and conditions, as well as the aquifer. The quantity of recharge of effluent released by the NIWTP is uncertain, as is the potential for recharge of effluent that might be released from the planned PTAR Los Alisos.

Although estimates of current recharge to the aquifer by effluent released from the NIWTP exist, these estimates cannot be assumed to accurately predict future conditions. Recharge by effluent released from the NIWTP in 1995 was estimated to be between 3,155 to 5,607 AF (Scott, MacNish, & Maddock III, 1997). The ADWR quasi-steady state groundwater model of the region<sup>89</sup> similarly predicted effluent recharge as approximately 3,300 AF/year between 1997 and 2002. Even were the quantity of effluent released from the NIWTP to remain constant, it cannot be assumed that future recharge would mirror the past. Increased pumping and climatic changes may have a sizeable impact on aquifer conditions, which would impact recharge rates. Changes to the intensity and duration of storm events will also impact recharge, as flood flows scour the streambed, and may wash away the clogging layer thought to occur downstream from the

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<sup>89</sup> See Chapter 4 for more information on this model.

NIWTP (ADWR, Personal Communication, September 17, 2007). The planned upgrade to the NIWTP will also impact this clogging layer, as it will lower the ammonia and nitrogen concentrations of the effluent.

Not only is future recharge of wastewater from the NIWTP uncertain, the potential for recharge of wastewater released by the planned PTAR Los Alisos is completely unknown. Interviews with water managers in Mexico indicate no studies of recharge potential in Los Alisos have been conducted (OOMAPAS, Personal Communication, September 22, 2007; COCEF, Personal Communication, September 27, 2007; CONAGUA, Personal Communication, October 7, 2007; CEAS, Personal Communication, October 8, 2007). The Ambos Nogales Facility Plan is the only study to analyze locations for recharge possibilities on the Mexican side of the border yet it includes the caveat that “none of the sites considered have been characterized to sufficient detail for purposes of applying sophisticated numerical analysis methods” (Camp Dresser & McGee, 1997, pp 8-61). The study uses assumed infiltration rates, rather than empirical data, to estimate potential recharge, and thus its recharge estimates are quite rudimentary. Water managers in Mexico hold different conceptions regarding how recharge will occur. Recharge by effluent released from the planned new treatment plant to the Los Alisos riverbed is either expected to provide additional water to OOMAPAS wells located downstream in the Los Alisos basin (OOMAPAS, Personal Communication, May 30, 2006) or to follow a groundwater gradient away from the Los Alisos river and back towards the Nogales Wash aquifer that runs through the center of Heroica Nogales (OOMAPAS, Personal Communication, September 21, 2007). Without knowledge of which of these conceptual models is correct, OOMAPAS cannot accurately predict how treated effluent from the PTAR Los Alisos might contribute to water availability.

#### 4.2.3 Climate Change

Not only are groundwater flow processes and the potential for effluent recharge poorly understood, uncertainty in the region also stems from the unknown impact of future climate change. The USCRB experienced an extended drought between 1996 and 2004 (Goodrich & Ellis, 2006) and there are fears drought conditions will continue into the future. Although 2007-2008 was wetter than average (ADWR, 2008a), it is expected the US southwest and northern Mexico will become hotter and drier (Kaufman, 2007; Stonestrom & Harrill, 2007) and that climate change will impact the frequency and intensity of precipitation events in the region. As these changes are at present, unpredictable, they serve to increase uncertainty about future water availability in the USCRB.

### 4.3 Interaction of Institutions with Hydrologic Uncertainty

The above discussion describes how uncertainty regarding water availability, the impacts of water use, and the potential for aquifer recharge stem from incomplete understandings of physical processes in the USCRB. In addition, institutional factors mediate knowledge of water resources in the region, adding to hydrologic uncertainty. In the USCRB, three institutional factors serve to increase uncertainty: legal definitions, uncontrolled abstractions, and institutional technical capacity.

#### 4.3.1 Legal Definitions

On the US side of the border, legal distinctions between groundwater and surface waters increase uncertainty regarding water availability. In the SCAMA, surface waters rights are appropriable, whereas the right to use ground waters is only granted to those owning grandfathered groundwater rights, service providers, and people withdrawing water from ‘exempt’ wells.<sup>90</sup> As most water in the SCAMA is withdrawn from wells located in close proximity to the Santa Cruz River, distinguishing between water that is sub-flow (underground surface waters), which would be considered appropriable, and that is percolating ground water is key to estimating water availability (ADWR, 1997).<sup>91</sup> While categorizing the water as surface or ground water does not change the total amount of water available in the region, it impacts knowledge of and the ability to control water use.

Many water rights holders in the SCAMA own duplicative rights to water, i.e., they possess both a surface and a groundwater right to the same water. Duplicative rights arose when the Arizona Groundwater Management Act of 1980 was passed, and all groundwater users in Active Management Areas were required to file for grandfathered water rights in order to continue to withdraw water. Water users in the SCAMA were unsure if the water they had historically used, which was extracted from shallow wells, would be classified as surface or ground water. Thus, in order to protect their rights, most water users filed for grandfathered ground water rights, despite already holding surface water rights. As a result, large water rights holders in the SCAMA possess both surface and groundwater rights for the water they have historically used. In addition, more surface water rights have been granted than physical water exists (ADWR, 1997).<sup>92</sup> Although water rights holders with duplicate rights do not use twice as much water as previously, the presence of dual rights represents a management challenge because it makes it difficult for ADWR to predict the amount of water that will be used in the SCAMA.<sup>93</sup> Knowledge of the amount of water already in use is important when predicting the availability of water supplies for the purpose of granting additional rights.

#### 4.3.2 Unrestricted Exempt Well Pumping

Abstractions from ‘exempt’ wells in the SCAMA also create uncertainties in estimates of available water on the US side of the border. Exempt wells are wells from which less than 35 gallons per minute or 10 AF per year is abstracted (ADWR, 2008b). These wells are primarily

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<sup>90</sup> For a definition and additional details on ‘exempt’ wells, see below in section 0. In addition to water abstracted by service providers, grandfathered groundwater rights holders, and exempt well owners, a user may obtain a “withdraw” permit to abstract groundwater. These permits are usually only provided for uses such as dewatering or industrial use (ADWR, n.d.).

<sup>91</sup> A 1994 court ruling provides guidance on distinguishing between subflow and percolating groundwater in the SCAMA. This definition considers subflow to be waters located in the “saturated floodplain holocene alluvium”, among other characteristics considered to distinguish sub-flow (ADWR, 1997, pp 36). However, this definition has yet to be certified by the Arizona Supreme Court.

<sup>92</sup> Adjudication of property rights for the Gila River basin, to which the Santa Cruz is a tributary, is in process. In anticipation of this adjudication, large water rights holders in the SCAMA have hired legal counsel and are working to reach a settlement agreement (ADWR, Personal Communication, September 21, 2006; Lawyer, Personal Communication, October 5, 2007; Lawyer, Personal Communication, October 12, 2007; Lawyer, Personal Communication, October 18, 2007).

<sup>93</sup> Although with the exception of ‘exempt wells,’ both surface water and groundwater users report their water use to ADWR on an annual basis, this reporting is made post-facto, and technically, dual rights holders could use the full amount of their surface and ground water rights in any given year.

used for domestic use or stock watering. Exempt well owners are not required to measure or report withdrawals to ADWR. Any private land owner who wishes to drill an exempt well may do so, so long as the well meets certain location requirements. Similar to the duplicates rights problem, exempt wells make it difficult for ADWR to predict the amount of water that will be in use in the future.

The Arizona Groundwater Management Code was developed in order to assure sufficient water to meet the needs of citizens. The code requires those wishing to sub-divide their land to demonstrate a 100-year assured water supply<sup>94</sup> before permits are approved. However, land may be subdivided into up to six lots without demonstrating an assured supply. Subsequently, those six lots may subdivide into up to six additional lots, and so on. Each of these smaller lots can drill its own private exempt well. The result, as one land developer in the region describes it, could be “thousands of straws all drawing out of the same bucket, and you don’t know how much they are taking out” (Real Estate Developer, Personal Communication, October 10, 2007). Consequently, ADWR cannot know much water is being or will be withdrawn from the system, even were all other aspects of the water budget to be accurate.

#### 4.3.3 Data Information and Technical Capacities

The above mentioned institutional arrangements create uncertainty by impeding the ability of water managers in the region to estimate how much water in the system is available for use. In addition, the technical capacity of the water management in the USCRB adds to this uncertainty.

Within the US side of the basin, resource constraints faced by water management agencies limit technical capacity. In the SCAMA, the institution most responsible for managing hydrologic information is the Arizona Department of Water Resources. ADWR is a highly respected institution, known to be staffed by trained specialists and to be thorough in data collection and management. However, the ADWR office for the SCAMA is quite small. It is staffed by three employees, who are largely tasked with permitting, supervisory and coordination activities. Although two possess in-depth understandings of water, none of the three staff members are trained hydrologists. Technical studies are performed by hydrologists in the ADWR central office or by hired contractors. Yet specialists in the ADWR central office are responsible for conducting studies and developing models for the entire state and must balance their time and resources across a diversity of locations. Moreover, although ADWR has collected a large amount of data from stream gauges (some run by the USGS) and well monitoring, it does not have measurements of stream flow in tributaries to the Santa Cruz River. ADWR has also been unable to conduct the extent of hydrogeologic testing needed to fully characterize the aquifer in the USCRB, nor has it been able to develop a groundwater model of the Potrero Creek sub-area. Stream gauges, well monitoring devices, hydrogeologic testing, and other monitoring and research activities require funding and personnel time, both of which are limited by budget and other resource constraints. In truth, ADWR probably collects more data and contains more technical know-how than many other water management institutions in the world. The fact that, despite their efforts, uncertainties remain is emblematic of the inherent complexity of groundwater combined with real-world constraints faced by all water management agencies.

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<sup>94</sup> See Chapter 2 footnote 37 for additional details on the assured supply requirements.

Within the Mexican portion of the basin, resource constraints also impact technical capabilities. Mexico is not as economically well-to-do as the US, and, it also faces many problems that extending beyond water management.<sup>95</sup> In terms of hydrologic importance, the Santa Cruz River basin is not the most pressing of Mexico's water management concerns, in part because relative to other areas in Mexico, it has a small population, it is not the most environmentally impacted, and it is not economically marginalized.

Beyond (although closely related to) resource constraints, hydrologic uncertainty in the Mexican portion of the basin also results from of a lack of hydrologic monitoring/data collection combined with limited technical expertise. The Mexican National Water Commission is the agency with the most information on the hydrology of the region. The CONAGUA has collected some information on groundwater abstractions, mostly based on concession permits; however, measurements of flow in the Santa Cruz river and its tributaries and observations of depth to water levels are not collected on a regular basis. Hydrogeologic testing has also been sparse.<sup>96</sup> The limited data on the aquifer which exists is distributed between the CONAGUA central office, located in Mexico City, and various departments within the CONAGUA Sonora office, located in Hermosillo. The exact whereabouts of where data is stored is not well known by CONAGUA employees. For example, although one technical report cites piezometric measurements from a number of years in the past<sup>97</sup> (SeismoControl, 1995), CONAGUA employees I met with in Hermosillo were only able to locate the most recent (2002) water level measurements. Moreover, officials in the Sonora office were unaware of reports and studies previously conducted that were stored in the Mexico City office. As I discuss in Chapter 5, Mexico has been decentralizing management and control over water resources. This transfer of responsibilities, combined with changes within offices,<sup>98</sup> contributes to confusion over the data and studies that exist.

In addition to uncertainty created by a lack of data, additional uncertainty arises from the paucity of trained hydrogeologists and groundwater specialists in Mexico. One 2003 study claims "there are only thirteen Ph.D.'s in hydrogeology in Mexico...If one considers related disciplines such as mathematics, geophysics, geochemistry and geology, the number of scientists working in groundwater related areas increases to over 30 persons" (Ragone et al., 2003, pp 295). During an interview with technical personnel in the CONAGUA Hermosillo office, I was told only one employee in that office was familiar with groundwater modeling, and, as the CONAGUA was just beginning to adopt modeling as a general practice, most employees do not have the expertise to develop, run, or interpret those models ( CONAGUA, Personal Communication, October 7, 2007). Although groundwater modeling studies have been performed in Mexico,<sup>99</sup> these are

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<sup>95</sup> For example, in Heroica Nogales, drug trafficking, violence, and poverty are salient problems.

<sup>96</sup> A detailed analysis of the availability of hydrologic data for the Mexican portion of the basin is included in Chapter 4.

<sup>97</sup> According to (SeismoControl, 1996), piezometric measurements are available for 1963, 1972, 1974, 1989, and 1997.

<sup>98</sup> One such internal change was that the CONAGUA library in Hermosillo was reorganized and moved (Martin CONAGUA, personal communication, October 7, 2007).

<sup>99</sup> Most groundwater modeling studies in Mexico analyze flows for aquifers that serve large populations and are in critical condition, such as the Hermosillo aquifer, which is experiencing severe salt-water intrusion problems (CONAGUA, Personal Communication, October 7, 2007). In Chapter 4, I discuss the groundwater studies that have been conducted on the Mexican portion of the USCRB.



primarily developed by contractors and the results have not been used or interpreted by water managers in the USCRB.

The above discussion on data collection and management, technical expertise, exempt wells, and duplicate water rights, illustrates some of the ways in which institutional arrangements in the USCRB mediate knowledge. Insufficient data and technical expertise impede understandings of groundwater flow processes, as information about the physical system and knowledge of how to interpret that information are essential to the development and validation of conceptual models of the aquifer. Institutional management policies that hinder monitoring and prediction of water use, such as exempt wells and duplicate water rights, serve to increase uncertainty by impeding estimates of water availability. Both contribute to analytic uncertainty, in that they result in incomplete understandings of physical processes, which translate into uncertainty regarding water availability and the impact of water use.

#### **4.4 Perceptions of Availability, Impact of Use**

I have now shown how the complexity of hydrologic processes (groundwater flows and wastewater recharge) and institutional factors contribute to analytic uncertainty. I have also explained how the literature on transboundary waters fails to address the role of analytic uncertainty, despite the fact that ground and wastewaters are characterized by a high degree of uncertainty. Next, I describe how differing management paradigms combine with this uncertainty, allowing for the formation of disparate perceptions of water availability and the impact of water use. The opinions each country holds influence which water management activities it deems necessary and its expected utility of those activities; in other words, these perceptions determine the acceptability of water management strategies.

##### **4.4.1 Management Paradigms**

As described in Chapter 3, the US and Mexico hold differing views on how water use should be prioritized. Within the SCAMA, environmental water needs are protected, whereas within Mexico, human water needs take priority. These differences contribute to disparate perspectives of water availability as they influence how each country defines the amount of water acceptable to withdraw from the aquifer.

The stated goals of the SCAMA are to achieve safe yield and to prevent local water tables from experiencing long-term declines (ADWR, 1995b). Determining what constitutes safe yield or stable water levels is complex, due to the inherent variability in climate, spatial heterogeneity, and ambiguity in the definition of safe yield (Kalf & Woolley, 2005). ADWR has adopted a mathematical approach, based on standard deviations of historic water levels and water balance<sup>100</sup> calculations (ADWR, 2007; Corkhill, 2006) to defining these goals. This method is intended to be value neutral, in that it does not directly address debates within Arizona regarding prioritization of water uses, rather it preferences historic water uses. Nonetheless, this goal serves to protect environmental water uses, in that it assures the aquifer will not be over-exploited and water table levels will not drop substantially.

Environmental protection and conservation is a salient concern in the SCAMA, and a topic frequently mentioned at public meetings, including meetings of the ADWR Groundwater User

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<sup>100</sup> ADWR estimates of water balances of course, are subject to the above mentioned uncertainties.

Advisory Council, the Transboundary Aquifer Assessment Act, and the Santa Cruz County Department of Community Development. Although the extent of environmental protection required is debated, it is generally agreed that some degree of protection is required. Even developers in the region who disagree on the extent of the riparian corridor that should be protected agree it is an amenity and should be maintained (Real Estate Developer, Personal Communication, October 10, 2007; Real Estate Agent, Personal Communication, October 1, 2007; GUAC Member, Personal Communication June 16, 2006).

This mindset, of ensuring some water for environmental protection, is very different from that in Mexico, where water managers are more concerned with meeting the needs of their growing population. Water for human use is prioritized over water for the environment. This paradigm was expressed quite clearly by one Mexican official, who, at a meeting for the Transboundary Aquifer Assessment Act on January 28, 2008, said

“The main thing in Mexico is we still haven’t developed our supplies, we have not yet gotten to worries about trees and the environment. We still need water for people.”

This statement is in agreement with recommendations made in a 1995 water availability study of the Santa Cruz and Los Alisos aquifers. The study recommended increasing pumping in order to capture water transpired by the riparian vegetation (SeismoControl, 1995, pp 54). This prioritization of human water needs before environmental needs is also evidenced by efforts of the CONAGUA to preference water for municipal providers, even if they will withdraw water from aquifers considered to be over exploited.

“We are talking about water for human consumption and we can’t say they [municipal water providers] can’t use it just because they are located in a restricted zone.<sup>101</sup>”  
(CONAGUA, Personal Communication, October 8, 2007).

Differences in prioritization of water use between the US and Mexico contribute to disparate perceptions of the amount of water availability. In the US, the amount of water seen as available for use is limited by safe yield and stable water level requirements. In Mexico, water availability is not limited by environmental concerns; rather the priority is to obtain the water needed to meet human needs. Thus the two countries hold conflicting views of how much water ‘can’ or rather ‘should’ be abstracted from the aquifer. This difference in management paradigms represents value differences and is illustrative of the challenges of incommensurability, discussed in Chapter 3, to the management of internationally shared waters.

#### 4.4.2 US Perspectives

Within the SCAMA, there are conflicting views about the availability of water and the impact of additional water use. For example, one rancher, who is a member of the SCAMA Groundwater User Advisory Council (GUAC), claims “There is a limit on the amount of water available and the county is quickly reaching that limit” (GUAC, Personal Communication, October 1, 2007). Whereas another member of the GUAC, a developer, believes “The SCAMA is quite away from impacting the water table. There is enough water, the problem is the riparian habitat is on

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<sup>101</sup> The CONAGUA closely regulates groundwater extractions in designated restriction zones, termed “zonas de veda.” In these zones, the CONAGUA does not authorize additional water concessions due to deterioration in water quality or over exploitation of the aquifer (Estados Unidos Mexicanos, 2004).

steroids and exempt wells are uncontrolled” (GUAC, Personal Communication, June 16, 2006). Differences in views on the availability of water are related to individual preferences for development versus environmental protection. None-the-less, all persons I interviewed agreed water in the region is a limited resource, that unlimited growth is not possible, and that water needs to be managed carefully.

Increased groundwater pumping in Mexico is thought to have an adverse impact on both water availability and stream flow in Arizona. An ADWR evaluation of the impact of future Mexico well field expansion states that “(n)egative effects on the Santa Cruz AMA would occur from the expansion of the Mascarenas-Paredes well fields” (ADWR, 1995a, pp 6). This study claims increased groundwater abstractions in Mexico would result in depleted alluvial storage and a reduction in stream flow crossing the border. The result would be reduced supplies to the City of Nogales, Arizona during low flow-seasons seasons (late spring-early summer, and late fall) and drought years and possible damage to the riparian environment. Interviews with large water rights holders, developers, and environmentalists indicate they concur with this assessment and feel the detrimental impacts of increased Mexican water use must be addressed. As one interviewee describes the situation, “We’ve got to come to some sort of agreement with Mexico, the (SC)AMA cannot go on a lot longer with the dark cloud of what is going to happen hanging over our heads” (Water rights holder, Personal Communication, October 10, 2007).

However, water specialists in the region also acknowledge the complexity of the aquifer. The top and most productive layer of the aquifer, the younger alluvium, is relatively shallow and has a high conductivity. This, as well as the presence of microbasin formations may limit the impact of Mexican pumping on underflow into Arizona (ADWR, Personal Communication, September 17, 2007). Moreover, although declines in the summer baseflow at the Nogales stream gauge (Shamir, Georgakakos, Graham, & Wang, 2005) may be attributable to capture by Mexican pumping, they may also be caused by other changes, such as channelization of the river or increased riparian vegetation (ADWR, TAA meeting, April 28, 2007). Thus although in general it is believed that Mexican water use has a negative impact on water supplies in Arizona, there remains some uncertainty regarding those impacts.

#### 4.4.3 Mexico Perspectives

In Mexico, water managers have a different perception regarding water availability and the impact of water use across the border. OOMAPAS claims to have experienced a water shortage of approximately 350 lps in 2005 (OOMAPAS, Personal Communication, July 14, 2005) or 200 lps in 2007 ( OOMAPAS, Personal Communication, September 21, 2007). However, this shortage is not believed to have been caused to a lack of water; rather it is believed to be the result of insufficient funding for the construction of additional infrastructure as well as the need to repair existing infrastructure (OOMAPAS, Personal Communication, September 22, 2007). As an OOMAPAS employee describes the situation, “there is enough water in the subsoil, the problem is not the availability of water, the problem is the funding to provide infrastructure. There are many places where OOMAPAS could drill more wells and capture subflow, and there is plenty of groundwater, but we cannot access it because we do not have the funds to pay for the infrastructure” ( OOMAPAS, October 4, 2007).

This perspective, that there is indeed additional water available for use, is supported by CONAGUA studies of the Santa Cruz aquifer. One study conducts a water balance analysis and determines withdrawals are less than recharge (Comision Nacional del Agua, n.d.). Two other studies also recommend increasing pumping in the Paredes and Mezquital sections of the Santa Cruz aquifer (SeismoControl, 1995, 1996).<sup>102</sup>

With respect to the impact of water use across the border, it is thought that any effect will be minimal. Interviewees told me they expect no significant impact on Arizona for a variety of reasons. First, cross-border underflow into the US is thought to be small, less than 1 Mm<sup>3</sup>/year (SeismoControl, 1995), a quantity not considered to be significant. Interviewees also claimed OOMAPAS mostly extracts water from shallow wells, thus any impacts would affect sub-flow (underground surface waters associated with the river), rather than on groundwater in Arizona. Moreover, the aquifer is shallow and highly transmissive, which, combined with the microbasin geology, limits the distance impacts will be felt downstream. Lastly, water managers stated that the Santa Cruz river is (and remains) a gaining stream, and thus OOMAPAS is only diverting water that stems from Mexican territory. Although these factors serve to signify some constraints on impact of pumping across the border, they are insufficient to conclusively rule out negative cross-border impacts of increased groundwater use. Instead, the incompleteness of these rationales serves to illustrate limited understandings of hydrologic processes. Regardless, responses by interviewees demonstrate the Mexican perspective that there is additional water available for use and that increased water use will not have a detrimental impact across the border.

I highlight the differences in perspectives held by the US and Mexico regarding the availability of water and the impact of water use in the USCRB because these differences are useful for understanding the position of each country when evaluating the usefulness of alternate water management strategies. For example, the US holds the view that water resource availability is limited and additional pumping in Mexico will negatively impact supplies in Arizona. Whereas the perspective of Mexico is that additional water can be abstracted from the aquifer and that this abstraction will have a minimal impact on the US. Thus, from the Mexican point of view, an agreement to limit pumping in the Santa Cruz aquifer is not needed to protect the US<sup>103</sup>.

#### **4.5 Impact of Hydrologic Uncertainty on Water Management in the USCRB**

In this chapter I demonstrated neither the US nor Mexico knows the quantity of groundwater available nor the expected impact additional groundwater pumping will have on water table levels and stream flows. Rather, as is explained in detail in Chapter 5, groundwater flows in the region are poorly understood and conceptualizations of the aquifer are incomplete. Furthermore, both the amount of the effluent currently infiltrating to the aquifer and the recharge which could be achieved were the effluent to be released elsewhere have yet to be determined. Institutional arrangements mediate the production and interpretation of information and thus compound

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<sup>102</sup> However, as discussed in depth in Chapter 6, the Seismocontrol (1996) study makes the assumption that the aquifer is in steady-state equilibrium and then calibrates the amount of recharge that would be required to be in equilibrium. The study's recommendation to increase pumping relies on this steady-state assumption, which is contestable.

<sup>103</sup> Here I do not claim that Mexico would not see other benefits to entering into an agreement limiting abstractions, such as improved relations/good will.

uncertainty. Both the existence of exempt wells and ill-defined legal distinctions between ground and surface waters make it such that water managers cannot track all historic or monitor/control current and future water abstractions. This, combined with limited technical capacity, increases hydrologic uncertainty. I then explained how the US and Mexico prioritize water use differently and this, combined with hydrologic uncertainty, has lead each country to hold different perceptions of water availability and the impacts of water use.

The implication of my findings is that, where a high degree of hydrologic uncertainty exists countries will not have complete understandings of the expected outcomes from water management activities. Moreover, where management paradigms and thus values differ, perceptions of the costs and benefits of enacting alternate water management strategies will differ. These uncertainties argue against the usefulness seeking a “pareto-optimal” water management plan.

The uncertainties I find in the USCRB support my claim that we need to move beyond rationalist approaches to transboundary water management. The analytic uncertainty which characterizes knowledge of groundwater flows in the USCRB fits Rathbun’s description of the role played by uncertainty in cognitivism. Rathbun explains that in cognitivism, uncertainty arises from the fact that “actors do not understand the cause and effect relationships of the environment in which they are operating” (Rathbun, 2007, pp 545). This contrasts with uncertainty in rationalism, where uncertainty is manifest in actor’s lack of knowledge of the intentions of other actors. Moreover, differences between the US’s and Mexico’s perceptions of water availability and the impact of water use fit Rathbun’s claim that “in rationalism and realism, individual actors will perceive and interpret the same stimuli similarly, whereas in cognitive and constructivist theories they are filtered through belief systems, identities, norms, images, or other heuristics that often vary across actors and states.” (Rathbun, 2007, pp 535). In this thesis, I argue neither for completely discarding rationalist approaches, nor assuming a purely cognitive or a constructivist approach to transboundary waters. The best characterization of actors and decision making in the management of shared ground and waste waters is a topic for further inquiry.

In the next chapter, I adopt a more technical analysis of hydrologic uncertainty in the USCRB. Using groundwater modeling, I describe in more detail the availability of information on the aquifer and what can be discerned from this information. The goal of that chapter is not only to determine the uncertainty characterizing the aquifer, but to provide constructive suggestions to water managers in the region on what can be done to reduce that uncertainty. Following Chapter 5, in the remainder of this dissertation, I return to my explanation of factors creating uncertainty and elucidate in more depth how institutional arrangements and the ‘ethos’ of water management held by each country impact water management decisions.

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## **Chapter 5 : Hydrologic Uncertainty – Knowledge of Aquifer Behavior**

### **5.1 Introduction**

As discussed in Chapter 4, neither side of the border has a complete understanding of flows of groundwater in the region; they do not know how much water is available at any given location and time, how much water flows across the border, and what the impact of future stresses will be on the system. That uncertainty exists is clear, what remains unclear is what are the causes of this uncertainty, what are the implications of this uncertainty, and to what degree this uncertainty can be reduced.

In this chapter and in Chapter 6, I address these questions through an analysis of the hydro-geologic data available and via groundwater modeling. Through my analysis, I demonstrate the complexity of groundwater and the many uncertainties that characterize our knowledge of groundwater systems. I show how understanding aquifer behavior requires large amounts of data, which in many cases either does not exist or is inconsistent. I evaluate our ability, given the amount of available information and the uncertainty that exists, to understand and predict behavior of the portion of the aquifer located on the Mexican side of the border. I also explain what aspects of the aquifer are unknown and which of these unknowns appears to be most important. Lastly, I explain how, in the face of uncertainty, the assumptions we make about the aquifer can influence our predictions of aquifer behavior and I draw conclusions about the implications of this for transboundary groundwater management in general.

My results indicate there remain many unresolved questions regarding the hydrology of the region. These uncertainties stem from a combination of factors including: i) insufficient data, data consistency problems, and measurement variability and error in data collection and storage, ii) the complexity of the hydrogeology of the region, iii) limitations on our ability to predict future stresses, iv) and limitations on our ability to model groundwater processes. The implication of this uncertainty is there remain a number of divergent ways to interpret the available information and each interpretation leads to different perceptions of how the aquifer behaves under a given set of stresses. In Chapter 4, I discussed how water managers hold different opinions about the amount of water available and the impact of pumping on flows in the region and I explained how these differences of opinion were partly discursive. Here I build on Chapter 4 to show how the complexity of groundwater systems, combined with limited data availability, results in neither the USA nor Mexico having a full understanding of flows of water in the USCRB. In Chapter 8, I take this analysis one step further, to show how perceptions of aquifer behavior relate to each country's ethos of water management and to the management strategies the country eventually adopts.

Much of my discussion (in this chapter and in Chapter 6) centers on groundwater models that have been developed for the region and the challenges which arise when attempting to model the Mexican portion of the aquifer. I am using this discussion on groundwater modeling instrumentally – as a way of structuring my analysis of the uncertainty in the region. Models are representations, simplifications of the system which can be useful tools in augmenting our understandings; they help us in understanding complex processes and interactions. Development



of a functioning model is not the end-goal, nor does the existence of a model mean we have an accurate or a complete understanding of the system. None-the-less, in order to develop a model, we must start with assumptions and understandings of the system. Thus by evaluating the groundwater simulation models which exist and the understandings upon which they are based, what I am actually doing is determining our state of knowledge of the aquifer.

I also choose to discuss groundwater modeling in detail for another reason. Much of the discussion on transboundary water management has focused on adopting “economic” approaches to cooperation; these approaches involve ‘objectively’ analyzing the basin (or in this case, the aquifer) in order to develop the optimal management activities and to distribute the benefits amongst countries (Phillips & Jagerskog, 2006; Sadoff & Grey, 2005; Wolf, 2007). Modeling is often presented as the most scientifically objective mechanism for understanding flows through an aquifer – the idea is that if the physics is correct, the scientific data accurate, then the model results will tell a “truth”, which will become a non-contested starting point for international negotiations. It is argued that the process of jointly developing water models can help to reduce tensions and build consensus (Lund & Palmer, 1997; Nandalal & Simonovic, 2003).<sup>104</sup> Yet, my research shows that that in the case of transboundary aquifers, modeling may not be the panacea it is believed to be. Throughout this chapter and the next, I make three points regarding the usefulness of groundwater modeling in transboundary settings. The first is quite simply that developing a cross-border model may be quite challenging due to difficulties in obtaining, sharing, and merging data across a border. The second is that even scientifically advanced tools such as groundwater modeling may not be able to resolve the uncertainty that exists. And my last, and perhaps most important point, which has implications that will be discussed in Chapter 8, is that in the face of uncertainty, even a seemingly objective tool can be biased or used strategically.

The focus of my analysis is on the Mexican side of the border. I adopted this focus for two primary reasons. First, due to the topography and hydrogeology of the region, flows of water in Sonora have a greater impact on Arizona than flows in Arizona have on Sonora.<sup>105</sup> Thus understanding flows of water in Arizona requires knowledge about processes on the Mexican side of the border. Secondly, the Mexican portion of the aquifer is less studied and less well understood. The Arizona Department of Water Resources has invested a large amount of resources/energy in studying the Arizona portion of the basin, and continues to actively advance research for the region. Thus in directing my efforts to the Sonoran portion of the basin, my analysis will be most useful to stakeholders in the region.

I begin with a discussion on groundwater modeling and its constraints. This discussion is followed by a description of past groundwater modeling efforts in the USCRB, their

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<sup>104</sup> The joint development of computer models is thought to be useful in conflict resolution because the process leads to “further understanding of the problem, formalizing performance objectives, developing promising alternatives, evaluation of alternatives, providing confidence in solutions and providing a forum for negotiation” (Nandalal & Simonovic, 2003)

<sup>105</sup> In Appendix A, I explain that the nature of flow in aquifers is different from that of rivers, in that flows through an aquifer may not be uni-directional and directionality may change depending upon the stresses in the aquifer. In the USCRB, Arizona is more affected by stresses on the aquifer that occur in Mexico than vice versa due to the topography of the area, the nature of the micro-basins, and the reliance of Arizona on river floods recharging the micro-basin region.

achievements, and their limitations. I then review the data that exists for the Mexican portion of the aquifer. I discuss the gaps in our knowledge of the system and the key uncertainties which exist. Next I explain how I used groundwater modeling as a way to explore which of these uncertainties may be the most important in understanding the behavior of the aquifer. Lastly, I discuss the implications of the modeling results both for the USCRB and more generally, for all shared aquifers. Much of my analysis is quite technical in nature and contains detailed descriptions of the data and model results. To make my analysis more accessible, I have divided it into two chapters. This chapter is a synthesis of my work and its implications. The nitty-gritty details have been separated out and are included as Chapter 6, which is structured as the technical report that would accompany a groundwater model.

## **5.2 Groundwater Modeling: Uncertainty and Limitations**

Mathematical modeling is frequently used to simulate the complex processes of flows throughout an aquifer. This modeling is used to predict how an aquifer might react to changes in stresses, such as increased pumping or reduced recharge. These predictions are useful in analyzing the possible outcomes of policy decisions and water management strategies. In the case of the USCRB, groundwater modeling could be used to determine how increases in pumping might impact water table levels and flows of water both within and across the border or to estimate a sustainable yield for the aquifer. Groundwater modeling of the region could also lead to insights regarding hydrologic processes, as incongruencies between the model simulation and measured observations can point to errors in the conceptual model or the assumptions employed in the model development. However, the usefulness of groundwater modeling is often questioned (Bear, Beljin, & Ross, 1992; Oreskes, 2003; Poeter, 2007); primarily due to the uncertainty which characterizes such models.

Uncertainty in groundwater modeling is a result of both modeling limitations and model error. In developing groundwater models, "...we have to contend with sparse data, sparseness being dictated by resource limitations as well as philosophical limitations."(Narasimham, 1998). Groundwater models, like most earth sciences models, are open systems; they are under-determined, as knowledge of input parameters is incomplete (Oreskes, Shrader-Frechette, & Belitz, 1994). In other words, there is never enough information or available data to completely describe the system. As a result, models suffer from what Beven (2000) describes as equifinality: different model structures and parameter sets may lead to the same (or similarly acceptable) model simulations.

There are two implications of this non-uniqueness: the first is that it is possible an incorrect conceptual model could be calibrated to fit the data and the second is that when used to make future predictions, two similarly well calibrated models, may lead to different results (Beven, 2005; Bredehoeft, 2003). Model calibration involves adapting parameters so that model simulation results reasonably well approximate observed information.<sup>106</sup> Consequently, even though a model matches observed data well, there is no assurance the model is correct or that it will accurately predict future scenarios. Errors in the model may cancel each other out or small errors may exist that have limited impact when simulating historically observed data but that

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<sup>106</sup> Thus by altering input parameters, models with different structures can still yield similar values. Moreover, models with similar structures may also contain different combinations of input parameters and yet yield similar results.

may lead to undesired effects when the model is used for simulating scenarios of differing system stresses (Oreskes et al., 1994).

Error in groundwater models stem from a variety of sources, including errors associated with the conceptual models employed, the field data used, the input data assigned, and predictive uncertainty. Inaccurate conceptual models are the most incipient cause of model error (Anderson & Woessner, 1992; Environment Agency, 2002), as an incorrect conceptual model may still appear correct, yet will have poor predictive capacity (Bredehoeft, 2003; Oreskes et al., 1994). Field data used both for determining prior information (input parameter values) and as sample information (calibration data) are subject to measurement errors due both to human mistakes and limitations in measurement techniques. Input parameters have a degree of error associated with them due to variation in field testing results; due to differences between measurement scales and the scale used in the model; and due to the averaging that must occur in line with model discretization. Furthermore, models are simplifications, and model equations may inaccurately represent physical processes. Lastly, truncation errors occur during the process of numerically solving the model. Errors associated with any one part of the model formulation can propagate throughout the entire model (Oreskes et al., 1994)

Not all groundwater models are so fraught with error and uncertainty so as to be of limited use. Where a significant amount of data and information is available, the error and uncertainty associated with the models can be small, and the models provide invaluable information about the impact of stresses upon the system. And even models that do contain a larger degree of uncertainty can be useful in predicting trends, understanding sensitivity of the system to changes, corroborating hypotheses, and developing better ways to monitor and understand the system (Bear et al., 1992; Oreskes et al., 1994). However, development and use of groundwater models in a transboundary setting is especially problematic.

The development and use of groundwater models requires large quantities of data and a significant amount of technical expertise. Obtaining the necessary data can be a time and resource intensive activity in any situation, but in a transboundary setting this process is made all the more difficult because it involves coordinating and sharing information across the border. Because data is usually collected by domestic water management agencies for their individual purposes, the data available may have been collected at different scales, resolutions, and time-frames for each side of the border. Methods for measuring and observing data likely differ from one country to the next as well, and thus measurement errors and biases may also differ across the border. As a result, merging data across a border can be fraught with difficulty (Brown, Granados, Greenlee, & Hurd, 2003).

The above discussion presumes there is data available for both sides of the border. However, the data required to develop a groundwater model frequently does not exist. As mentioned in the Introduction and Appendix A, management of groundwater resources is a relatively new concern, and until recently, many countries did not have institutions in place that monitored groundwater use or allocated permits or rights. Rather, groundwater has traditionally been subject the right of capture. Therefore the institutional framework of a country may be such that the data needed to develop a groundwater model (such as historic and current abstraction regimes and piezometric heads) may not exist. Even where such data does exist, countries may be

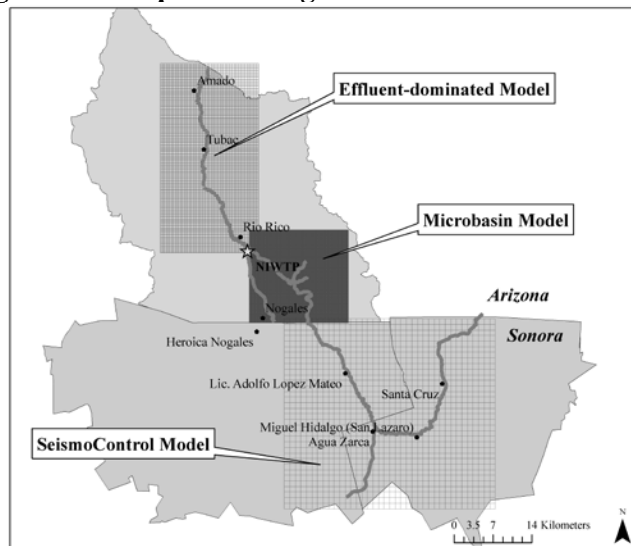
unwilling to share that information, due to a variety of reasons including national security concerns or political and strategic purposes (Elhance, 2000; Timmerman & Langaas, 2005).

Beyond the challenges in developing a model of a transboundary aquifer, there still remains the issue of the usefulness of such models to the formation of cooperative water management strategies. If there is sufficient information and expertise to develop a good groundwater model and put it to use, such models could provide invaluable information, as both sides of the border analyze and evaluate the impact of alternative management strategies. However, more frequently it will be the case that there is little information and either a model cannot be developed, or one that is developed will contain a good deal of uncertainty. From this, it can be surmised that the complexity of groundwater is such that frequently countries do not know the ‘bargaining chips’; they do not know how much water they have, how much they need, nor do they know the impact of potential water management strategies. Beyond making it impossible for countries to understand the true costs and benefits of water management strategies being negotiated, this uncertainty has three other implications: i) countries may attempt to manipulate the data or frame the uncertainty in a manner that best benefits them, ii) uncertainties may become a point of contention during the negotiations and create friction between parties, or iii) a model may be developed and used without full disclosure and understanding of the uncertainty and error – which may lead to poor or misguided decisions.

### 5.3 Groundwater Simulation Models of the USCRB

Groundwater flow models have been developed for four portions of the Santa Cruz River basin. All four models were developed using MODFLOW, a program developed by the U.S. Geological Survey (Harbaugh, Banta, Hill, & McDonald, 2000; McDonald & Harbaugh, 1988). Model results provide information on hydraulic heads, flows, and water budgets for the regions covered. The geographic extent of each of the four models is depicted in Figure 5-1. The following is an in-depth description of these models, the information they provide, and their limitations.

**Figure 5-1: Map of Existing MODFLOW Models for the USCRB**



### 5.3.1 Models of the Aquifer in Arizona

#### 5.3.1.1 Model Extent and Discretization

The Arizona Department of Water Resources originally planned to create a single groundwater model that extended into Mexico and up to the SCAMA boundary. However, it was determined that such a project scope was infeasible, due insufficient data and the spatial and temporal discretization required for modeling as a result of the complexity of the aquifer (Erwin, 2007). Instead, ADWR decided to create three separate models of the aquifer in Arizona and not to model the Mexican side of the border. These three models cover a) the Microbasin region, which extends from the international boundary with Mexico up to the NIWTP; b) the Effluent-dominated region, which extends 21 miles from the NIWTP to the SCAMA boundary near Arivaca at Elephant Bridge; and c) the Potrero Canyon area. The Microbasin and Effluent-Dominated Reach models were completed in March 2007; however work on the Potrero Canyon area has been left to the City of Nogales to develop (ADWR, Personal Communication, August 12, 2008).<sup>107</sup>

The Microbasin and the Effluent-dominated reach models are three-dimensional groundwater flow models, calibrated to simulate flows from 1997-2002. Both models contain three layers, representing each of the hydro-geologic basin-fill units of the aquifer (the younger alluvium, the older alluvium, and the Nogales Formation). Together, the models cover the aquifer along the main stretch of the Santa Cruz River from the boundary with Mexico up through the SCAMA boundary. Although separate models, the models are coordinated. The southern boundary conditions of the Effluent-dominated model match the northern boundary conditions of the Microbasin model.

The Microbasin model extends over an area of 40 square miles (104 km<sup>2</sup>) and is divided into 82 rows and 88 columns, with a cell resolution of 1/8<sup>th</sup> of a mile by 1/8<sup>th</sup> of a mile (0.25 km) each. The Microbasin model contains 94 stress periods of between 3-4 weeks each. The Effluent-dominated model covers an area of 230 square miles (596 km<sup>2</sup>) and is divided into 84 rows and 44 columns, with a cell resolution of 1/4 mile by 1/4 mile. This model contains 25 stress periods, based on five seasons per year (winter rains, spring transition, summer dry, summer monsoons, and fall transition) of between 2-3 months each. Due to the dynamic nature of the microbasin area and the hydro-geologic complexity of the area, the Microbasin model has a much smaller temporal and spatial resolution than the Effluent-dominated model. Even with this scale of discretization, the Microbasin model experienced instability and non-convergence problems (Erwin, 2007; Nelson, 2007).

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<sup>107</sup> The decision not to develop a model for the Potrero Canyon area was based on the recognition that at the moment there is insufficient information to create a reasonable model. "As you might imagine there are some real potential difficulties/challenges for that area - perched aquifers, no data, recharge (or not) along Nogales Wash which has never really been gauged, etc" (ADWR, Personal Communication, August 12, 2008). It deserves that hydrologists at the Arizona Department of Water Resources have a considerable amount of expertise in groundwater modeling and are some of the most highly regarded hydrologists and groundwater modelers in the world. If, given their technical knowledge and abilities, hydrologists at ADWR believe that it would not be advisable to create a groundwater model, due to complexity and data constraints, it can be inferred that other agencies would experience similar (if not greater) difficulties in developing such a model. I mention this to accentuate my claim that the use of groundwater modeling for transboundary aquifers may be of limited use, as the necessary data and technical expertise is often lacking.

### **5.3.1.2 Model Assumptions and Uncertainty**

In developing any model of groundwater flows, many assumptions are made. The Arizona models are no exception. Assumptions had to be made regarding boundary conditions and inflows to the system (especially along the boundary with Mexico) as well as regarding model parameters, system geometry, and water flows. While some of the assumptions made are common to all groundwater modeling, others are region specific and were made in order to address processes that are not well understood due to data limitations.

The Arizona groundwater models make several assumptions quite common to groundwater models. The primary assumption is of saturated laminar flow through a continuous isotropic, porous medium. Although necessary in order to use the MODFLOW program, this assumption may be incorrect, as portions of the aquifer are frequently unsaturated (or dry) and as studies have shown flow in the Older Alluvium and the Nogales Formation may be controlled by faults and fractures (Erwin, 2007). Other assumptions include that the hydraulic heads observed and calculated represent the average for each model grid cell and that specific yield is uniform across each model layer. With respect to inflows and outflows of water, it is assumed recharge is driven by mountain front recharge, which is held constant throughout the year and applied directly and instantaneously. Evapotranspiration is modeled as occurring only via the upper most layer (younger alluvium) and transfers of water between the stream and aquifer are considered to be a function of pressure rather than suction head (Nelson, 2007).

In developing the model, ADWR also had to make a number of assumptions about processes occurring outside the modeled region. Aquifer and stream conditions in Mexico, especially as they relate to underflow and surface water flows across the border are key determinants of water levels in the Microbasin region. Those in turn, influence water levels and flows in the Effluent-dominated area. Yet underflow and streamflow inputs to the Microbasin model are uncertain. Underflow in to the Microbasin area from Mexico was estimated using a Darcy Strip analysis. However, the Darcy Strip analysis is based on assumptions regarding the geometry of the boundary, which, as is discussed in Chapter 6, has not been well characterized. Similarly, surface water inputs to the model are uncertain. For the model calibration, surface water inputs were based on measured stream flow data from the Nogales gage. Those conditions may not hold into the future, as Shamir et al.'s (Shamir, Georgakakos, Graham, & Wang, 2005) stream flow analysis indicated a possible declining trend in summer base-flow. Consequently, the accuracy of the models in predicting future hydrologic conditions depends on the stresses occurring in and assumptions about conditions on the Mexican side of the border.

The Effluent-dominated reach model is not only impacted by underflow and surface flows originating across the border in Mexico; it also is impacted by the quantity of wastewater that is received and treated by the NIWTP. Wastewater treated at the NIWTP is released into the Santa Cruz River. The portion of this water that infiltrates into the aquifer is uncertain and variable, as the dynamics of a clogging layer that builds in the region immediately downstream of the plant are not yet fully understood (Nelson, 2007). Nonetheless, the amount of water available to infiltrate depends on how much wastewater flow is received from Mexico. Thus, until the wastewater treatment plans are resolved, the true value for this parameter in the model will remain unknown.

Conditions created outside of the model boundary are not the only source of uncertainty in the model. Rather the amount of data available contributes to model uncertainty as well. A paucity of measurements, lacking or “ambiguous” (Erwin, 2007) drilling logs, and insufficient testing make it difficult to determine how water levels vary between the hydrogeologic layers of the aquifer (Erwin, 2007; Nelson, 2007). Consequently, the hydraulic connections between the layers and vertical hydraulic conductivities are unknown, and flow patterns outside the younger alluvium have to be assumed (Erwin, 2007; Nelson, 2007). Modeling also was constrained by a lack of data needed to define basin geometry, which may be the cause of difficulties in calibrating some specific wells (Nelson, 2007); and by unreliable or scarce pumping and observed flow levels prior to the 1990’s (Nelson, 2007). Even the recharge and evapotranspiration values are uncertain, and as a result mountain front recharge processes (Wilson & Guan, 2004) and evapotranspiration through saturated and unsaturated zones may be poorly represented by the model (Nelson, 2007)

### **5.3.1.3 Modeling limitations**

In developing the groundwater models, ADWR faced problems related to model instability and non-convergence.<sup>108</sup> Model instability and non-convergence can result for a variety of reasons including: “a) cycling of cells between wet and dry during calculation iterations, b) sharp contrasts in hydraulic conductivity between adjacent cells, c) lateral discontinuity (large changes in elevation) between cells in the same layer, and d) active cells surrounded by dry cells during model simulation” (Erwin, 2007) Unfortunately, the region and the models are characterized by all of the above conditions. MODFLOW was designed to simulate saturated flows, but the USCRB often experiences unsaturated conditions. Furthermore, due to the high transmissivity and low storage space in the younger alluvium, groundwater depletion naturally occurs and wells run dry.<sup>109</sup> Outcroppings and geologic conditions also result in regions with adjacent yet highly contrasting hydraulic conductivities (Erwin, 2007).

Although ADWR was, for the most part, able to overcome these challenges, use of the model for simulating future scenarios is limited by these issues. For example, in running sensitivity analyses using the Microbasin model, small changes in input parameters, sometimes as little as 10%, resulted in non-convergence. These instabilities caused attempts to calibrate the model using automated parameter estimation to fail (Erwin, 2007). As a result, the particular solution found through model calibration should be considered non-unique (Erwin, 2007). The Effluent-dominated model, which is more robust to parameter changes, similarly experienced non-convergence problems when running 100-year simulated scenarios (ADWR, Personal Communication, June and August 2008).

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<sup>108</sup> Groundwater simulation models developed using the MODFLOW code use represent flow through an aquifer using a set of differential equations that describe the movement of water through a porous medium. These equations are then solved numerically, using iterative methods. The computer starts with a trial value for the simulated heads, calculates heads using the trial value, and uses those as the new heads. Iteration continues and the difference between the trial value and the calculated value should decrease with each iteration. The process ends, or converges on a solution, when the difference between the trial value and the calculated values is less than a user-defined value, known as the closure criterion. See Chapter 2 of the 1988 MODFLOW manual (McDonald & Harbaugh, 1988, pp 20) for more information.

<sup>109</sup> This depletion and rewetting can be seen through the way the City of Nogales, Arizona must stagger which wells it pumps from on a daily or weekly basis.

The fact that, despite the expertise and the reasonably large amount of data available on the Arizona side of the border, there remain many uncertainties and technical challenges to developing a groundwater models of the Arizona portion of the basin serves to illustrate my claims regarding how the complexity of groundwater impedes full knowledge of the costs and benefits of various management strategies. That development of the Arizona groundwater models involved a number of assumptions about uncertain features of the aquifer likely have a critical impact on model results (e.g. expected underflow from Mexico into Arizona) supports my claim that even an objective tool may include bias, as model developers by necessity must subjectively interpret data and make predictions about future conditions.

### 5.3.2 Models of the Aquifer in Sonora

#### 5.3.2.1 *Model Accessibility and Use*

The Mexican National Water Commission (CONAGUA) also developed two groundwater simulation models for the Mexican portion of the USCRB. One of these models covers the aquifer associated with the Santa Cruz River as it passes through Mexico and the other model domain includes only the Nogales Wash. Although the Nogales Wash becomes a tributary to the Santa Cruz after entering Arizona, for the purposes of this discussion I focus on the Santa Cruz River model. The Santa Cruz aquifer model was created by a sub-contractor (SeismoControl) to the CONAGUA in 1996. Although this model is not available to the general public, I obtained a print copy of the model report from the CONAGUA central offices in Mexico City and I obtained permission from the CONAGUA for the sub-contractor to email me datasets of the electronic simulation model. Through the course of the many interviews I conducted as part of my research, it was apparent that this model is not in use.<sup>110</sup>

#### 5.3.2.2 *Model Extent and Discretization*

The model of the Mexican portion of the Santa Cruz aquifer (hereafter referred to as the SeismoControl model) covers the area from where the SC River enters into Mexico near Lochiel to where the river re-enters Arizona near Nogales. Geographically this includes the 1292 km<sup>2</sup> (499 square miles) region between latitude 31° 06' and 31° 20' and longitude 110° 32' and 111° 00'. The model is divided into a grid with a resolution of 1 km by 1 km cells and three layers, representing each of the three hydrogeologic layers of the aquifer. Two separate datasets exist for the model: i) datasets for a model with a 20 stress periods of one year each and ii) datasets for a model with 24 stress periods of one month each (for a total of two years). The monthly model does not converge if extended (using the same stresses and inflows) for a longer period of time.

#### 5.3.2.3 *Modeling Assumptions and Uncertainty*

The SeismoControl model represents the aquifer as an unconfined aquifer with three connected hydrogeologic layers; the geometry assigned to each layer was based on resistivity studies, topographic maps, and interpolation. The Younger Alluvium (YA) is characterized as having an

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<sup>110</sup> I argue that the model is not in use because i) the hard-drive of the only CONAGUA computer containing the model files and datasets (necessary to run and use the model) had broken several years before my request for the information and the CONAGUA no longer had access to the datasets necessary to run the model, ii) during the course of my research, interviewees across multiple water management agencies in Mexico mentioned they did not know such a model existed, and iii) interviewees indicated that few water managers in the region have the expertise to run and interpret groundwater simulation models. I obtained the model datasets by locating the sub-contractor who created the model and receiving permission from the CONAGUA for the sub-contractor to email a copy of the original files to me.



average width of 1.5 km and an average thickness of 17m; the Older Alluvium (OA) is, on average is 3.5km wide and 60m thick. The Nogales Formation (NF) is deeper, wider, and comparatively impermeable. Although fractured zones exist in the NF, these are not explicitly considered in the model. All three aquifer layers are isotropic.

The datasets for the annual model are based on the assumption that in 1997 the aquifer was in steady-state. The datasets for the monthly model represents the aquifer as in a seasonal-oscillatory or quasi-steady state. For both models, it was assumed abstraction from wells and the infiltration gallery located along the margins of the river, occurred at a constant rate of 900 lps in 1997 and had not impacted natural flows within the aquifer. Beyond pumping, other sinks and sources of water include underflow at the model boundaries, precipitation, and evapotranspiration. At the northeastern boundary of the model, groundwater inflows from the San Rafael Valley enter laterally. Underflow leaves the system both in the northwest, near Buena Vista/Nogales, and at the southern model boundary. Both boundaries are represented by constant head conditions. No information is available as to how those values were chosen. Recharge in the model occurs via infiltration of precipitation and is distributed evenly across the river valley. The annual quantity of recharge used was not assigned as prior information, rather it was the outcome of model calibration. For the monthly model, this annual quantity was distributed throughout the year proportionally to 1992 stream-flow measurements from the Lochiel & Nogales stream gages for each month. The river is not an important source of recharge for the aquifer, rather it is for the most part a gaining stream. No tributaries are represented in the model. Evapotranspiration is based on the cottonwood and short vegetation zones from Unland et al. (1998) (Personal Communication, Roberto Mendina, SeismoControl, November 26, 2007). Any other assumptions included in the modeling process and any uncertainty which exists are not made explicit.

#### ***5.3.2.4 Modeling Limitations***

The groundwater model of the Mexican portion of the basin contains many of the same limitations as those on the Arizona side of the border, including instability and non-convergence problems and the difficulty in addressing regions characterized by unsaturated flow. Yet the greatest limitation in modeling the Mexican portion of the aquifer is related to the limited amount of information that was available for model development. There is little historical data on piezometric head, flux into and out of the aquifer, or tributaries and stream flow. Historic groundwater abstraction information is similarly limited to estimates from the well census for one year, and well construction data does not exist. Similarly, hydro-geologic data on aquifer properties and geometry is sparse.<sup>111</sup> As result, the conceptual model used in development of the model is incomplete<sup>112</sup> and the model parameters are highly uncertain. Furthermore, the annual model was calibrated as a steady-state model to water levels measured at a single point in time, and likely represents a non-unique solution. No observations existed for calibration of the monthly model. The paucity of data available both for use as input data and for ensuring it adequately represents system processes restrict the usefulness of the model in predicting future behavior.

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<sup>111</sup> A detailed analysis of the available data and the associated limitations is included in Chapter 6.

<sup>112</sup> The conceptual model used in the development of the SeismoControl model only included the younger alluvium and does not take into consideration evapotranspiration, underflow out of the system to the south, or outflows from the aquifer to the river (SeismoControl, 1996).

### 5.3.3 Merging the Models – Possibilities and Constraints

As mentioned above, originally ADWR had planned for the scope of its modeling efforts to extend into Mexico. This is because, as the aquifer is not physically affected by the international boundary and thus what happens on one side of the border impacts the other, it makes the most sense to model the aquifer as a continuous unit across the international border. The predicament that arises when the model boundary is defined by international border rather than by the physical boundaries of the aquifer is that the model does not allow for a complete analysis of flows that occur at the border. In the real world, stresses and changes that occur within the center of the region being modeled might propagate out to the location of the model boundary, changing the aquifer conditions at that point. However, conditions at the edges of a groundwater model are fixed during creation of the model, and thus changes that would occur at the boundary may not be reflected in the model simulation. In the USCRB, the amount of flow crossing the border and how that flow regime changes with stresses on the aquifer is one of the primary points of interest. Thus by modeling each side of the border separately, the full relationship between the two cannot be understood.

A number of factors impede modeling of the aquifer across the border, yet support my claim that developing a cross-border model may be challenging, if not impossible. These factors are related to the availability of data and the complexity of modeling the aquifer. Groundwater models are typically calibrated to a set of piezometric heads and fluxes that were observed during a period for which stresses on the aquifer were well known. Yet the frequency and timing of observations on each side of the border is incongruent. Frequent (some daily and some seasonal) observations are available for multiple years for the Arizona side of the border, yet observations for the same time periods and of a similar frequency do not exist for the Mexican portion of the aquifer. Data concerns are not the only issue; the complexity of the aquifer also makes it difficult to build a joint model. Due to large variation in groundwater levels caused by the small storage space available and the high transmissivity of the Younger Alluvium in the Micro-basin region, ADWR needed to develop a model with small grid cell size and short (three-week) stress periods (Erwin, 2007). Yet to expand a model with this fine resolution to a larger aerial extent would require vast amounts of computing time and effort, even if the grid cells did not retain the same resolution throughout the entire model. Furthermore, the model already experiences instability problems, which would likely continue. Even if a stable model could be created of the Micro-basin region at a lower resolution, such a model would have less predictive power. In addition, as is explained in detail below, the limited amount of information on the Mexican portion of the basin would constrain any ability to assure the model reasonably represents behavior of the aquifer in that region.

## 5.4 Modeling the Mexican Portion of the Basin

Given the high level of uncertainty associated with the existing groundwater simulation model of the Mexican portion of the aquifer, I conducted an evaluation of the data available on and studies of the Mexican portion of the aquifer. Based on this evaluation I then explored the implications of assuming alternate conceptual models of the aquifer on predictions of fluxes of water across the border and on water table levels.

To conduct this analysis, I began by collecting and evaluating the data available to determine the gaps and inconsistencies which existed. From this information, I developed several alternative conceptualizations of the aquifer. Then, using the SeismoControl model as a base, I created MODFLOW simulation models for each of these conceptualizations and calibrated them to 1997 measured water levels. I then compare how each of these models fit the observation data that exists. Given the limited data available, I do not expect any one of these alternative models to be an accurate representation of the aquifer. Rather, patterns and trends across the models can reveal information regarding the likelihood that that model conceptualization is reasonable, how and where additional information may be useful in narrowing the uncertainty that exists, and to place some bounds on our knowledge of flows of water through the aquifer.

Data used in this analysis was collected from a variety of sources, some of which are publically available and others which are not. Information was collected from the Arizona Department of Water Resources, the United States Geological Survey, the International Boundary and Waters Commission, the Mexican National Water Commission, The Sonora State Water Commission, the Municipio de Heroica Nogales, Sonora and OOMAPAS, the Mexican Geologic Survey (SGS), the Instituto Nacional de Estadística y Geografía (INEGI), the Border Environmental Cooperation Commission, Secretaría de Agricultura Ganadería Desarrollo Rural Pesca y Alimentación (SAGARPA). Additional data was obtained from academic journal articles and reports. Conversations with water managers in the region, including contractors who drilled wells for OOMAPAS, geologists, and participants in bi-national meetings related to the Transboundary Aquifer Assessment Act provided meaningful insights as well as both quantitative data and qualitative analysis.

### **5.5 Conceptual Models of the Mexican Portion of the Basin**

The most important step in development of a groundwater simulation model is development of the conceptual model of groundwater flows. The conceptual model includes a depiction of the sources and sinks of water; of how water flows (both horizontally and vertically) throughout the modeled region; of the location and characteristics of flow boundaries; and of aquifer properties. The simulation model is designed to match the conceptual model; i.e., it mathematically represents our expectations of the physical processes in the study region and then calculates what the expected results would be given this physical description. Hence, a groundwater model is only as good as the conceptual model it is based on and the validity of its results is predicated on the assumptions made holding true.

Knowledge of the Santa Cruz river aquifer is incomplete and field observations are scarce and as a result, many of the key processes that should be included in a conceptual model (and thus also in the mathematical model) of the aquifer are unknown. A summary of these processes and the types of information that is missing is included below in Table 5-1. The details of my analysis of the available data and understandings of aquifer processes are included in Chapter 6.

**Table 5-1: Understandings of Aquifer Properties**

Aquifer System Property/Behavior	Uncertainty/Unknown
Estimates of underflow at system boundaries (into and out of the aquifer)	<p>Estimates only exist at for the top layer (YA) of the aquifer at the northern model boundary (international border).</p> <p>Estimates for other layers of the aquifer at the northern model boundary cannot be developed due to a lack of data on the thickness of and groundwater gradient in those layers.</p> <p>No information exists regarding layer thicknesses or groundwater gradients for the southern model boundary.</p>
Inter-connections between aquifer layers	<p>Limited piezometric head observations exist from which to determine the presence (and direction) of vertical flow between the layers.</p> <p>Pumping tests do not extend to the OA or the NF.</p> <p>Reports and models are incongruent in their characterization of the lower layers of the aquifer as unconfined or confined.</p> <p>Studies have indicated possible fractures within the Nogales Formation.</p> <p>The Santa Barbara well field was drilled on a fault.</p>
Streams and stream-aquifer interaction	<p>Very few measurements of stream flow and stream stage exist within the study region making it difficult to estimate baseflow, stream flux and reactions to recharge events.</p> <p>No measurements of tributaries exist, nor is it clear if any are perennial.</p>
System geometry	<p>Cross-sections only exist for the western portion of the aquifer and do not include the boundaries of the region to be modeled.</p> <p>Microbasins are known to exist in the region yet may not be accurately depicted by to the limited cross-sectional data available.</p>

<p>Historic water levels and fluxes</p>	<p>Comparison of 1989 and 1997 water levels suggest the aquifer may be in steady-state, but this analysis did not account for changes in precipitation/recharge or pumping during this time period.</p> <p>The 2002 water level observations occurred in the middle of the summer monsoon season, and due to season variation in the aquifer, comparing those with the 1989 or 1997 values would provide little information.</p>
<p>Historic abstraction rates</p>	<p>Data reports listing historic abstraction rates are inconsistent.</p>
<p>Recharge mechanisms and quantities</p>	<p>Studies of recharge in the arid US southwest suggest mountain front recharge may be the dominant recharge mechanisms in the region.</p> <p>Limited groundwater level measurements and a lack of a time series for individual wells make it difficult to determine the relationship between precipitation/recharge events and groundwater levels.</p> <p>Conceptual estimates of tributary recharge do not exist, nor is there sufficient data on tributaries and flow to develop such estimates.</p> <p>The lack of estimates for underflow into and out of the OA and NF combined with unknown historic pumping rates and tributary flows, makes it difficult to estimate recharge inversely through a water balance calculation.</p>

As result of the above mentioned uncertainties, there are a range of possible ways to conceptualize or represent flows of water in the aquifer. The SeismoControl model developed for the CONAGUA is based on one particular conceptual model of the aquifer. Based on my analysis of the available data and on insights from interviews conducted with experts on water in the USCRB, I selected four uncertain aspects of the aquifer to explore in further depth:

1. the presence or absence of a groundwater divide at the southern edge of the study region,
2. recharge mechanisms (mountain front versus direct precipitation) and quantities
3. the historical water abstraction/pumping regime, and
4. the geometry and connections between of the aquifer layers

How each of these four processes or characteristics of the aquifer are conceptualized may have little impact on groundwater model results or they might also lead to significantly different results. Due to the complexity of the hydrogeology of the region, it is difficult to know a priori (i.e., before modeling) which of the above uncertainties are likely to have the largest impact. Thus the goal of this part of my research was to determine how each of the above

conceptualizations impacts the simulation of groundwater flows and heads in the aquifer. This analysis is useful in helping to understand (and possibly reduce) the uncertainty that exists. In Chapter 6 I explain the uncertainty surrounding each of the above conceptualizations.

As I explain in Chapter 6, these four aspects of the aquifer are not the only unknowns, and in fact, they may not be the most important. A variety of other parameters and system processes are equally uncertain. I chose to explore these aspects of the system because they are system characteristics for which existing models and datasets were most incongruent. The role played by several of the remaining uncertain parameters, such as the values assigned to constant head boundaries; river stage and conductance; and evapotranspiration rates and locations can be evaluated through sensitivity analyses. The implications of other uncertainties, such as the presence of confining layers, faults, fractures, and high and low conductivity lenses or the role and quantity of tributary recharge, can only be explored through the development of additional models.

### 5.6 Model Development & Calibration

Based on the debates about how to conceptualize the aquifer discussed above, I created 18 groundwater simulation models and calibrated them as annual steady-state models to match 1997 observed water table levels. These models cover the range of permutations of the following conditions:

**Table 5-2: Aquifer Conditions Modeled**

Southern boundary:	underflow to the south vs. no underflow to the south
Recharge mechanism:	direct precipitation vs. mountain front recharge
Recharge rate:	high (21 – 35% of mean annual precipitation) vs. low (3 – 11% of mean annual precipitation)
Hydraulic conductivity:	higher (2E-4 to 5E-5 m/s) vs. lower (5E-5 to 9E-6 m/s)

It was expected that, of the above characterizations of the aquifer, model results would be most sensitive to the hydraulic conductivity assigned to the model layers. In general, hydraulic conductivity (K) and recharge rates are the parameters most used for model calibration, so it may seem odd that I choose to use these values as part of my analysis, as it is already known that those will be important. The K values assigned to the existing groundwater models in the region are quite divergent (an order of magnitude or more). I wanted to develop models that included both high and low K values as a way of demonstrating how such assumptions will have a large impact on predictions of availability of water in the region and consequently on perceptions of the need for and impact of different water managements strategies.

Two of the aspects of the aquifer mentioned above as perhaps representing the greatest uncertainties, namely historic rates of groundwater abstraction and the geometry and connections between aquifer layers, I did not address directly in my modeling efforts. I did not have enough information on faults, fractures, and layer elevations to even begin to develop alternative

conceptualizations of these. Thus I used the grid and layer elevations assigned to the SeismoControl model. With respect to historic rates of groundwater abstraction, I considered the possibility of developing additional models that assumed the historic pumping rate was 483 lps. Yet, after developing two, I found that those models yielded results quite similar to models that assumed a historic pumping rate of 900 lps. Based on these results, I decided, rather than develop an additional 16 models, to address the impact of assumptions about historic pumping rates through dry-well losses and model sensitivity analyses.

Given the limited data available and the many uncertainties regarding flow processes, the models were developed using the principle of parsimony (Hill & Tiedeman, 2007). Each of the 18 models was developed as an annual steady-state model. Key features, such as evapotranspiration, recharge, aquifer properties, etc. were represented as simply as possible. Each layer of the aquifer is assigned homogeneous properties, in other words, the same hydraulic conductivity and storage properties are assigned to all cells representing the same hydro-geographic formation. All cells receiving recharge do so at the same rate. Evapotranspiration is divided into two categories: high (cottonwood, willow, or agricultural) and low (low shrubs or bare soil). Wells are assumed to be screened across their entire depth and pumping is assumed to be constant over time. Tributaries are not included and river stage is held constant across a given reach. The grid developed by SeismoControl was used as the basis for the models. The 18 models differed in how each represented flow to the south, recharge mechanisms and quantity, and hydraulic conductivity. Detailed information on model inputs and assumptions are explained in Chapter 6.

Two of the challenges in developing a model of the Mexican portion of the aquifer are related: I have an incomplete conceptual model of the aquifer and I do not have sufficient observation data. Part of the reason for the conceptual model is this paucity of data. The problem that arises in this circumstance is that without a good conceptual model of the aquifer, and without sufficient (and good quality data) it is difficult to determine how well the numerical model I have created represents the expected aquifer behavior. Moreover, the lack of data for calibration, the lack of flux observation data, and the fact that the existing data only represent single point in time, mostly only in one aquifer layer, guarantee the models I have developed are non-unique (Hill & Tiedeman, 2007). This non-uniqueness is demonstrated (see the results section below) by the ability of high conductivity low recharge models to match observations equally as well as low conductivity low recharge models. Moreover, the presence of non-unique solutions is illustrative of my claim that the tools available for understanding groundwater flows (i.e., computer modeling) may not be useful in reducing the uncertainty characterizing groundwater flows.

My objective in developing this groundwater models was not to develop the groundwater model that best captured the aquifer's behavior, because it is apparent there is not enough information to corroborate or validate such a model. Instead, I wanted to determine how assumptions made about each of the four aspects of the aquifer mentioned above impacted the ability of the model to match the limited observations that exist. In other words, through my modeling efforts, I attempted to determine how important each of those four processes is to our ability to predict aquifer behavior. To do this, I evaluated model fit based on comparing simulated values with water levels measured in 1997. I then compared fit (in terms of the water balance, RSS,

observed versus simulated values, observed vs residual, residual maps, and contour maps) of each of the models developed.

Calibration of groundwater models, even when using automated parameter estimation processes, is an artful practice that usually involves manipulating parameters and parameter zones so that simulated values best match field observations. As it was clear from the outset that there is a paucity of data for use in calibrating the model and that my models were likely to be non-unique, I choose not to calibrate the models in the traditional sense. The only calibration that occurred was I varied the quantity of recharge assigned to each model so as to obtain the lowest residual sum squares value possible for each model that simultaneously included a spread of residuals that was as even as possible.

There are many steps I could have taken that would have improved model fit; however, each of those steps would have resulted in each of the 18 models having completely different input parameters, making it difficult to compare across them and determine the impact of each of the four assumptions I wanted to explore (flow to the south, recharge mechanisms and quantity, hydraulic conductivity). If my goal had instead been to develop the best model of the region, I could have allowed for more than one hydraulic conductivity zone per layer (thus allowing calibration to account for errors in the geometry that are localized, rather than extending across the entire layers). I also could have assigned more than one recharge zone, allowing calibration to account for differences in recharge stemming from each of the three mountain front areas in the modeled region. A more complete list of recommendations for improving efforts aimed at modeling the Mexican portion of the aquifer is included in Chapter 6.

In developing the groundwater models I encountered a number of non-convergence problems. As mentioned above, I varied the quantity of recharge assigned to each model to obtain the best fit for that model. Yet small variations in the amount of recharge assigned to the models frequently caused the model to no-longer converge. Varying other model parameters similarly demonstrated model instability (See Chapter 6 sensitivity analysis section). This instability problem made it impossible to use inverse modeling techniques such as PEST, UCODE, or the MODFLOW PES package. Furthermore, model instability inhibits the use of the models for predicting the outcome of scenarios representing changes in the stresses on the aquifer. For example, changes in precipitation patterns due to climate change cannot easily be examined.

In addition to the factors described by ADWR that may cause model non-convergence (see section on ADWR model limitations above), groundwater model instability and non-convergence may be related to a number of factors including: i) an incomplete conceptual model, ii) too stringent criteria for convergence and computation precision, iii) inefficient solvers and/or an insufficient number of iterations permitted, iv) and too large time steps in time-variant models (Environment Agency, 2002). That the conceptual model is incomplete has already been well explained. In attempting to improve model stability, I did vary the convergence criteria (I tried values ranging between 0.001 and 0.05), I also tried increasing the number of outer iterations, and I tried using different solvers (SIP, PCG, GMG). Although some combinations of these changes did improve convergence for some of the models, none proved successful for all models. To improve model convergence in the future, steps should be taken to evaluate differences in



transmissivity across the layers and to alter the elevations assigned to cells that oscillate between wet and dry calculation iterations.

### **5.7 Comparison of Results from Alternate Models**

Although I have explained in great detail how the conceptual model is incomplete and the uncertainties which exist, it should be noted that many groundwater models have been developed using less information. The question that most determines the amount of data that is needed, is how accurate does the model need to be. I would argue that for the USCRB, the model needs to be more accurate than allowed for by the amount of information available. The upper layer of the aquifer is the most productive (in terms of extracting water) yet it is relatively shallow. Most recharge occurs during the late summer monsoons and the winter rains, so in between these periods, water levels can drop dramatically. Most of the models here, including the SeismoControl model, predicted heads that were 10 meters off many of observed water levels and some simulated values were even up to 40 meters off. Moreover, the water balances calculated by models differ at times by more than a factor of seven. Without sufficient information to more accurately simulate water levels and to corroborate the expected flows of water, choosing which of these models is most representative of aquifer behavior not possible. None-the-less, it is possible to glean some useful information about which aspects of this uncertainty have the greatest impact on the model simulations.

As expected, of the various aspects of the aquifer I explored, the combination of hydraulic conductivity and recharge applied to the model had the largest impact on model fit and the greatest influence on values estimated as part of the water balance. Models with different combinations of conductivity and recharge differed by at times up to 20 meters. Models that assumed higher recharge rates tended to have lower RSS (independent of conductivity values assigned); however those models also more systematically overestimated heads. Within models that assumed lower conductivities, there was less variation than within models that assumed higher conductivities – this suggests that the influence of errors in the values of the model parameters assigned on model predictions will be greater for higher conductivity models. In general, the combination of low conductivity and low recharge appears to lead to the most even distribution of residuals. None-the-less, given the amount of data available, it is impossible to say which model conceptualization most accurate.

The importance of choosing the model with combination of conductivity and recharge that best approximates aquifer behavior cannot be understated. As demonstrated by the models developed, a model that assumes high conductivity and high recharge might match head observations as well as a model that assumes low conductivity. Yet the high conductivity high recharge model will predict much larger fluxes of water. Use of the higher recharge and higher conductivity model for policy making, if it is incorrect, could lead to water management strategies that overestimate the availability of water and might have devastating side effects. Due to scaling effects (Anderson & Woessner, 1992; Beven, 1993), values of hydraulic conductivity that create the best groundwater models are not always the same as the values obtained from pumping tests. Thus, the best way to resolve the question of which conductivity and recharge values best predict aquifer behavior would be to develop better estimates of expected fluxes of water throughout the system (i.e., a more comprehensive water budget) as this

information would narrow the combinations of recharge and conductivity that are considered acceptable.

Although the quantity of recharge applied to the model is important, relative to the importance of the hydraulic conductivity and recharge values assigned, the mechanism through which recharge occurs appears to be of little importance. The fit of models that represented recharge as occurring via the direct infiltration of precipitation did not appear systematically different than models that represented recharge as occurring along mountain fronts. Representation of the recharge mechanism may be unimportant due to the narrowness of the river valley or the low resolution of the model.

The possibility of underflow leaving the aquifer towards the south similarly seemed to have little impact on the ability of the models to match target observations. Nor did the possibility of underflow to the south have a large impact on estimates of fluxes into or out of the system at the northern boundaries. Rather, total recharge was predicted to be greater for models that allowed flow to the south. However, much of that recharge stemmed from the areas near the southern boundary, and thus was not available to other areas of the aquifer. Flow to the south varied little with changes to the value assigned to the constant head boundary. Models that allowed flow to the south did indicate the river was a losing stream along the East-West reach between San Lazaro and Paredes, yet signs point to this as a gaining stretch. This indicates it is unlikely that much water leaves the system to the south.

All of the models developed poorly matched head observations at the southwest bend in the river (near Agua Zarca), in the northwest (near Ejido Aldofo Lopez and Ejido Cadillal), and in the northeast portion of the aquifer (just after the river crosses into Mexico). Many of the models also have difficulty matching observed water levels just north of the southeast bend of the river (near Migel Hidalgo/San Lazaro) and at both Pozo Arroyo San Luis and Noria El Cadial. These results suggest there are either errors in how the model represents the geometry of the aquifer at these points, or there are lenses, faults, and fractures that have a large impact on water levels at those points. As cross-sections of the aquifer have been developed using resistivity logs for the Pozo Arroyo San Luis and Noria El Cadial region, the large residuals calculated in all models may be due more likely to errors in measurements of head at those points than due to problems in the geometry of the area as assigned to the model.

Through the sensitivity analysis I performed, it also is clear that uncertainty in the model stems from aspects of the aquifer beyond four factors varied between the models. The high sensitivity of the models to changes in the CHB indicates that better understandings of the model boundaries are needed to develop an accurate water-balance for the aquifer. The large variation in flux as riverbed conductivity is varied indicates that an accurate estimate of riverbed conductivity is also an important element in developing an accurate water-balance for the aquifer. Yet the low sensitivity of the models to changes in the pumping regime imposed, suggest generating a clearer understanding of the other uncertain aspects of the aquifer may be more important than improving estimates of the historic rates of groundwater abstraction.

## **5.8 Modeling Limitations**

Given the incompleteness of the conceptual model and the uncertainty in the data, it is not possible to know whether or not the models of the Mexican portion of the aquifer accurately represent the physical processes occurring nor whether or not the simulated values approximate actual aquifer behavior. As the models cannot be corroborated, they should not be used to predict actual conditions in the aquifer. Instead, the usefulness of this exercise stems from how it helps in determining which processes in the aquifer seem to most contribute to, or most influence, our ability to model the aquifer. The models also serve to demonstrate how assumptions made in conceptualizing the aquifer lead to different predictions of how the aquifer behaves. For instance, high recharge high conductivity models that allowed underflow to the south all predicted the E-W reach of the stream between San Lazaro and Paredes was a losing stream, whereas other model conceptualizations show this reach to be a gaining stream.

Ideally, I would have explored how these conceptualizations portray aquifer behavior on a seasonal basis, as variability throughout the year is a key characteristic of the aquifer that is overlooked by the annual models. Understanding seasonal fluxes is exceedingly important, as wells in the region do go dry during the summer months prior to the monsoons, when demands for water are the greatest. Yet model instability (combined with a paucity of seasonal data, although instability was the limiting factor) made it so that I could not develop a seasonal model. I would have also liked to have selected several of the models and used them to simulate scenarios representing future conditions of the aquifer so as to determine not just how well each conceptual model matched the observation data that exists and the fluxes of water it estimated but also how each conceptualization predicts the aquifer would respond to stresses. This analysis would provide valuable information, as water managers would be able to see a range of possible outcomes which might allow them to select the most appropriate water management strategies in the face of uncertainty.

Part of the problem in developing a stable model was related to the shallowness and high transmissivity of the aquifer. These conditions lead to cycling of several cells as they dried and rewet during the numerical approximation of a model solution. Although there are ways to work around this problem, including slightly altering cell elevations, using shorter time steps, and increasing the convergence criteria, this problem is emblematic of one of the greatest constraints in modeling: our ability to mathematically represent complex physical processes and solve those models.

Even had I have been able to create a stable model, there would still be limitations to the modeling. Modeling is a simplification of the real-world, and the models I created were unable to fully capture the aquifer's properties. For example, the models did not include information on the faults near Santa Barbara, the possible fractures in the Nogales Formation, and the inherent variability in precipitation (recharge), stream-flow, evapotranspiration, and pumping that occurs. Furthermore, as mentioned above, the model boundary is located at the international border, and the constant head boundary assigned limits the amount of drawdown that will occur in model simulations.

Modeling is also based on assumptions about the processes which are occurring and making predictions using models requires assumptions about what will occur in the future. Within the

Santa Cruz River Basin, many changes are constantly occurring. Climate, land use, stream channelization, and anthropogenic water uses have been changing over time and will continue to do so. Moreover, existing understandings of these processes are incomplete. For example, water experts in Arizona are still uncertain as to what has caused declines in baseflow at the Buenavista gage (ADWR, Personal Communication, multiple occasions 2006-2008). Using a model calibrated to historic observations to make future predictions inherently assumes processes occurring in the past will continue to act in the same way into the future. Yet this may not be the case. Additionally, if the calibration is non-unique, model predictions may be inaccurate when simulating different conditions (Anderson & Woessner, 1992; Oreskes et al., 1994). Consequently, groundwater models should not be used to make predictions for conditions that vary widely from those for which they were calibrated. Adding to these limitations is the fact that estimations of future stresses is an exercise in prediction, and likely to include errors and inaccuracies.

### **5.9 Implications for the USCRB and Transboundary Aquifer Management**

Through my analysis, both in this chapter and in Chapter 6, I have demonstrated that the hydrologic processes occurring in the USCRB, and thus the availability of water and the impact of pumping on cross-border flows, are not fully understood. The uncertainty which exist stems from a variety of causes. In Chapter 6, I explain in depth the challenges that arise due to a lack of data, data consistency problems, and measurement variability. Data issues make it difficult not only to develop an accurate conceptual model of the aquifer, but also to merge data and develop understandings of cross-border flows. Part of the difficulty in understanding flows in the aquifer stems not just from a lack of information, but also from the complexity of the hydrogeology of the region. Estimating flows of groundwater is inherently more complex than surface water, and in the USCRB the micro-basins, the shallowness and high-transmissivity of the aquifer, and the complex topography make developing understandings aquifer behavior all the more challenging. Limitations on our ability to address these issues, including our ability to model complex physical processes, means it may not be possible to fully overcome this uncertainty.

In the USCRB, the collection of additional data especially on the Mexican portion of the aquifer would, without a doubt, improve the situation. Section 12 of Chapter 6 includes recommendations on the types of information, data collection and analysis that would help improve the conceptual model and our ability to develop a reasonable mathematical model. However, the collection of additional data is resource intensive. Moreover, observations need to cover a range of conditions, and are most useful when collected over a longer time horizon. Thus there are constraints to the extent and the rate at which the existing uncertainty can be reduced.

The availability of data is going to be a challenge for developing understandings of many transboundary aquifers. As is discussed in Appendix A in more detail, the extensive use of groundwater is relatively recent phenomena, and as groundwater is frequently subject to the right of capture, monitoring of water abstraction and standardized collection of data on piezometric heads is not common. Arizona has one of the most innovative and comprehensive groundwater monitoring and regulation programs in the world and it is unlikely that other countries (or states) will have the same quality and quantity of data available. More likely, the amount of data

available will be similar to that found on the Mexican side of the border. If data is equally sparse on both sides of the border and subject to similar inconsistencies as that found in Mexico, creating groundwater models of most transboundary aquifers is likely to be problematic. Moreover, merging such data across the border may be near impossible, especially if the data is collected at different points in time, using different methods, and is of different qualities. Lastly, it should be noted that even if the data that exists is sparse, countries may be unwilling to share that information for strategic or cultural reasons (Elhance, 2000; Timmerman & Langaas, 2005)

Understanding flows in aquifers and estimating the impact of management strategies is not contingent upon the development of a groundwater model, but a significant amount of hydro-geologic knowledge is necessary and modeling can definitely provide a useful tool. Unfortunately, a fair amount of technical expertise is needed to not only to develop and run groundwater models but also to interpret their results. Even if this expertise exists, this complex information and the uncertainty involved needs to be understood by decision makers.

The lesson that can be drawn from my research is that, due to the complexity of groundwater systems, transboundary aquifers are characterized by uncertainty. Through my analysis of the available information and the existing groundwater models of the region, I have demonstrated that in the USCRB, neither side of the border had a complete understanding of flows of water in the region, rather there exists a large degree of uncertainty regarding the amount of water that is available and the impact of any water management strategy on water availability, water levels, and instream flows. My evaluation of possibilities for creating a cross-border groundwater simulation model, serves to confirm my claim that development of a bi-national model of groundwater flows is inhibited by difficulties related to the availability of data and merging data across the border. I have also established that, given the lack of data available and the incomplete conceptual model, groundwater modeling, which is frequently used to develop understandings of the complexity of aquifer behavior, may not be useful in reducing uncertainty.

The effect of these many uncertainties is that there is room for subjective interpretation of the information available, and many different perspectives which can be formed regarding aquifer behavior. This room for subjectivity has multiple ramifications. As is discussed in Chapter 8, it allows countries to use information discursively to support existing (or promote planned) policies and practices. It also may allow countries to use data strategically in the bargaining process. For example, a country might claim a higher water use, so as to demonstrate a greater need or a larger hardship. Lastly, differences in interpretation of the data may become a point of contention during international negotiations, creating friction between parties.

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## **Chapter 6 : Groundwater Modeling**

### **6.1 Introduction**

This chapter provides more information on the hydro-geologic data available on the Mexican portion of the aquifer and the technical details of the groundwater models that were developed. As explained in Chapter 5, my goal in conducting this analysis was to develop a clearer picture of what is known and unknown about flows of water in the Mexican portion of the river basin. In doing so, I aimed to determine, given the limited data available, how well the aquifer's behavior can be modeled and how important knowledge of uncertain aspects of the aquifer are to our ability to understand and make useful predictions about the aquifer's behavior. This analysis serves two purposes: it points to where additional information would be most useful in narrowing uncertainty and it illustrates how assumptions made in the face of uncertainties influence predictions of aquifer behavior.

The chapter is structured similar to a report that would accompany a groundwater model. I begin with a brief description of the aquifer and the region. Next, I present an analysis of the availability of data on the aquifer and how this information is insufficient to develop a complete conceptual model of the aquifer. I then explain in detail debates that exist about regarding the nature of four aspects of the aquifer and how, based on those debates, I developed a number of different groundwater simulation models so as to generate a greater understanding of which of those processes most influence our ability to simulate aquifer behavior. Following this, I describe in detail the specifications of the model, including information on the parameters assigned, the values used to evaluate model fit and the uncertainty associated with each of these. I then compare how each of the models matches water levels observed in 1997 and, based on this comparison and a sensitivity analysis, I draw conclusions about which of the main uncertainties most impact simulation results. I end the chapter with recommendations on efforts to model the aquifer could be improved in the future, both by conducting additional analyses using existing data and via the collection of additional information on the aquifer.

### **6.2 Hydrogeology of the Upper Santa Cruz River Basin**

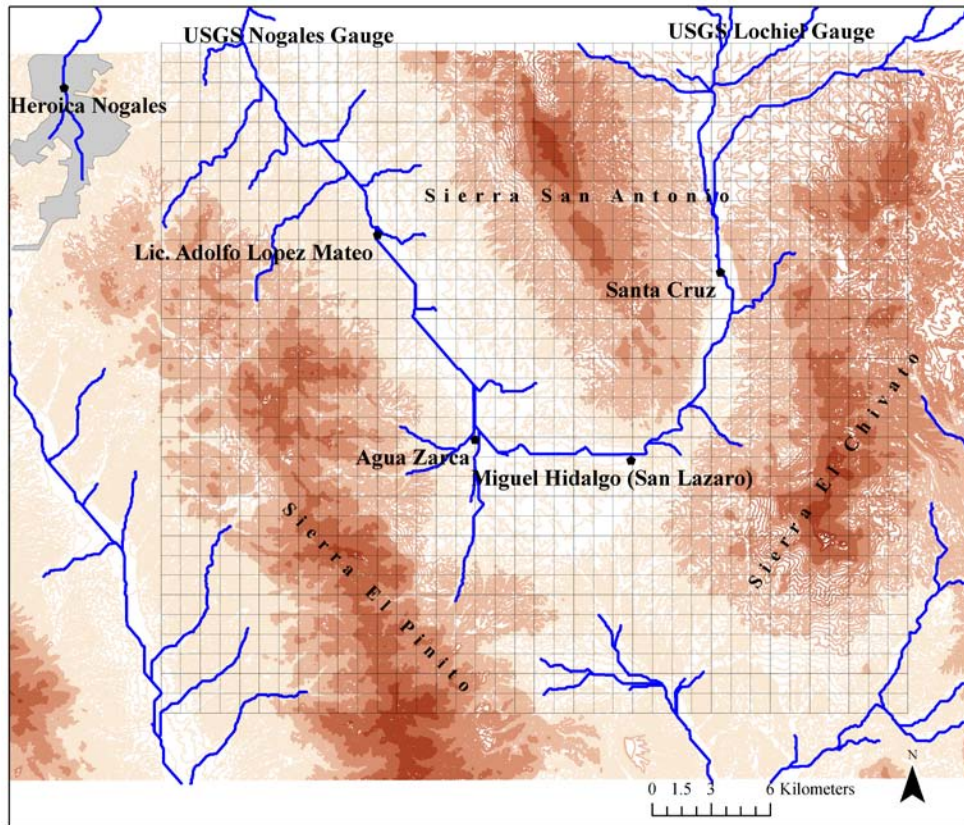
#### **6.2.1 Location**

The Upper Santa Cruz River Valley spans the US-Mexico border between Arizona and Sonora. Geologically, the region forms part of the Basin and Range province of southeastern Arizona (Nelson, 2007). The Santa Cruz River begins in the San Rafael Valley, where it drains the parts of the Patagonia and Huachuca Mountains in the San Rafael Valley, and enters Mexico at an elevation of 1414 m (4640 ft) (C. A. Anderson, 1955). The river forms a 137 kilometer (35 mile) 'U' through Mexico, crossing back into Arizona at an elevation of 1127 m (3,700 ft) and then heading north to Tucson and eventually, the Gila River. The width of the river valley varies between 610 to 915 m (2000 and 3000 ft) except for the region near San Lazaro, where the channel narrows to 91 – 183 m (300-600 ft) wide for a 4.82 km (3 mile) stretch (C. A. Anderson, 1955). The alluvial aquifer is bounded by the San Antonio and the Chivato mountain ranges as it heads south into Mexico and the Pinito and San Antonio mountains as it returns north to Arizona. Within Arizona, the aquifer is surrounded by the Santa Rita and San Cayetano Mountains to the east and the Tumacacori and Atascosa mountains to the west (Erwin, 2007;



Nelson, 2007). A map of the portion of the aquifer that lies within Mexico is included in Figure 6-1.

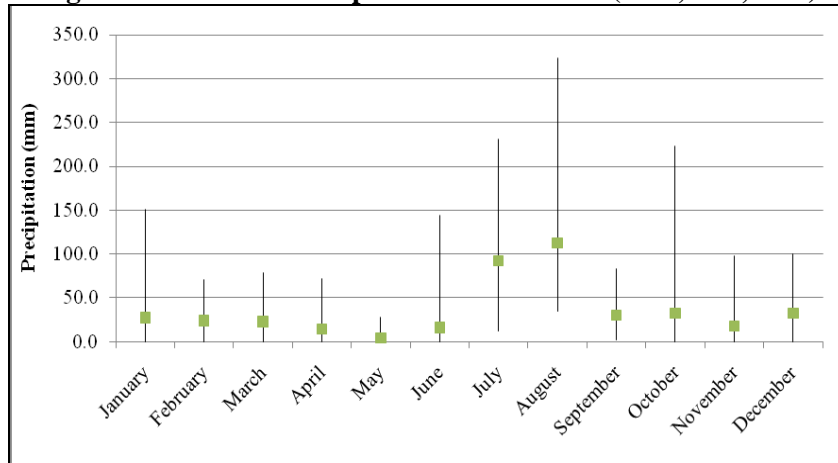
**Figure 6-1: Mexican Portion of the USCRB**



### 6.2.2 Climate and Vegetation

The USCRB is located in the Sonoran Desert and is characterized by a semi-arid climate. Average temperatures range between 43 and 80 degrees Fahrenheit (Erwin, 2007); however the full range of temperature is much larger. The recorded low was  $-3^{\circ}\text{F}$  in December of 1978 and the record high of  $110^{\circ}\text{F}$  has been reached with some frequency. The region also experiences extreme variability in precipitation. On average, precipitation Nogales Arizona is 422 mm (16.6 inches) per year, however it has ranged between 78 mm (3.1 inches) in 1956 to 682 mm (26.8 inches) in 1978 (Western Region Climate Center, n.d.). Precipitation generally occurs during two periods: intense but shorter summer storms in August and September and lower intensity but longer duration winter storms during December through February. The remainder of the year is dry. Figure 6-2 depicts the monthly and annual variability in precipitation between 1988 and 2007. Climate variability is connected with global weather patterns, including El Nino/Southern Oscillation (ENSO), Pacific Decadal Oscillation (PDO), and NINO3 conditions (Erwin, 2007).

**Figure 6-2: Annual Precipitation 1988 – 2007 (Max, Ave, Min)**

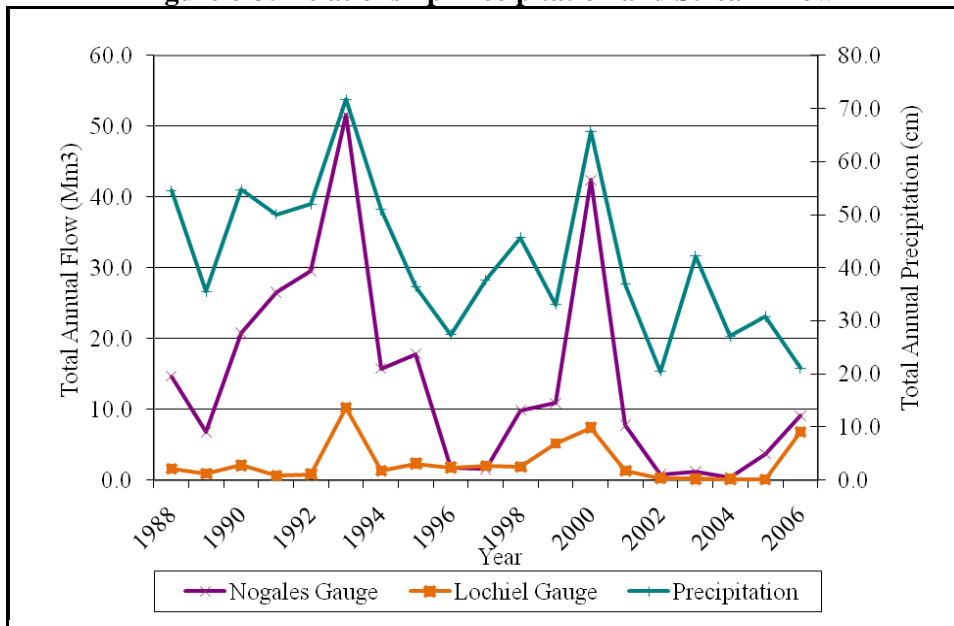


### 6.2.3 The Santa Cruz River

The Santa Cruz River is a gaining stream throughout much of its trajectory through Mexico up to Tubac, Arizona. Within Mexico, the river is classified as perennial however, the riverbed is frequently dry, with the exception of the reach passing between San Lazaro and Parque Recreativa Mascareñas, where surface flow has been consistent, due to a bedrock constriction that forces groundwater to the surface (Nelson & Erwin, 2001; Padilla, 2005; Solis et al., 2004). Within Arizona, the river historically flowed perennially up to Tubac (Nelson, 2007), yet the stretch between the international border and the NIWTP is now ephemeral or intermittent (Erwin, 2007). North of Tubac the aquifer widens and the riverbed is often dry. Discharge from the NIWTP contributes to the consistent flow of water between Rio Rico and Tubac. Several tributaries join the Santa Cruz river, providing tributary recharge to the aquifer, particularly after storm events. As demonstrated in Figure 6-3, stream flow is highly correlated with precipitation.

Flow measurements and stream stage measurements in Arizona are taken regularly at two USGS stream gauges: one at Lochiel and one in Nogales. Stream measurements within Mexico are limited, due to difficulties with the El Cajon gauge. The gauge at Lochiel is located just north of the border in the San Rafael Valley and measures flow from the headwaters as the river enters Mexico. Between 1954 and 2006, mean annual flows into Mexico were 3.25Mm<sup>3</sup> (USGS, 2008a). The gauge at Nogales is located just north of the border and measures the flows exiting Mexico. Between 1914 and 2006, mean annual flow from Mexico into the US was 22.8 Mm<sup>3</sup> (USGS, 2008b). The gauge at El Cajon is located a few miles downstream from the town of Santa Cruz and a few miles upstream from San Lazaro. The El Cajon gauge, which was operated by the Comisión Internacional de Limites y Agua (CILA) between 1954 and 1974, reported a mean estimated annual discharge of 8.63 Mm<sup>3</sup> (7,000 AF) (Nelson, 2007; Padilla, 2005). Unfortunately, the stream gauge was damaged by flooding in 1974, and although it was repaired in 2000, it was destroyed shortly after by vandals. The gauge has recently been replaced but is not yet operational (CILA, Personal Communication, CILA, October 2, 2007). Flows measured at the Nogales gauge are on an order of seven times higher than at Lochiel, indicating that much of the flow into Arizona originates in Mexico. No gauges exist along tributaries to the river in Mexico.

**Figure 6-3: Relationship Precipitation and Stream Flow**



#### 6.2.4 Hydro-geology

Groundwater in the river valley region occurs primarily in three hydrogeologic units: the Younger Alluvium (YA), also considered the alluvial floodplain aquifer; the Older Alluvium (OA), also known as the upper basin fill; and the Nogales Formation (NF), known as the lower basin fill. The YA is comprised primarily of unconsolidated yet well sorted sands. This layer is 14 - 30m thick (Liverman, Merideth, & Holdsworth, 1997).<sup>113</sup> It has a high transmissivity/hydraulic conductivity, and wells drilled within it have produced yields of greater than 252 lps (4000 gpm) (Nelson, 2007). The Older Alluvium covers the majority of the valley floor, and extends below the YA. The OA consists of unconsolidated to moderately consolidated gravel, sand, silt, and clay. This layer has a maximum depth of up to 90 m.<sup>114</sup> The Older Alluvium has low permeability/conductivity but a relatively large water storage capacity. Connections between the Older Alluvium and the Nogales Formation are not fully understood. The Nogales Formation, consists of well-cemented conglomerates (Liverman et al., 1997), and, due to its low permeability, is frequently considered hydrologic bedrock (Halpenny & Halpenny, 1991). However, in some localized areas, the NF may be less consolidated and contain fractured or faulted zones, allowing for higher conductivities (Nelson, 2007). Its thickness can reach more than 2130 m. Wells in the Nogales Formation produce less than 2 lps (30 gpm) (Liverman et al., 1997).

Although the aquifer is conceptually represented as containing three overlapping layers, in some regions, the Nogales formation rises to the surface. Additionally, in several locations, outcrops of the Nogales Formation or bedrock constrictions create narrows and cause pockets known as microbasins; which act as mini-storage basins. These microbasins have limited hydraulic

<sup>113</sup> In contrast, the SeismoControl model report cites an average thickness of 50 m.

<sup>114</sup> In contrast, the SeismoControl model report indicates the thickness of the OA varies immensely, but on average is 200 m.

conductivity, and at their edges, force groundwater to the surface (Erwin, 2007; Geologist, Personal Communication, October 13, 2007).

Throughout the region there are numerous faults and fractures, the exact details of these are not well known (Geologist, Personal Communication, October 13, 2007; ADWR, Personal Communication, October 2007; Geologist, Personal Communication, November 5, 2007; CEAS, Personal Communication, October 10, 2007). The Santa Barbara wellfield, in Mexico, was constructed along one such fault (CEAS, Personal Communications, October 10, 2007; Geologist, Personal Communication, November 5, 2007). The impact of the faults on flows of water is unknown, but could have a potentially significant influence.

The aquifer is characterized as unconfined or semi-confined,<sup>115</sup> and water table levels fluctuate seasonally. Levels are the lowest in June and July, prior to the start of the summer monsoons. Due to the high transmissivity and the shallowness of the YA, overall storage is limited and recharge (and conversely, drawdown) occur rapidly. There is a strong interaction between surface and ground water. Recharge, particularly of the micro-basin area, is highly dependent on seasonal flooding. At the same time, the magnitude of baseflow in Arizona is highly dependent on the available storage capacity in the microbasins, as the microbasins act as reservoirs that discharge water down gradient as baseflow for several months after flood events (Nelson, 2007). Recharge in the microbasins is thought to be dependent on surface water flows in the river (Nelson, 2007), thus if pumping of groundwater in Mexico impacts surface water flows to the US, it may have a significant impact on flows in Arizona. Further details on the geology and the hydrogeology of the region can be obtained from the ADWR and the SeismoControl model reports.

### **6.3 Data Analysis**

Table 6-1 lists the types of data used as input to the model and the availability of information. As can be seen by this table, there is a fair amount of information. However, several key pieces are absent. These include information on the geometry of the aquifer layers for the eastern portion of the aquifer; information on the hydro-geologic properties of the Older Alluvium and Nogales Formation layers of the aquifer; stream and tributary flow measurements throughout the study region; data on historic groundwater abstraction rates and surface water diversions; and observations of piezometric head that are spatially and temporally distributed and that cover a wide range of hydrologic conditions.

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<sup>115</sup> The SeismoControl model report section on hydrogeology characterizes the YA as unconfined and the OA as unconfined with some semiconfined regions. However, in previous sections the report states the Nogales Formation could constitute a confined aquifer. A geologist in the region, considers the aquifer to be confined in the Santa Barbara region, based on the presence of an artesian well and a temperature difference in the water from that well and Santa Barbara I well water (Personal Communication, October 30, 2007). The SeismoControl model represents all three layers as unconfined or convertible. In models of the Arizona side of the border, ADWR represents the top layer of the aquifer as unconfined, and the OA and NF as convertible confined/unconfined layer (Erwin, 2007; Nelson, 2007).

**Table 6-1: Available Data**

Data used for describing the aquifer	Data Available
Precipitation	Daily precipitation <ul style="list-style-type: none"> <li>- San Rafael, AZ<sup>116</sup> <ul style="list-style-type: none"> <li>o July 1948 – March 1970</li> <li>o March 2006 – Present</li> </ul> </li> <li>- Nogales, AZ<sup>117</sup> <ul style="list-style-type: none"> <li>o July 1948 – Present</li> </ul> </li> </ul> Average monthly precipitation <ul style="list-style-type: none"> <li>- San Lazaro, SO<sup>118</sup> <ul style="list-style-type: none"> <li>o 1961 - 1981</li> </ul> </li> <li>- Nogales, SO<sup>119</sup> <ul style="list-style-type: none"> <li>o 1988 - 1998</li> </ul> </li> </ul> Sporadic measurements <ul style="list-style-type: none"> <li>- Santa Cruz, SO<sup>120</sup> <ul style="list-style-type: none"> <li>o 1977 – Present</li> </ul> </li> </ul>
Soils	INEGI map 1:1,000,000 and 1:50,000 scale <sup>121</sup>
Geology (rocks, structures, and faults)	Carta Geológico - Mineral <sup>122</sup> 1:250,000 scale INEGI map 1:250,000 scale
Vegetation	INEGI maps 1:000,000 and 1:50,000 scale LandSat Remote Sensing Land-Cover data <sup>123</sup> Evapotranspiration studies of Arizona <sup>124</sup>
Topography	USGS Digital Elevation Models <sup>125</sup> INEGI maps 1:100,000 or 1:50,000 scale
Aquifer properties (hydraulic conductivity, storage coefficients)	Pumping tests <sup>126</sup> <ul style="list-style-type: none"> <li>- SeismoControl model report<sup>127</sup> <ul style="list-style-type: none"> <li>o 8 of the younger alluvium</li> <li>o 1 test across the younger and older alluvium</li> </ul> </li> <li>- SeismoControl Los Alisos report<sup>128</sup></li> </ul>

<sup>116</sup> The San Rafael, AZ meteorological station is located at latitude 31°21' north, longitude 110°37' west (<http://www4.ncdc.noaa.gov/cgi-win/wwcgi.dll?wwDI~StnSrch~StnID~20000819#ONLINE>)

<sup>117</sup> The Nogales, AX meteorological station is located at latitude 31°26' -110°58' (<http://cdo.ncdc.noaa.gov/cThegi-bin/cdo/cdostnsearch.pl> (hourly also available)

<sup>118</sup> The San Lazaro, Sonora meteorological station is located at latitude 31° 18' 54" north, longitude 110° 38' 48" west and is approximately 10.5 kilometers south of Santa Cruz, Sonora and 35 kilometers Southeast of Nogales, Sonora. (Padilla, G., 2005)

<sup>119</sup> The Nogales, SO meteorological station is located at latitude 31° 19' 08" north, longitude 110° 56' 50" west.

<sup>120</sup> The Santa Cruz, SO, meteorological station is located at latitude 31° 14' 00" north, longitude 110° 35' 38" west.

<sup>121</sup> Refer to INEGI (n.d.)

<sup>122</sup> Refer to Servicios Geológico Mexicano (2000)

<sup>123</sup> Refer to Hutchins, J., Keys, Eric, et. al (2006)

<sup>124</sup> Refer to Unland et al. (1998)

<sup>125</sup> Refer to the USGS National Elevation Dataset (<http://ned.usgs.gov/>) and the Instituto Nacional de Estadística y Geografía (INEGI) (<http://www.inegi.gob.mx>)

<sup>126</sup> None of the pumping tests conducted made use of observation wells.

<sup>127</sup> Ten pumping tests were conducted but one had inconclusive results. Refer to SeismoControl (1996)

	<ul style="list-style-type: none"> <li>○ 4 additional tests (with unstated depths)</li> <li>– Técnicas Geológicas report<sup>129</sup> <ul style="list-style-type: none"> <li>○ 5 pumping tests (unknown location and depth)</li> <li>○ Reported data from 4 pumping tests from 1970</li> </ul> </li> </ul>
Aquifer geometry	<p>Cross-sections developed from resistivity logs</p> <ul style="list-style-type: none"> <li>– SeismoControl model report <ul style="list-style-type: none"> <li>○ 5 cross-sections developed via 40 resistivity logs located along the western portion of the aquifer</li> </ul> </li> <li>– Técnicas Geológicas report <ul style="list-style-type: none"> <li>○ unknown number of cross-sections developed via 70 resistivity logs located along the western portion of the aquifer<sup>130</sup></li> </ul> </li> </ul>
Surface water flows (river and tributaries)	<p>Daily measurements</p> <ul style="list-style-type: none"> <li>- USGS stream gauge at Nogales<sup>131</sup> <ul style="list-style-type: none"> <li>○ 1913 - Present</li> </ul> </li> <li>- USGS stream gauge at Lochiel<sup>132</sup> <ul style="list-style-type: none"> <li>○ 1949 - Present</li> </ul> </li> </ul> <p>Monthly measurements</p> <ul style="list-style-type: none"> <li>- CILA stream gauge at El Cajon<sup>133</sup> <ul style="list-style-type: none"> <li>○ 1954 – 1974</li> </ul> </li> </ul> <p>Sporadic Measurements</p> <ul style="list-style-type: none"> <li>- Gabrielle Tapia Padilla Master’s Thesis<sup>134</sup> <ul style="list-style-type: none"> <li>○ Quarterly 2000 – 2002</li> </ul> </li> </ul>
Surface water diversions	No data available
Groundwater levels	Depth to water level

<sup>128</sup> Refer to SeismoControl (1995)

<sup>129</sup> No one at the CONAGUA or CEAS was able to locate a copy of the report: Técnicas Geológicas y Mineras (1989) “Estudio de evaluación de la disponibilidad de agua y definición de explotación en el Valle del Río Santa Cruz con fines de abastecimiento de agua en la ciudad de Nogales, Sonora. CONAGUA Contrato: VI-89-313-D173p.” although documents citing this report indicate it includes additional cross-sections.

<sup>130</sup> From the photocopied map in the SeismoControl model report, it appears there may have been between 10 -11 cross-sections developed, all west of Agua Zarca; however, due to the quality of the copy, it is difficult to be sure.

<sup>131</sup> Refer to USGS National Water Information Service information for the Nogales Gauge:

[http://waterdata.usgs.gov/nwis/dv?cb\\_00060=on&cb\\_00065=on&format=html&begin\\_date=1988-01-01&end\\_date=2008-04-01&site\\_no=09480500&referred\\_module=sw](http://waterdata.usgs.gov/nwis/dv?cb_00060=on&cb_00065=on&format=html&begin_date=1988-01-01&end_date=2008-04-01&site_no=09480500&referred_module=sw)

<sup>132</sup> Refer to USGS National Water Information Service information for the Lochiel Gauge:

[http://waterdata.usgs.gov/nwis/dv/?site\\_no=09480000&agency\\_cd=USGS&referred\\_module=sw](http://waterdata.usgs.gov/nwis/dv/?site_no=09480000&agency_cd=USGS&referred_module=sw)

<sup>133</sup> The El Cajon stream gauge was operated by the Comisión Internacional de Límites y Agua between 1954 and 1974. The gauge was destroyed by a flood and not reinstalled until recently. Unfortunately, shortly after it was reinstalled, it was broken by vandals. CILA is currently working to repair the gauge and set up a monitoring system. (CILA, Personal Communication, October 2, 2007 and April 30, 2008)

<sup>134</sup> Refer to Padilla, G. T. (2005).

(Piezometric head)	<ul style="list-style-type: none"> <li>– CONAGUA well census<sup>135</sup> <ul style="list-style-type: none"> <li>○ November 1989 (52 wells)</li> <li>○ December 1997 (56 wells)</li> <li>○ August 2002 (134 wells)</li> </ul> </li> <li>– Gabrielle Tapia Padilla Master’s Thesis (11 wells) <ul style="list-style-type: none"> <li>○ Quarterly 2000-2002</li> </ul> </li> <li>– OOMAPAS Measurements (7 wells) <ul style="list-style-type: none"> <li>○ June 2005</li> </ul> </li> </ul>
Groundwater abstractions	Pumping data <ul style="list-style-type: none"> <li>– CONAGUA well census <ul style="list-style-type: none"> <li>○ December 1997<sup>136</sup></li> </ul> </li> <li>– CONAGUA REPDA<sup>137</sup> <ul style="list-style-type: none"> <li>○ Inscriptions for 2002</li> </ul> </li> <li>– OOMAPAS pumping data<sup>138</sup> <ul style="list-style-type: none"> <li>○ 2004-2005</li> </ul> </li> </ul>
Groundwater discharge/ flux (springs, connection with river, etc)	No measurements available

A number of Schlumberger resistivity soundings were conducted in 1989 and 1995 with the purpose of developing cross-sections of the aquifer (SeismoControl, 1995; 1996). However, data is only available for five cross-sections, and, as seen in Figure 6-4, none of those cross-sections covers the eastern portion of the model, nor do they characterize the model boundaries. The location of pumping tests conducted to characterize aquifer properties (such as hydraulic conductivity and specific yield), are more evenly distributed.<sup>139</sup> However, the pumping tests were mainly conducted in shallow wells, and thus do not provide information on the hydraulic properties of the lower aquifer layers.

The availability of water level and flux observation data is similarly limited. Depth to water level information is only available for the census of wells conducted in November 1989, December 1996, and August 2002 (SeismoControl, 1996); CONAGUA, Personal Communication, October 8, 2007). Additional measurements, taken by Gabrielle Tapia Padilla for her Master’s thesis, are available for eleven wells on the western portion of the basis, quarterly from 2000-2002 (Padilla, 2005), and seven measurements are available for OOMAPAS wells for 2005 (OOMAPAS, Personal Communication, June 25, 2006). Unfortunately, none of the data specifies if the observations are for dynamic or static water levels. Moreover, limited information is available on well construction and measurement standards, making it difficult to

<sup>135</sup> The SeismoControl (1996) model report states that piezometric head levels were also measured in May 1963, October 1972, and May 1974; however I was unable to obtain this data.

<sup>136</sup> Data from this census is included as an appendix to the SeismoControl(1996) model report

<sup>137</sup> El Registro Público de Derechos de Agua (REPDA) is the CONAGUA registry for public water rights. Data was provided to me directly from CONAGUA employees in Hermosillo.

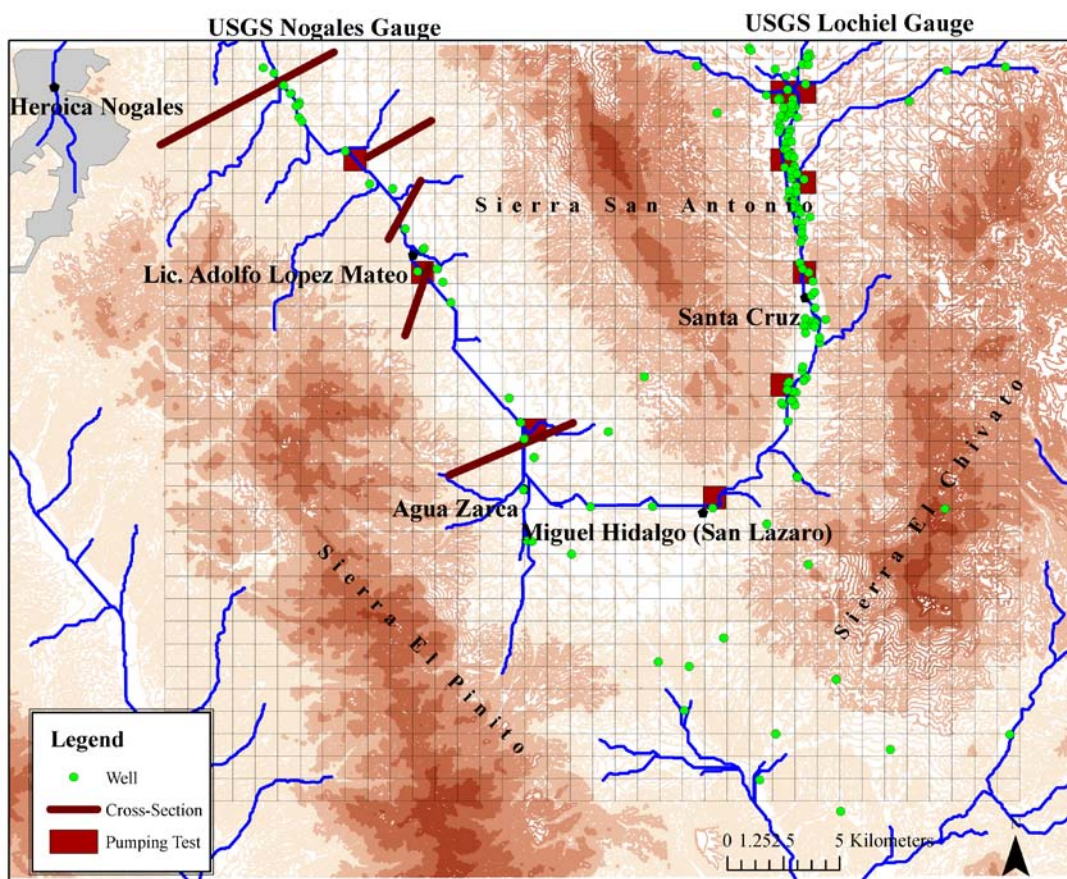
<sup>138</sup> Total annual pumping in lps by each well was provided to me by the OOMAPAS employee responsible for maintaining and operating OOMAPAS wells.

<sup>139</sup> Information on the geographic location of pumping tests was only available for the 10 tests described in the SeismoControl (1996) model report.

determine the piezometric head or to accurately place the measurements in the correct layer of the aquifer. Furthermore, given the well depth information available from the 1997 well census, it appears none of the measurements are of piezometric head in the Nogales Formation, and few are of head in the Older Alluvium.

Measurements of flows in the river and its tributaries are similarly lacking. Although there are continuous measurements just north of the border at the Nogales and Lochiel Arizona stream gauges, there are no working stream gauges along the Mexican portion of the river during the time periods for which there are depth to water measurements. Tributary flow has also never been measured. The only recent observations of stream flow within Mexico are several measurements made by Gabrielle Tapia as part of her master's thesis research for the 2000-2002 period, during which much of the region was in a drought (Padilla, 2005).

**Figure 6-4: Location of Hydrogeologic Testing Data Presented in the 1996 SeismoControl Model Report**



While the availability of data to describe the system is essential when building a groundwater model, the most important part of developing a groundwater model is development of a conceptual model. This includes not just a description of the geometry of the aquifer and properties of the soils, but also a description of flow mechanisms in the aquifer. Understanding of the hydrologic processes occurring in the aquifer is developed through analyses of temporal data and of the physical structure of the aquifer structure. Environment Agency (2002) list the



types of data and analyses that are most useful for developing understandings of system processes. A summary of their recommendations along with an analysis of the availability of data on the aquifer is included in Table 6-2.

**Table 6-2: Data Used in Development of a Conceptual Model and Its Availability**

<b>System understanding to be developed</b>	<b>Datasets which can be compared</b>	<b>Data available</b>
Run-off response, evidence of interflow and aquifer discharge	Rainfall, effective rainfall, river flow and groundwater base flow	Precipitation data and stream flow measurements were taken just north of the model boundaries at Lochiel and Nogales. Yet there are few recent measurements within the region modeled.
Recharge Processes	Drift geology, soil types, land use, effective rainfall, groundwater levels	Studies suggest recharge occurs via mountain front recharge <sup>140</sup> . Limited measurements of depth to groundwater and inexact knowledge of the dates when observations were made make it impossible to track the response of groundwater levels to precipitation events.
River-aquifer interaction and stream flow depletion due to groundwater abstractions	Piezometric surface, riverbed/ ground surface elevations, river flow, groundwater abstraction locations	Limited stream flow information available for estimating stream gains and losses.
Areas of confined aquifer and inter-aquifer communications	Geology and water table/piezometric surface	Faults and fractures are known to be present in some locations but the geologic map does not include details for the region near the younger alluvium and is of a low resolution.  Piezometric head observations do not span all three layers of the aquifer and thus no conclusions can be drawn about movement of groundwater between the three layers of the aquifer.
Groundwater flow directions and	Piezometric surface elevation, groundwater	Piezometric head observations do not include all three layers of the

<sup>140</sup> See section 6.6.4.2 below for more details.

transmissivity	abstraction locations and pumping test results	aquifer and exist for a limited time period, thus no conclusions can be drawn about movement of groundwater between the three layers of the aquifer.
Evidence for hydraulic conductivity or specific yield as a function of depth	Groundwater level and river flow variations, geophysical logs indicating zones of enhanced conductivity	No pumping tests included the Nogales Formation and limited data exists for the Older Alluvium.
Evidence for recent actual operational control of impoundments and abstraction licenses and the impact of these conditions on river flows	Daily (or 15 minute) river flow, surface water abstraction returns (& surface water discharges), reservoir operational rules	No information has been collected on surface water diversions. This is not expected to be a major issue, as water in the region is primarily abstracted from wells.
Understand distribution of existing licensed stress on groundwater resources	Licensed groundwater abstraction rates and recharge	Registration of groundwater abstractions and assignment of groundwater concessions has been recently enacted yet not all wells are registered.  Estimates of pumping and well census data are incongruent. <sup>141</sup>
Evidence of the impact of recent actual surface influences on river flows	Surface water abstractions/discharge locations, spot flow gauging	Insufficient information to correlate groundwater abstraction with surface water flows.

This table is adapted from Environment Agency (2002) Table 4.1.1 pp. 4.1-4.5

The above table shows that many of the underlying processes that influence aquifer behavior are not well characterized. Several of the key processes that are uncertain include underflow at the boundaries of the study region; inter-connections between aquifer layers (faults, fractures, confinement), stream-aquifer interaction; recharge mechanisms and quantities; and system state (steady-state oscillatory vs. transient state). This uncertainty stems in part, from a lack of information. For example, there are no observations of piezometric levels of the Nogales Formation, and few observations in the Older Alluvium. Consequently, flow between the layers of the aquifer is not well understood. Development of estimates of underflow into and out of the

<sup>141</sup> For further explanation, see section 6.4.3 historic abstraction regime below.

system, especially in the Older Alluvium and the Nogales Formation is thwarted by a lack of information regarding the geometry of the aquifer layers and groundwater gradients at the model boundaries. Similarly, understandings of stream-aquifer interaction and tributary recharge are incomplete due to a lack of surface water measurements. Not only is the paucity of data problematic, but inconsistencies in the limited data available also impede development of the conceptual model.

#### **6.4 Conceptual Model Development**

Development of a conceptual model of the aquifer is the most important step in the formulation of a groundwater simulation model. The conceptual model is a synthesis of the region to be modeled; it is a description of the aquifer structure, its hydro-geologic properties, flow mechanisms, recharge processes and withdrawals. As demonstrated through the above data analysis, there are limitations to our knowledge of the aquifer and consequently, any conceptual model of the aquifer will be incomplete.

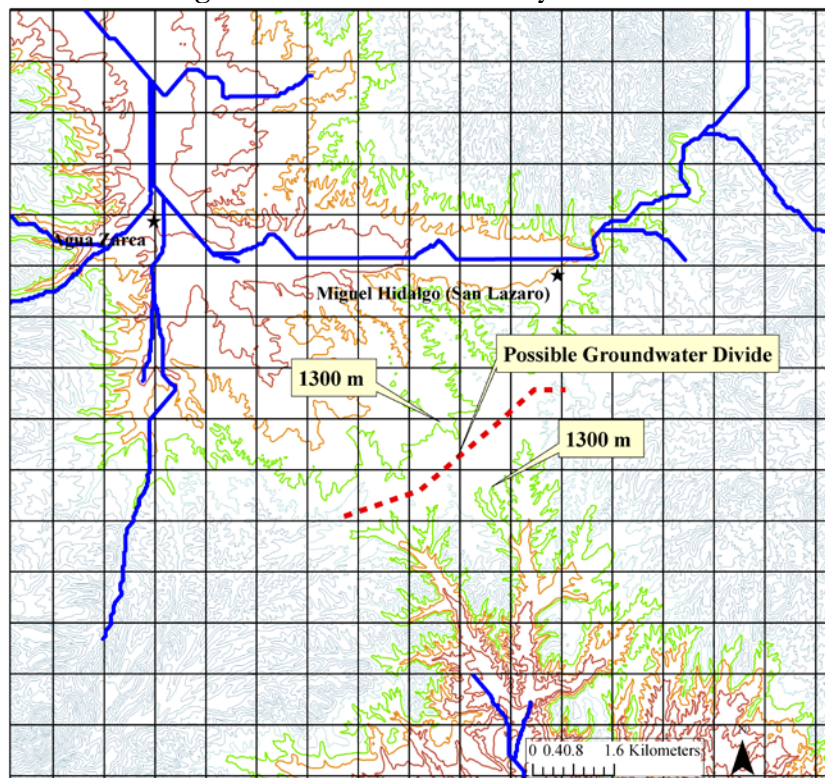
Interviews with key water managers in the region, my analysis of the existing data, and an examination of the SeismoControl groundwater model indicate several conflicting hypotheses regarding the structure of the aquifer and flow processes. These include assumptions about i) the presence or absence of a groundwater divide at the southern edge of the study region, ii) recharge mechanisms (mountain front versus direct precipitation) and quantities, iii) the historical pumping regime, and iv) the geometry and connections between of the aquifer layers. Rather than assuming a priori which of these hypotheses is correct and developing a model based on one conceptualization of the aquifer, I decided to explore how the aquifer would be expected to behave were different combinations of the above assumptions to be correct. My goal was not to develop a model to be used for predictive purposes, as it is apparent there is insufficient data to have much confidence in such a model. Instead, I choose to evaluate the implication of different conceptualizations of the aquifer on our ability to match the few observations that exist. This type of analysis is useful in determining how important knowledge of certain aspects of the aquifer is to our ability to understand and make useful predictions about the aquifer's behavior. Differences between model predictions and observation data, and between the predictions of separate models (each of which was based on different conceptualizations of the aquifer) can then lead to insights into the system.

##### **6.4.1 Underflow to the South of the Study Region**

The southern boundary of the study region is formed by a small mesa located at an elevation of 1300m. South of the mesa is part of the drainage area for a separate watershed. Few wells are located in the immediate surroundings and even fewer water level observations have been made. As a result, the nature of groundwater flows in this area is unknown. It is possible groundwater exits the Santa Cruz aquifer at this point, heading towards the south. On the other hand, it is also conceivable that beneath the mesa is a groundwater divide. Three wells in the southern part of the study region had shallow static water levels but yield 60 lps without drawdown; whereas wells in the watershed immediately to the south were found to have much larger depth to water levels (SeismoControl, 1996). Based on this information, SeismoControl model assumes groundwater exits the system at the southeastern boundary of the study region. Yet, several

water experts in the region questioned if this is indeed the case,<sup>142</sup> as it may also be that drawdown was not observed due to the high transmissivity of the aquifer. This question can be resolved with the collection of additional field data; however, for the time being, the groundwater model must be created without this information.

Figure 6-5: Southern Boundary Condition



#### 6.4.2 Mechanisms for Recharge: Precipitation vs Mountain Front Recharge

In arid and semi-arid regions such as the US southwest, evapotranspiration rates exceed precipitation throughout much of the year and thus direct recharge from precipitation is thought to provide minimal recharge to the aquifer (Wilson & Guan, 2004).<sup>143</sup> Rather, the main pathways for recharge include ephemeral channel recharge and mountain front (MFR) recharge (Erwin, 2007; Nelson, 2007).<sup>144</sup> The SeismoControl model assumes the main source of recharge to the aquifer is from precipitation on the valley floor and applies distributed recharge in the model simulations (SeismoControl 1996). Conversely, the ADWR models assume recharge

<sup>142</sup> This discussion arose in during a meeting of a bi-national workgroup responsible for planning activities for the USCRB as part of the Transboundary Aquifer Assessment Act held in Nogales, Arizona on April 30, 2008.

<sup>143</sup> See Erwin (2007, pp 35) “Halpenny (1963) noted there was no evidence indicating groundwater recharge from precipitation falling directly on the land surface was of hydrologic importance in the southwestern United States. Recharge from precipitation falling directly on the desert floor is considered negligible on the basis of soil-moisture tests before and after storms. This is because of a deficiency in soil moisture due to an evaporation potential of about 91 inches per year in Nogales, use by native desert plants, and relatively impermeable caliche zones of calcium carbonate cementation that are commonly present.”

<sup>144</sup> Mountain front recharge is the process by which water enters the aquifer that is transmitted via infiltration by runoff from streams or subsurface water located along the mountain front, or via openings in the bedrock or contact between mountain bedrock and aquifer sediments (Wilson and Guan, 2004).

occurs through mountain front recharge. A model which assumes MFR rather than direct precipitation will have result in a different water flows dynamic, as the location, timing, and quantity of recharge will be different.

The amount of recharge applied to a model is frequently determined during the model calibration process. None-the-less, the upper and lower limits for recharge are part of the conceptual model, as multiple combinations of recharge and hydraulic conductivity can result in similar simulated values. Determining the amount of MFR that occurs is complex, as the process is not well understood.<sup>145</sup>

Conceptual estimates of mountain front recharge used in the Arizona models are based on a study by Osterkamp (1973), who estimated between 200-400 acre-feet per year per mile of mountain front in the USCRB. Approximately 60% of Osterkamp’s estimate could be considered tributary recharge and the remaining 40% is considered MFR. The ADWR model assumes this recharge is relatively constant throughout the year (Erwin 2007). Actual recharge rates used in the DWR models are calibrated estimates of long-term rates of MFR and tributary recharge. Other estimates of MFR for the Santa Cruz River Basin can be obtained from two additional studies (T. W. Anderson, Freethey, & Tucci, 1992; Chavez, Davis, & Sorooshian, 1994).<sup>146,147</sup> Neither specifically applies to the upper basin as it flows through Mexico and each includes caveats about applying their results to other basins.

Applying the estimated rate of MFR from all four studies (Chavez et al., Osterkamp, Anderson et al., and ADWR) to the geography of the Mexican study region yields a range of values for total recharge. These values are compared with the amount of annual recharge assumed in the SeismoControl model and with annual average precipitation rates in Table 6-3.

**Table 6-3: Comparison of Recharge Estimates**

	Mountain Front Recharge		Total Recharge		% of Precipitation	
	m3/km - year		m3/year		3.92E+08	m3/yr
SeismoControl model	n/a		7.33E+07		18.7%	
	Low	High	Low	High	Low	High
Chavez et al. (1994)	7.00E+03	9.00E+03	7.84E+05	7.77E+05	0.2%	0.2%
Osterkamp (1973)	1.53E+05	3.07E+05	1.72E+07	3.43E+07	4.4%	8.8%
Anderson et al. (1992)	1.08E+05	---	1.21E+07	---	3.1%	---
ADWR models	1.53E+05	---	1.71E+07	---	4.4%	---

<sup>145</sup> Water balance methods, precipitation runoff regression models, chloride mass balance methods, Darcy’s law strip estimates, and numerical modeling are some of the primary methods that have been used for estimating mountain front recharge. Estimations of MFR are complicated by the high spatial variation of precipitation in mountains, uncertainty regarding evapotranspiration, and a lack of geological data and understandings of flows through mountain front areas (Wilson and Guan, 2004). Empirical studies of MFR have resulted in quite different estimates, indicating that these estimates are not transferrable to other basins (Wilson and Guan, 2004).

<sup>146</sup> Anderson et. al. (1992) estimate that  $\log Q_{rch} = -1.40 + 0.98 \log P$ ; for basins where total precipitation is greater than 8 inches/year, P in total annual volume of precipitation given in AFY, yields Q in AFY. This equation was estimated for all basins in SW Arizona, but the entire basin, not just a subsection such as the Mexican model covers and the paper states this equation should not be applied to smaller watersheds or isolated areas.

<sup>147</sup> Chavez et. al. (1994) estimate 1.1 mm/year MFR, which is equal to 0.2% of precipitation, for the Tucson Basin/Santa Catalina mountains located in Arizona.

### 6.4.3 Historical Pumping Regimes/Rate of Abstraction

Groundwater models are calibrated by altering model parameters such that simulated values under the imposed set of stresses match piezometric head and fluxes that were observed in the field under a similar set of stresses. However, data on historical pumping patterns in the region is limited, and at times, contradictory. The 1997 well census conducted by the CONAGUA contains information on pumping rates and estimated hours of operation (hours per day, days per month, months per year) as well as the total volume pumped for that year per well. But, the value listed as total volume pumped per well does not match the pumping rates and hours of operation. Furthermore, this level of detail is not available for 1989 or 2002. Thus assumptions need to be made about the true quantity of water withdrawn from the aquifer during those time periods.

The SeismoControl model assumes in both 1989 and 1997 groundwater pumping occurred at a constant rate of 900 lps. However, both the CONAGUA Disponibilidad study (n.d.), which is internally inconsistent, and the 1997 well census report a lower rate of water abstraction. The divergence in these estimates can be seen most clearly in data on municipal pumping. The CONAGUA study reports 588 lps pumping for municipal purposes in the Santa Cruz aquifer. Liverman et al. (1997) and the BECC's (1995) estimate municipal pumping was 250 lps. Yet the 1997 well census reports total water use as 483 lps (9.77 Mm<sup>3</sup>), of which 50.86% was used for agriculture, 36.21% for domestic purposes, 10.34% for piped water supply, and 2.59% for livestock. A comparison of historical pumping estimates is included in Table 6-4.

**Table 6-4: Comparison of Historical Pumping Estimates**

Year of Pumping	Source	Total Volume		Municipal Pumping	
		Mm <sup>3</sup> /yr	Lps	Mm <sup>3</sup> /yr	Lps
1989 & 1997	SeismoControl (1995) <sup>148</sup>	28.4	900	--	--
1989 & 1997	SeismoControl (1996)	28.4	900	--	--
1995	BECC (1995)	--	--	7.9	250
1996	CONAGUA Disponibilidad (n.d.) <sup>149</sup>	28.4	900	--	--
1996	CONAGUA Disponibilidad (n.d.)	19.6	622	15.4	488
1997	CONAGUA Well Census	9.77	483	3.37	274
1995	Liverman et al. (1997)	--	--	7.9	250
no date	COAPAES Powerpoint <sup>150</sup>	--	--	10.7	340
2002	REPDA <sup>151</sup>	0.86	283	0.01	22
2004	OOMAPAS <sup>152</sup>	--	--	4.9	155
2005	OOMAPAS	--	--	7.4	236

<sup>148</sup> SeismoControl (1995; 1996) produced two separate reports on the USCRB, the first was produced in 1995 and is a diagnostic of conditions in both the Santa Cruz and Los Alisos river basins.

<sup>149</sup> The CONAGUA Disponibilidad document is listed twice, as it contains two inconsistent estimates of historic groundwater abstractions.

<sup>150</sup> A copy of the slides for this official presentation were provided to me by employees at OOMAPAS.

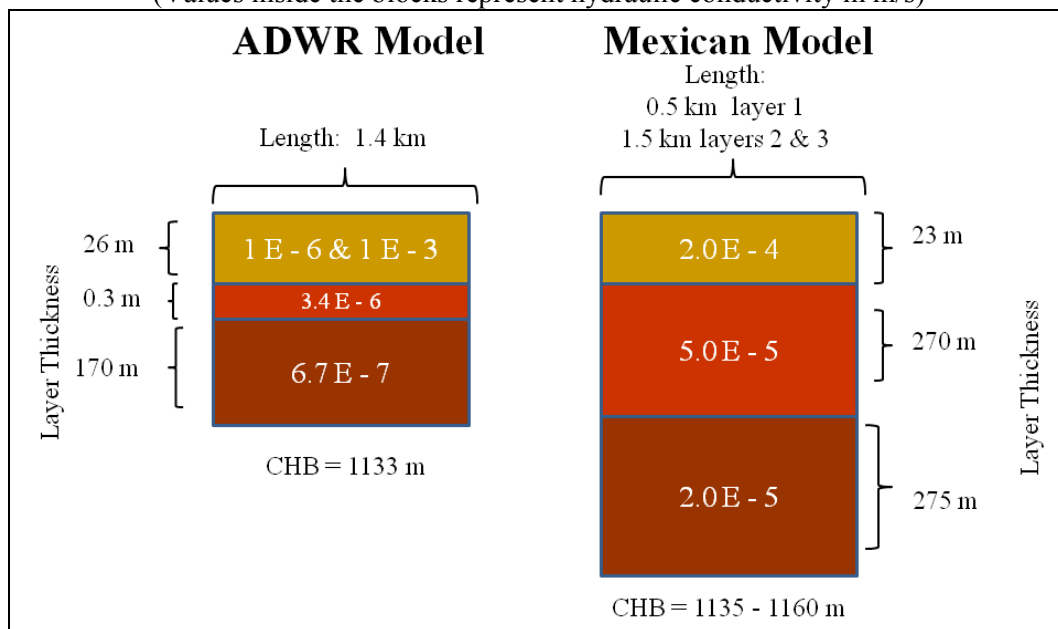
<sup>151</sup> REPDA data was obtained directly from CONAGUA officials in Hermosillo.

<sup>152</sup> Data on OOMAPAS municipal pumping rates was obtained directly from OOMAPAS employees.

#### 6.4.4 Aquifer Geometry and Layer Connections

As mentioned above, there is not a lot of data available on the geometry of the layers within the aquifer or on the connections that exist between these layers. Interpolation of the geometry of the aquifer forms a large part of the groundwater modeling process. As mentioned above, no cross-sections have been developed for the eastern portion of the study region, and limited information is available for the western portion of the study region. Interpretation of resistivity logs is subjective (Personal Communication, James Callegary, USGS, April 30, 2007). Moreover, no testing has been done to define the geometry of the aquifer at the northwest boundary with Arizona. In general, a groundwater model should be developed so that the region of interest is not located at the model boundaries (M. Anderson & Woessner, 1992), as those boundaries are usually fixed by the model developer and may not accurately represent conditions as stresses on the system change through time. However, particularly in this study, where the boundary represents the international border and one of the main points of interest, the understanding the flows across the boundary is a key concern. Thus how the boundary is represented in the model is exceedingly important. Unfortunately, not much information exists on the geometry of the aquifer at the international border nor on the existing groundwater gradients for all three layers of the aquifer. The ADWR and the SeismoControl models assume quite different conditions for the NW international boundary, as can be seen in Figure 6-6. Not only are layer thickness and hydraulic conductivity quite different, but the lateral extent of the flow-boundary is much shorter for the ADWR model.

**Figure 6-6: Conceptualization of NW Boundary**  
(Values inside the blocks represent hydraulic conductivity in m/s)



In addition to the physical geometry of the layers, there remains much uncertainty regarding the role played by fractures and faults in the conveyance of groundwater throughout the region. The Nogales Formation is known to contain a number of fractures and there are several faults in the region. In fact, two of the wells in the Santa Barbara well-field were drilled along a fault. These wells produce dramatically higher yields than other wells in the region (CEAS, Personal Communication, October 10, 2007; Geologist, Personal Communication, November 5, 2007).

Water experts in Arizona posit the presences of underground faults in the region might explain some of the anomalies encountered in field observations and simulations of the microbasin groundwater model (ADWR, Personal Communication, August 14, 2008).<sup>153</sup> Unfortunately, as there is quite limited information regarding the location of faults and fractures, they cannot reasonably be included in the groundwater modeling process.

## 6.5 Alternative Models Developed

Based on the debates about how to conceptualize the aquifer discussed above, I created 18 groundwater simulation models and calibrated them as annual steady-state models to match 1997 observed water table levels. These models cover the range of permutations of the conditions listed in Table 6-5.

**Table 6-5: Alternative Conceptualizations of the Aquifer Considered**

Southern boundary:	underflow to the south vs. no underflow to the south
Recharge mechanism:	direct precipitation vs. mountain front recharge
Recharge rate:	high (21 – 35% of mean annual precipitation) vs. low (3 – 11% of mean annual precipitation)
Hydraulic conductivity:	higher (2E-4 to 5E-5 m/s) vs. lower (5E-5 to 9E-6 m/s)

It was expected that, of the above characterizations of the aquifer, model results would be most sensitive to the hydraulic conductivity assigned to the model layers (perhaps combined with the recharge rate assigned). In general, hydraulic conductivity (K) and recharge rates are the parameters most used for model calibration, so it may seem odd that I choose to use these values as part of my analysis, as it is already known that those will be important. The K values assigned to the existing groundwater models in the region are quite divergent (an order of magnitude or more). I wanted to develop models that included both high and low K values as a way of demonstrating how such assumptions will have a large impact on predictions of availability of water in the region and consequently on perceptions of the need for and impact of different water managements strategies.

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<sup>153</sup> ADWR’s original conception of groundwater flow processes in the region did not originally consider the role of deep faults. However, such faults might provide a reasonable explanation for some of the phenomena observed in the region. Data indicating declines in baseflow at the Buena Vista gauge suggest water may be being minded at a deeper level than originally thought, as despite the declining trend in baseflow, water table levels have remained relatively constant at that point. Additionally, as ADWR has attempted to run stochastic scenario analyses using the Microbasin model, the model simulation has produced results where the microbasins fill, which does not represent observed conditions. One possible explanation for this would be that more water is being conveyed through the system than originally expected. Deep faults and fractures, which would increase flow through the lower levels of the aquifer, might provide an explanation for this observation. As the Microbasin model has been developed with the purpose of informing important water management and policy decisions related to the AMA rules, ADWR is interested in obtaining more information on the hydrogeology of the border and the Mexican side of the border (ADWR, Personal Communication, August 14, 2008)



It deserves mention that these four aspects of the aquifer are not the only unknowns, and in fact, they may not be the most important. A variety of other parameters and system processes are equally uncertain. I chose to explore these aspects of the system because they are system characteristics for which existing models and datasets were most incongruent. The role played by several of the remaining uncertain parameters, such as the values assigned to constant head boundaries; river stage and conductance; and evapotranspiration rates and locations can be evaluated through sensitivity analyses. The implications of other uncertainties, such as the presence of confining layers, faults, fractures, and high and low conductivity lenses or the role and quantity of tributary recharge, can only be explored through the development of additional models.

All of the models represent the aquifer as containing three overlapping hydro-geographic strata: the Younger Alluvium, the Older Alluvium, and the Nogales Formation. Due to the absence of data indicating otherwise, each aquifer layer is considered unconfined. Each layer is treated as a homogenous unit, in other word, hydraulic conductivity and storage properties are considered to be the same across the entire layer. The models all assumed historic pumping was 900 lps; yet, due to dry well losses, the exact quantity of abstraction simulated varies from model to model. A sensitivity analysis was also used to determine how the assumption of a lower historic abstraction regime would have impacted model calibration. Alternative layer geometry and the addition of faults or fractures were not considered, as there is insufficient information available to reasonably represent those in the model. Below is a synthesis of the assumptions for each of the models developed.

**Table 6-6: Alternate Models Developed**

Model Conceptualization		Southern Boundary		Recharge Mechanism		Recharge Rate		Hydraulic Conductivity	
		Flow to South	No Flow South	Precipitation	MFR	High	Low	High	Low
1	SeismoControl	X		X		X		X	
2	SeismoControlNoS		X	X		X		X	
3	PrecHighKHighR	X		X		X		X	
4	PrecHighKHighRNoS		X	X		X		X	
5	MFRHighKHighR	X			X	X		X	
6	MFRHighKHighRNoS		X		X	X		X	
7	PrecHighKLowR	X		X		X			X
8	PrecHighKLowRNoS		X	X		X			X
9	MFRHighKLowR	X			X	X			X
10	MFRHighKLowRNoS		X		X	X			X
11	PrecLowKHighR	X		X			X	X	
12	PrecLowKHighRNoS		X	X			X	X	
13	MFRLowKHighR	X			X		X	X	
14 154	MFRLowKHighRNoS		X		X		X	X	
15	PrecLowKLowR	X		X			X		X
16	PrecLowKLowRNoS		X	X			X		X
17	MFRLowKLowR	X			X		X		X
18	MFRLowKLowRNoS		X		X		X		X

**6.6 Selection of Numerical Model and Code**

The groundwater models were created using the Modular Three Dimensions Finite-Difference Groundwater Flow Model 2000 ( MODFLOW), developed by the U.S. Geological Survey (Harbaugh, Banta, Hill, & McDonald, 2000; McDonald & Harbaugh, 1988). MODFLOW is a program that numerically solves a series of partial differential equations<sup>155</sup> that describe the flow of groundwater through a porous medium. MODFLOW was “designed to simulate aquifer systems in which 1) saturated-flow conditions exists, 2) Darcy’s Law applies, 3) the density of groundwater is constant, and 4) the principle directions of horizontal hydraulic conductivity or transmissivity do not vary within the system”(Erwin, 2007). The models used the following packages: BAS, LPF, WEL, RIV, CHB, RCH, ET, PCG solver. Groundwater Vistas 5 (www.Groundwater-Vistas.com) was the pre- and post-processor used.

<sup>154</sup> I could not find feasible solution for model number 14.

<sup>155</sup> The equation governing groundwater flow is:

$$\frac{d}{dx} \left( K_{xx} \frac{dh}{dx} \right) + \frac{d}{dy} \left( K_{yy} \frac{dh}{dy} \right) + \frac{d}{dz} \left( K_{zz} \frac{dh}{dz} \right) - W = S_s \frac{dh}{dt}$$

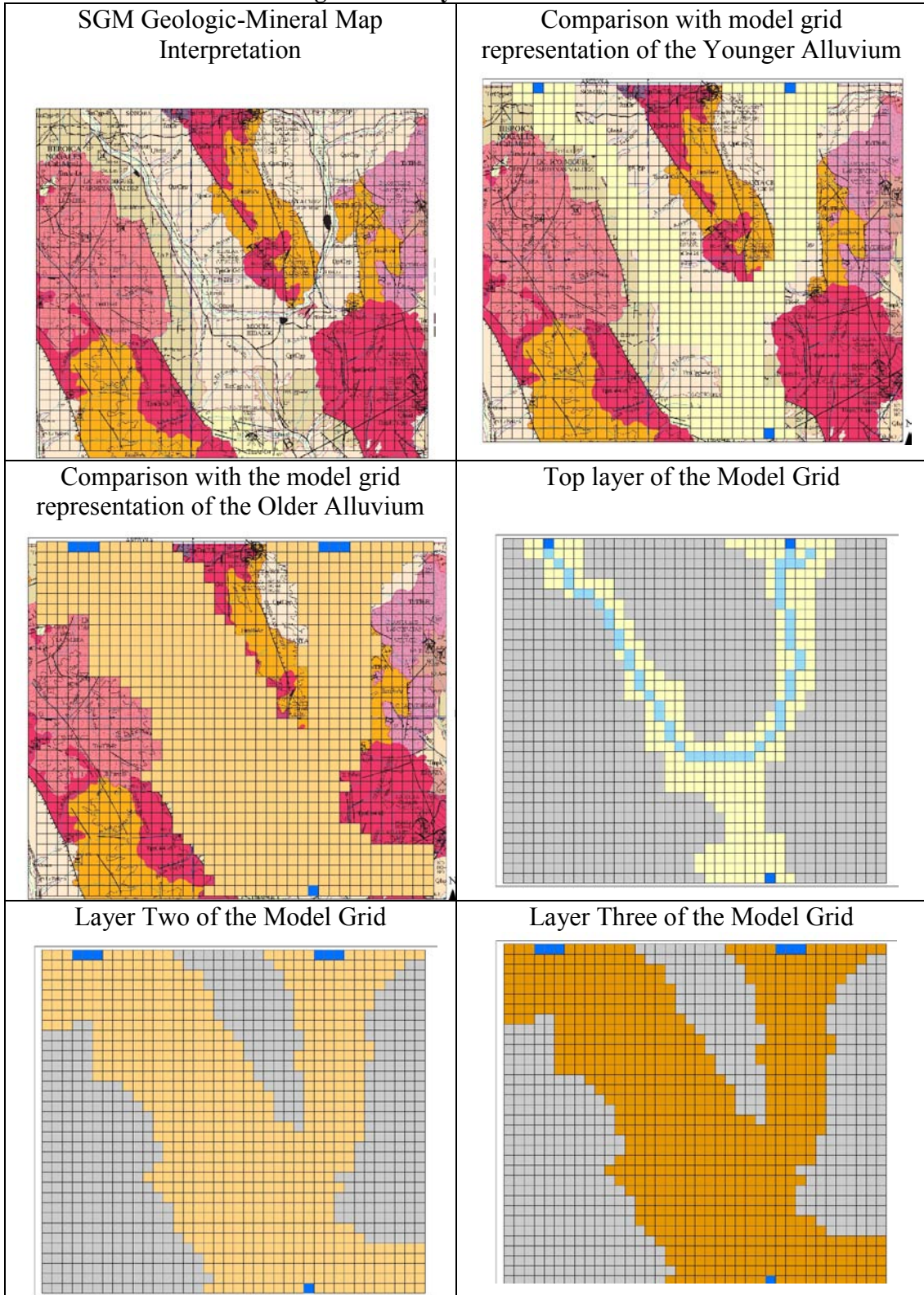
Where Kxx, Kyy, and Kzz represent hydraulic conductivity along the respective axes, W represents the volumetric flux of water from sources and sinks of water, Ss is the specific storage of the porous material, h is the potentiometric head, and t is time (McDonald & Harbaugh, 1988).

## **6.7 Model Specification**

### 6.7.1 Model Grid

The grid used for all models is the same as was used in the SeismoControl model. This grid reasonably well matches DEM topography data and the Servicios Geológico Mexicano (SGM) (Servicio Geológico Mexicano, 2000) geologic – mineral map of the region, with some discrepancies, likely due to averaging which occurs in defining the spatial resolution of the model. As demonstrated by Figure 6-7, the model grid assigns perhaps a slightly larger extent to the Younger Alluvium than suggested by the SGM map, and it does not consider the possibility that the Nogales Formation rises to the surface at the western edge of the river valley. As no additional information is available to improve this grid specification, and as not all of the data that was used in formulation of this grid was available to me, this appeared to be the best possible definition of the aquifer layers and elevations. All three layers were considered unconfined.

**Figure 6-7: Layout of Model Grid**



### 6.7.2 Aquifer Properties – Conductivity and Storage

Hydraulic conductivity (K) and storage values assigned to the model were based on information from pumping tests conducted throughout the modeled area<sup>156</sup> and on the values assigned to both the Arizona and the SeismoControl models (See Table 6-8 and Table 6-9). The aquifer layers were assumed to be isotropic. Although a number of pumping tests exist for the region, there is variation in the testing results and in the values assigned by ADWR and SeismoControl in their models. It is common for conductivity to vary, even within a geologic unit, due to natural variation in soil properties. Moreover, values for conductivity assigned to regional models frequently is different than the values obtained from pumping test, due to issues related to scale (M. Anderson & Woessner, 1992; Environment Agency, 2002). In order to better understand the impact of the conductivity value used in the model, both high conductivity models and low conductivity models were developed. Storage coefficients and specific yield values were assigned as per the SeismoControl model and remained constant for all models developed.<sup>157</sup> The conductivity and storage parameter input values used in the models are listed below in Table 6-9.

**Table 6-7: Hydraulic Conductivity Values From Existing Models**

(m/s)	ADWR Models		SeismoControl Model	
Layer	Microbasin	Effluent –Dominated	Annual	Monthly
1	1.2E-03 – 3.4E-03	3.9E-04 – 2.5E-03	1.0E-04 – 2.0E-04	5.0E-05 – 9.0E-05
2	6.7E-07 – 1.1E-05	1.3E-07 – 1.0E-04	5.0E-05	9.0E-06
3	6.7E-07	3.6E-07 – 1.9E-05	2.0E-05	2.0E-06
Kx:Kv	1:10	1:10	1:10	1:1

**Table 6-8: Storage Values from Existing Models**

		ADWR Models		SeismoControl Model	
Layer		Microbasin	Effluent –Dominated	Annual	Monthly
Sy (1/m)	1	0.18	0.14 – 0.20	0.15	0.15
	2	0.1	0.0015 – 0.0001	0.05	0.05
	3	0.05	1.1E-04	0.01	0.01
Ss (unitless)	1	---	3.5E-06	1.0E-03 – 5.0E-03	1.0E-03 – 5.0E-03
	2	---	0.0005	0.5E-03 – 3.0E-03	0.5E-03 – 3.0E-03
	3	6.67E-06	6.67E-06	3.0E-03 – 6.0E-03	3.0E-03 – 6.0E-03

**Table 6-9: Conductivity and Storage Values Used in this Study**

Layer	High Conductivity (m/s)	Low Conductivity (m/s)	Specific Storage – Ss (1/m)	Specific Yield - Sy (dimensionless)
1	0.0002	5.0E-5	0.001	0.15

<sup>156</sup> The SeismoControl model report included data from ten pumping tests conducted throughout the model region. These tests were interpreted using the Rushton method; however, results from one test could not be interpreted and only one of the nine tests includes a well that extends into the OA. (SeismoControl 1996).

<sup>157</sup> In the ADWR Effluent-Dominated model, Layer 1 is defined as an unconfined aquifer (i.e., LAYCON1). Layers 2 and 3 are convertible confined/unconfined aquifers assigned with LAYCON3. The ADWR Micro-Basin model characterizes layer 1 as unconfined, layer 2 as convertible, and layer 3 as confined (Erwin, 2007; Nelson, 2007). The SeismoControl model and the models I developed assign all three layers as convertible confined/unconfined with LAYCON3. As I am only running and developing steady-state models, these parameters are not used. Should the models be run as transient however, these parameters will be important.

2	5E-05	9E-06	0.001	0.15
3	2E-05	5E-06	2E-05	0.05
Kx:Kv	1:10	1:10	---	---

Although I assigned a single value for hydraulic conductivity per layer, due to the uncertainty regarding the geometry of the layers of the aquifer, it may make sense for future modeling efforts to allow for multiple K-zones per layer. This would allow for calibration of the model to account for errors in the assumed layer thickness, as it may be the elevations assigned are more accurate in the western portion of the aquifer than the eastern portion of the aquifer.

### 6.7.3 River Parameters

When the SeismoControl model was developed, the only current stream data available was from the Nogales and Lochiel stream gauges, with some historic data available from the El Cajon gauge (1950s-1970s). As a result, there was little information for assigning stream stage and river bed conductivity. The model assigned a constant river stage of 1m and a river bed conductance of 0.001 m<sup>2</sup>/s. However, between June 2001 and March of 2003, additional stream stage measurements were taken at a number of sites by Gabrielle Tapia Padilla, a master's student at the Universidad de Sonora (Padilla, 2005). Based on a combination of her data and the USGS stream gauge data at Nogales and Lochiel, I divided the river into four reaches and assigned the following stream stage.

**Table 6-10: River Stage**

River Reach	River Stage (m above bottom)
NE boundary near Lochiel south halfway to San Lazaro	0.31
Halfway to San Lazaro west halfway to Parque Mascareñas	0.03
Halfway to Parque Mascareñas north halfway to Nogales	0.02
Halfway to Nogales north up to the NW boundary of the model	0.94

The bottom of the river bed was assumed to be one meter below the top elevation assigned to each grid cell. River bed conductance remained at 0.001 m<sup>2</sup>/s.

### 6.7.4 Evapotranspiration Parameters

Given the aridity and the high temperatures in the region, evapotranspiration (ET) plays a large role in the water budget. Riparian vegetation represents the largest demand for water on the Arizona side of the border. Conceptual estimates of evapotranspiration do not exist for the Mexican side. A study by Unland et al. (1998) measured evapotranspiration rates by month in 1995 for different types of vegetation in the region just north of the border in Arizona.

Assigning ET to the model requires knowledge of the location and extent of each category of vegetative cover. The map of vegetative cover available from INEGI is at a scale of 1:120000 of vegetative cover, which translates into a very broad application of general categories. This map indicates three categories of riparian vegetation: Pastizal Natural (natural pasture), Bosque de Encino (pine forest) and Irrigated Agriculture (INEGI, n.d.). According to this map, the entire river corridor is considered irrigated agriculture and the mountain fronts are natural pasture and pine forest. Three other sources of information on vegetative cover include USGS land cover

data for the border region (Dohrenwend, Gray, & Miller, 2001), remote sensing analysis performed by Jana Hutchins at ASU (Hutchins et al., 2006), and GoogleEarth Satellite images (<http://www.googleearth.com>). A comparison of these data show they all identify similar regions as having higher and lower vegetative cover.

The models I developed use the same ET assumptions as the SeismoControl model. This model considers two classes of vegetation: low vegetation (low density, short vegetation or bare soils) and high vegetation (cottonwood, willow or obligatory phreatophytes). The majority of the model falls under the low vegetation category. The high vegetation zone is primarily located along the riverbed, and matches the regions identified as having higher vegetative cover in the above mentioned maps. Evapotranspiration rates are loosely based on the Unland et al. (1998) study;<sup>158</sup> however, the SeismoControl monthly model uses Unland et al.'s total annual measured ET and distributes it throughout the year based on the monthly ET estimates for the category of irrigated agriculture. The reason this distribution was chosen is unclear. Evapotranspiration was applied to the top layer only.

**Table 6-11: Evapotranspiration Rates**

Zone	ET Rate (m)	Extinction Depth(m)
Low Vegetation	4.7E-09	1
High Vegetation	5.0E-08	2

#### 6.7.5 Well Location and Pumping Quantities

As mentioned in Section 6.4.3, there are conflicting reports of the amount of groundwater that was abstracted during 1997 and the surrounding years. Consequently, I developed two different well packages to be used in the model: one which assumed 900 lps pumping occurred, and one which assumed 482 lps was abstracted. Both are based on well data from the CONAGUA 1997 well census. The location of the pumping assigned in the model is based on the latitude and longitude coordinates of wells in the census file. The bottom of the well is calculated by subtracting the well depth from the top elevation assigned to the model grid cell in which that well is spatially located. As no data is available on well construction, it was assumed that the well was screened along its entire length. Pumping was allocated based on screen elevation and layer depth. The 1997 census lists average total pumping to be 483 lps. Thus, for the 900 lps well package, pumping in all wells was multiplied by a factor of 1.86.

#### 6.7.6 Constant Head Boundaries

Constant head boundaries (CHB) are used to represent conditions at the edges of the model, where flow occurs into and out of the modeled area. At these points, the head assigned in the model is fixed throughout time. The result is an infinite supply of water is available to flow into the model (in the case where the constant head assigned is higher than the calculated head just inside the model boundary) or a drain allows water to indefinitely exit the model (in the case where the constant head assigned is lower than the head just inside the model boundary). Although these conditions may not be true when considering a larger portion of the aquifer, the purpose of applying them is to allow the modeler to place limits on the study region.

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<sup>158</sup> The SeismoControl Report is dated 1996, however it refers to papers and information from 1998, so I believe it may have been contracted in 1996 and completed at a later date. This remains unclear to me.

Three constant head boundaries are assigned to the models which allow for the possibility of flow to the south: one in the northeast, where the river enters Mexico; one in the northwest, where the river exits Mexico; and one to the south, where underflow is expected to occur out of the modeled region. For the models which do not consider underflow to the south, the southern CHB is replaced by no-flow cells. Head values assigned to the CHBs are the same as those assigned in the SeismoControl model. The northeast and northwest head values were corroborated with well monitoring data from wells located just outside the modeled area across the border in Arizona (ADWR, 2003; 2005). No observation data is available regarding piezometric head near the southern boundary. The southern CHB is located along what appears to be the start of a stream channel and thus an estimate for the head assigned to the southern CHB is the elevation of the terrain at that point.

**Table 6-12: Constant Head Boundaries**

Location	Head Assigned (m)
Northeast (at Lochiel)	1400 - 1415
Northwest (at Nogales)	1135 - 1160
Southern boundary	1180

#### 6.7.7 Targets: Piezometric Head/Water Levels

Development of a groundwater simulation model involves calibrating a steady-state groundwater model and then using that as the starting point for calibrating a transient model. This involves an analysis of the evolution of observed water levels over time to determine the steady-state characteristics of the aquifer. As mentioned previously, depth to water level measurements were measured for a large number of wells during the censuses conducted in the study region during November 1989, December 1997, and August 2002; for eleven wells on a quarterly basis between 2000 and 2002, and for six wells during June 2005.

Unfortunately, the spatial and temporal distribution of the targets is not evenly distributed. The majority of measurements from the well censuses are of the eastern portion of the modeled region, where the least hydrogeological information exists, and the data which exists for the western part of the study area is for a later time period. Furthermore, the measurements were taken at different months during the year. Although the November 1989 and December 1997 measurements might be comparable, as they both occur towards the end of the fall transition before the start of the winter rains, the August 2002 measurements likely were taken after the start of the summer monsoons and the June 2005 measurements were taken during the driest part of the year. Due to combination of the extreme seasonality of precipitation patterns and the high transmissivity of the aquifer, it is not reasonable to determine if the aquifer is in steady state by comparing measurements taken during different months throughout the year when conducting a steady-state analysis.

Nonetheless, it is useful to check the evolution of water levels to look for large differences. As the 1989 census wells are matched with the 1997 census wells it is possible to determine change in depth to water levels between those years. The average change in depth to water was -0.72m, with a standard deviation of 3.4m and a standard error of 0.46. Using a t-test against the hypothesis of no change, the results are that we cannot reject the hypothesis that water table



levels are stable. In other words, it appears water table levels did not decline between 1989 and 1997 in a statistically significant way.

However, a comparison of 1997 with 2002 water levels cannot be conducted as easily, because wells are identified in a different manner. Moreover, the geographic coordinates of the wells do not line up. Casual inspection makes it seem as though the wells should be relatively easy to match up via a proximity analysis in GIS, but a more careful analysis of the data shows that the wells that appear to be in close proximity have quite different pumping rates and water uses, as well different names. Thus, determining the evolution of depth to water level in the same well between 1989, 1997, and 2002 is not possible.

Determining the target head based on this data is problematic because there is a lack of information on well construction,<sup>159</sup> because there is no information on the measurement methods used,<sup>160</sup> and because determining water levels based on depth to water measurements is based on the ground elevation assumed.<sup>161</sup> Furthermore, within a dataset (as well as across datasets) there exist measurements taken in close proximity that indicate widely varying piezometric heads. For example, the ‘La Canada Ancha’ and ‘Predio el Desajje’ targets are less than half a kilometer apart but the measured piezometric heads are 15 m different. This dramatic head change is possible, should there be a high or low conductivity lens in that area, but could also be due to errors in measurement or differences in measuring techniques. No information is available on how depth to water was measured, thus it is possible for some wells, depth to water was measured from ground level and for other wells it was measured from the top of the well casing. Additionally, some measurements may represent dynamic water levels (i.e., they were taken while pumping was occurring) and others may represent static water levels. As there is no information to guide me in determining which measurements are more accurate, I am including all measurements and weighing each equally. This decision will lead to a higher overall RSS and may make it difficult to match target levels at all points in the model.

#### 6.7.8 Targets: Underflow In and Out of the System

Part of the calibration process involves comparing the simulated flows of water into and out of the system with measured or conceptual flows. Yet no measurements of groundwater flux across the region that forms the model boundaries exist. In developing the Microbasin model, ADWR used a Darcy Strip analysis to estimate underflow into Arizona via the Younger Alluvium to be

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<sup>159</sup> Well-boring logs do not exist, and thus there is no information on well screening. Given the majority of the wells are norias (shallow, hand-dug wells), the assumption can be made that they are screened across the entire depth. This assumption will result in some error, especially for targets measured in deeper wells which are likely screened only across a portion of the boring.

<sup>160</sup> The data include no indication of if the measurements are of static or dynamic water levels. Nor is there any indication of if depth to water was measured from ground level or the top of the well casing

<sup>161</sup> Piezometric head is calculated by subtracting the depth to water measured from the (ground, or casing see previous footnote) elevation. Although well elevation data is included in the 1989 and 1997 well census but not for 2002 census, nor for Tapia’s or OOMAPAS’s measurements. The elevation of the well can also be determined by extracting the value from a digital elevation model using GIS. The top elevation assigned to the model grid for each cell is based on an average of the entire area the grid cell covers. Because the topography of the region is extremely uneven (and because many of the wells are shallow), using the well elevation from the census or the DEM and subtracting the depth to water can result in a head value that is above the grid cell elevation assigned in the model. As artesian conditions are not thought to exist in the region, this is a modeling simplification error. Consequently, head needed to be calculated using the grid cell elevation rather than the measured well elevation.

between 0.6 – 0.7 Mm<sup>3</sup>/year (500 AFA). The conceptual model for the SeismoControl model is based on the CONAGUA Disponibilidad study, which similarly used a Darcy Strip analysis, and estimates underflow across the border into in the top layer of the aquifer (YA) as 1.7 Mm<sup>3</sup>/year. Differences in these estimates are due primarily to different assumptions about the geometry, hydraulic conductivity, and gradient at the international border (see Section 6.4.4 above).

Furthermore, these estimates do not consider underflow from the OA or the NF. ADWR assumes underflow in these layers is negligible, based on their analysis of groundwater flow directions (Erwin, 2007), but recognizes they do not have a lot of information, and underflow in the OA and NF may actually be much larger than expected (ADWR, Personal Communication, August 18, 2008). The CONAGUA Disponibilidad (n.d.) estimates do not explain their lack of consideration of the lower layers of the aquifer.

**Table 6-13: Conceptual Inflows and Outflows – Younger Alluvium Only**

(Mm <sup>3</sup> /year)	ADWR	CONAGUA Disponibilidad Document
Inflow from San Rafael, AZ		4.7
Outflow to South		Not included
Outflow North to Nogales, AZ	0.6 – 0.74	-1.7
Recharge		28.1
Evapotranspiration		Not included
Outflow to River		-2.7
Pumping/Well Abstractions		-28.4

## 6.8 Model Calibration

Two of the greatest challenges to developing a model of the Mexican portion of the aquifer are related: I have an incomplete and highly uncertain conceptual model of the aquifer and I have little observation data for use in calibrating the model. The problem that then arises is that without a good conceptual model and without sufficient (and good quality) observation data, it is difficult to judge how well the numerical model represents the true aquifer behavior.

Exacerbating the situation is that the available observation data includes only depth to water measurements and those exist only for a limited point in time and mainly for the younger alluvium. Thus model solutions are likely to be non-unique and my ability to select one model formulation over another is limited.

As it is apparent there is insufficient information to validate or corroborate model results, rather than adjusting a number of parameters for each model in an attempt to as best as possible calibrate each model separately to the water level data,<sup>162</sup> I chose to explore differences in the how the models fit the data and in the water balances each model predicts. Thus the four different model conceptualizations being evaluated (underflow to the south, recharge mechanisms, recharge quantities, and hydraulic conductivity) vary from model to model, but all of the other parameters remain the same. I then compared how each of the models, when run as

<sup>162</sup> For example, I could have increased the number of hydraulic conductivity zones and used conductivity as a calibration parameter, thus adjusting layer transmissivities to better fit the observation data.

annual steady-state model, matches depth to water level measurements from the 1997 well census.

## **6.9 Evaluation of Model Fit**

A number of different metrics are used to evaluate model fit. A comparison of the model water balance with conceptual estimates, including expected recharge, evapotranspiration, underflow into and out of the system, and stream-aquifer fluxes demonstrates how well the model predicts fluxes. However, as the conceptual model is incomplete, rather than compare model results with the conceptual model, I compared water balances across the model variations. The percent error in the model budget indicates how well all water in the system is accounted for. This value was acceptably low (between 0.1 – 0.2%) for all models. The sum square of residuals provides a measure of the total error in the system. Plots of observed versus simulated and observed versus residual values are helpful in determining if there are any systematic biases in the model. Residual maps are similarly useful in showing the geographic distribution of residuals, which could point to systematic bias. A histogram of the residual and a comparison of how many residuals fall within a multiple or two of the target associated error is another good indication of model fit. As the error associated with each target is completely unknown, this comparison could not be made. Lastly, a comparison of contours of water levels or piezometric head with observed values provides information on how well the model matches the data.

The models were calibrated to equally well match 1997 measured water levels, yet each has its strengths and weaknesses in terms of model fit. The range of Residual Sum Square (RSS) considered acceptable was between  $8.3E+03$  and  $1.2E+04$ . Due to the large uncertainty associated with each target and a complete lack of information on target associated error, it was felt that such a range was acceptable, especially when all other metrics (observed vs. simulated values, distribution of residuals, flow direction and magnitude, etc.) pointed to a reasonable model calibration. None of the models seemed to fit the data spectacularly well; and in fact all had difficulty matching many of the same targets (see residual maps below).

The models also each lead to quite different predictions of inflows and outflows to the system, although similarities exist across models with the same combination of high/low conductivity and high/low recharge. In general, higher recharge lead to lower RSS, but also lead to some flooding of model cells, a result that is unrealistic for an annual averaged model given the study area is the Sonoran Desert.<sup>163</sup> Moreover, the higher recharge models all overestimated head in the northeast section of the model. Conversely, lower recharge models were more balanced with respect to tending to both over and underestimate head, but lead to more dry well losses.<sup>164</sup> Neither higher nor lower conductivity models consistently had better RSS or less dry well losses; yet, as expected, the higher conductivity models simulated larger amounts of water flowing in and out of the system. Representing recharge as driven by direct precipitation versus mountain

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<sup>163</sup> Flooding does occur during the monsoon season, particularly during wetter years; however, the model averages precipitation across an entire year, and even during a high precipitation year, it is unlikely the monsoon rains when averaged, would lead to extended flooding throughout the year.

<sup>164</sup> Dry well losses indicate either that the wells were dry and unable to pump during steady-state conditions, which is possible, given during the summer wells run dry (OOMAPAS, Personal Communication, June 25, 2006), given there is a history of staggering pumping in the region (City of Nogales, Personal Communication, September 20, 2007) and given the model does not account for seasonality. However, the dry well losses may also be an indication that historic pumping levels were truly less than 900 lps.

front recharge did not appear to have any consistent impact on model calibration either, perhaps due to the narrowness of the river valley. Models which represented the aquifer as having a groundwater divide to the south (i.e., with no underflow to the south) matched targets slightly better than those that allowed flow to the south, but it should be noted that this could also be greatly influenced by the head assigned to the southern CHB. A detailed evaluation of the model fits is presented below.

Table 6-14 includes a comparison of the water balance for all three layers of the aquifer, as calculated by five of the models.<sup>165</sup> Water balances were similar for models with similar combinations of high/low conductivity and high/low recharge. Annual inflow from San Rafael ranges from almost 4 Mm<sup>3</sup> to 37 Mm<sup>3</sup>, with the low conductivity high recharge models at the low end of the spectrum and the high conductivity low recharge models at the high end of the spectrum. Inflow from San Rafael is on the same order of magnitude for all models that have similar conductivity and recharge values, regardless of if they allow underflow to the south or if they represent recharge as direct precipitation or mountain front recharge. Outflow to Nogales, Arizona ranges from very low (0.09/0.4 Mm<sup>3</sup>) for the low conductivity low recharge models to much higher (21 Mm<sup>3</sup>) for the high conductivity high recharge models. For the models which allow underflow to the south, this varies from 50 Mm<sup>3</sup> for the high conductivity high recharge models to 7Mm<sup>3</sup> for the low conductivity low recharge model. As expected, underflow to the south is higher for the higher conductivity models. Dry well losses are greatest for the low conductivity low recharge models. Evapotranspiration is greatest for the high recharge scenarios and lower for the low recharge scenarios, and is especially low for the low conductivity low recharge scenario. The river, which remains a gaining stream throughout, gains the most in the high recharge scenarios, yet seems less impacted by conductivity. For the models that conceptualize recharge via distributed precipitation, allowing flow to the south dramatically increases the amount of recharge which occurs, whereas allowing flow to the south does not have a large impact on the amount of recharge in the models that represent recharge via mountain front recharge mechanisms.<sup>166</sup>

**Table 6-14: Inflows and Outflows of Selected Models**

<b>ModelName</b>	Seismoasgiven	MFRHighKH ghRNoS	MFRHighKLo wR NoS	PrecLowKHig hR	MFRLowKLo wR
<b>Under Flow to South?</b>	Yes	No	No	Yes	Yes
<b>River Stage (m)</b>	1	0.03-0.94	0.03-0.94	0.03-0.94	0.03-0.94
<b>Type of Recharge</b>	Precip	MFR	MFR	Precip	MFR
<b>% of Precipitation</b>	20%	21%	7%	28%	7%
<b>Rate</b>	2E-09 & 5E-09	2.10E-08	7.50E-09	4.90E-09	5.50E-09
<b>K Values</b>					
Younger Alluvium	1 to 2E-04	0.0002	0.0002	5.00E-05	5.00E-05
Older Alluvium	5.00E-05	5.00E-05	5.00E-05	9.00E-06	9.00E-06
Nogales Formation	2.00E-05	2.00E-05	2.00E-05	5.00E-06	5.00E-06
<b>Pumping (lps)</b>	899	868	832	884	514

<sup>165</sup> Results are only presented in the table for five of the 17 models. The selected models capture the range of conceptualizations. Numbers included in the text cover all models.

<sup>166</sup> This result is likely because many of the cells receiving recharge as precipitation are converted to no-flow cells in models that do not allow

<b>RSS</b>	1.06E+04	9.34E+03	9.40E+03	8.30E+03	9.83E+03
<b>Flows (Mm<sup>3</sup>/yr):</b>					
In - From San Rafael	33.54	26.13	33.66	5.12	7.51
Out - To Arizona	-10.21	-14.74	-6.76	-4.99	-0.59
Out - To South	-35.21	0.00	0.00	-20.36	-7.45
Well Pumping	-38.13	-27.37	-26.24	-27.90	-16.22
Recharge	73.32	80.80	28.86	111.57	25.50
Evapotranspiration	-32.1	-55.99	-28.18	-53.57	-8.37

### 6.9.1 Observed vs. Simulated Values and Observed vs. Residuals

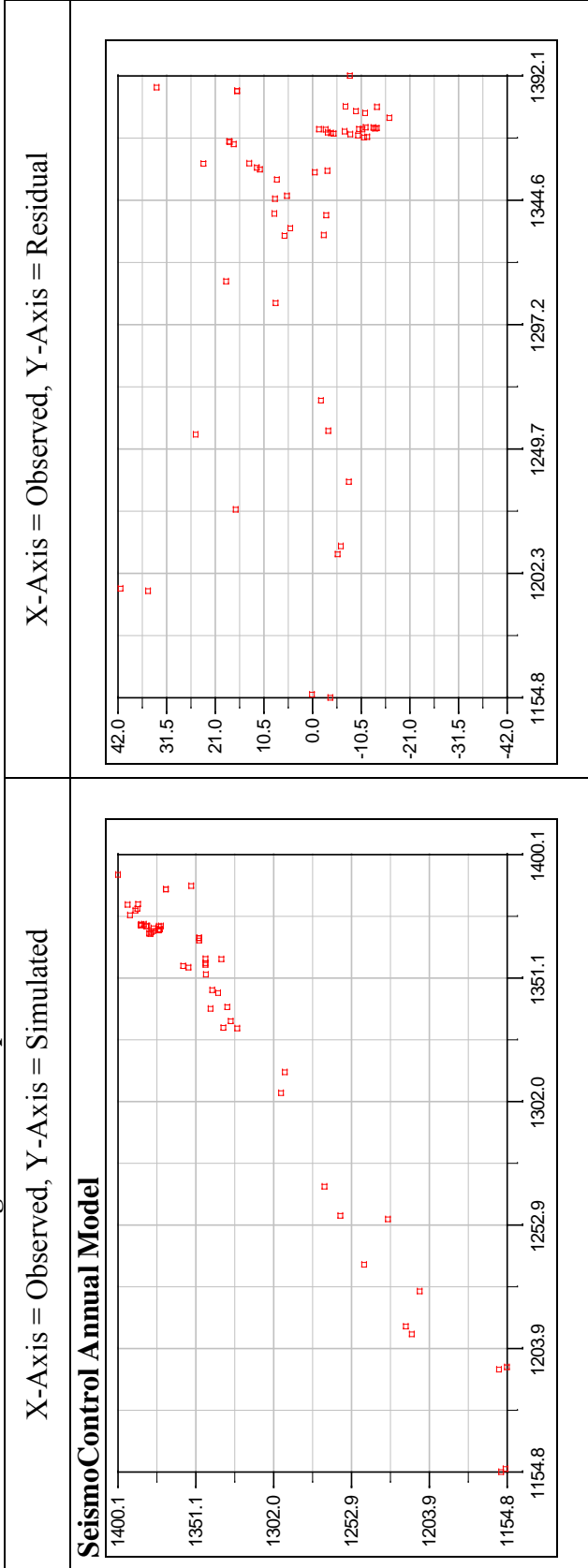
With the exception of a few targets, the models all match each of the targets within 20 meters. However, a discrepancy of 20 m is relatively large, given the younger alluvium layer of the aquifer is quite shallow.<sup>167</sup> This error greatly impedes the usefulness of the models: a discrepancy of this magnitude means the models cannot accurately predict the water table level nor where the water table falls in relation to the hydrostratigraphic units. This knowledge is important for determining aquifer yield and for predicting the impact of abstractions on well production.

In looking at the model fit, it appears the low conductivity and low recharge models have the best fit, in that the simulated water levels are within 10 meters of the observed values and, with the exception of the northeast (where simulated water levels are overestimated by all models) there does not appear to be a consistent bias in terms of over or under estimation of water levels. In general, the models with high recharge rates tend to systematically overestimate water levels and models with low recharge rates tend to underestimate water levels. The presence or absence of a groundwater divide to the south appears to have no consistent impact on model residuals, suggesting that this parameter is not near as influential as conductivity and recharge values. Similarly, the recharge mechanism appears to be less important than conductivity and recharge. However, all models that employ a combination of a mountain front recharge mechanism and low conductivity appear to have a good fit.

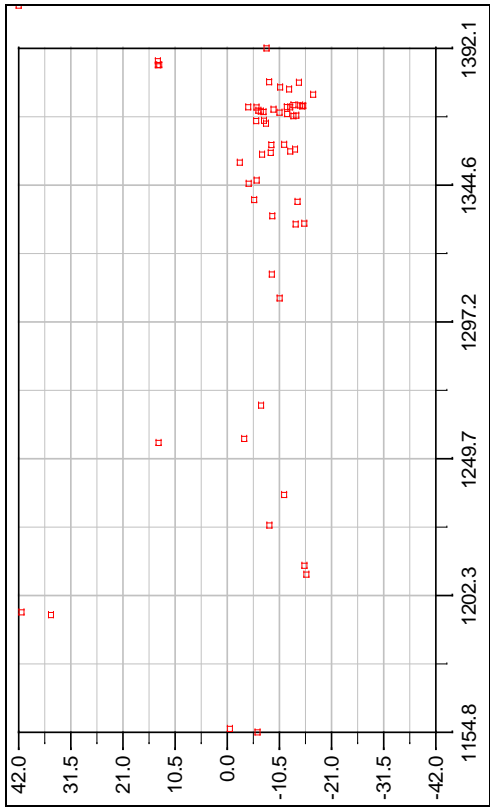
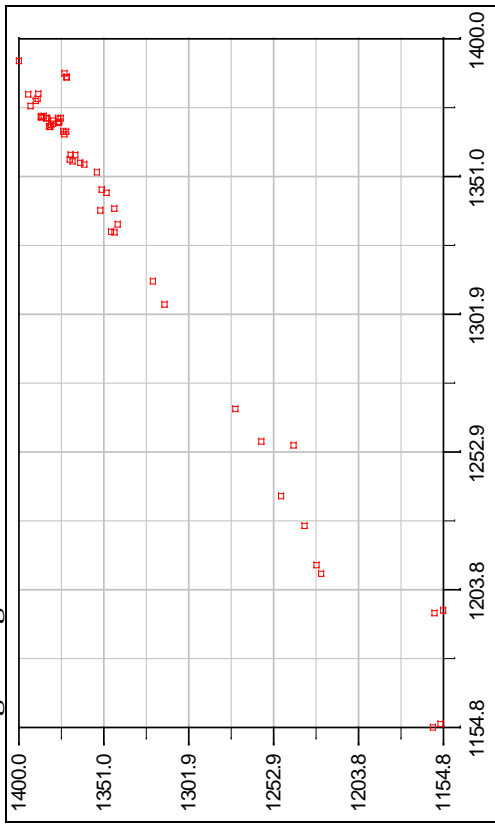
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<sup>167</sup> Resistivity log data indicates the YA is approximately 20 m thick; however, the SeismoControl model report assumes the YA is on average, 50m thick.

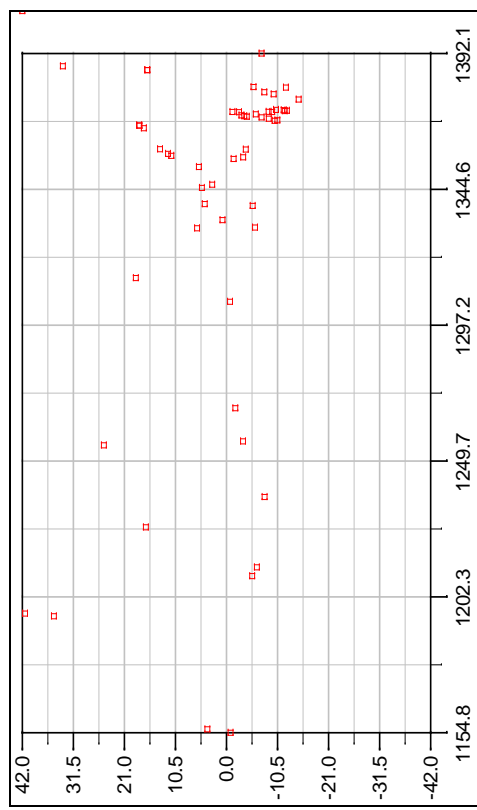
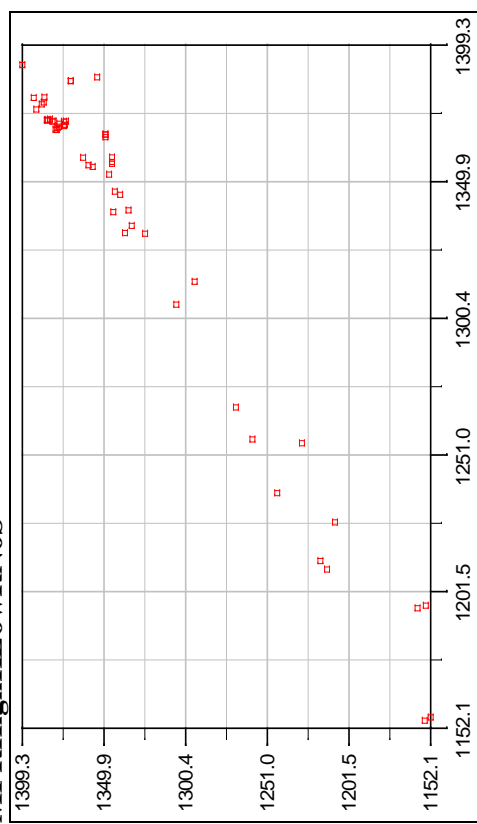
Figure 6-8: Comparison of Observed vs. Simulated Values of Selected Models



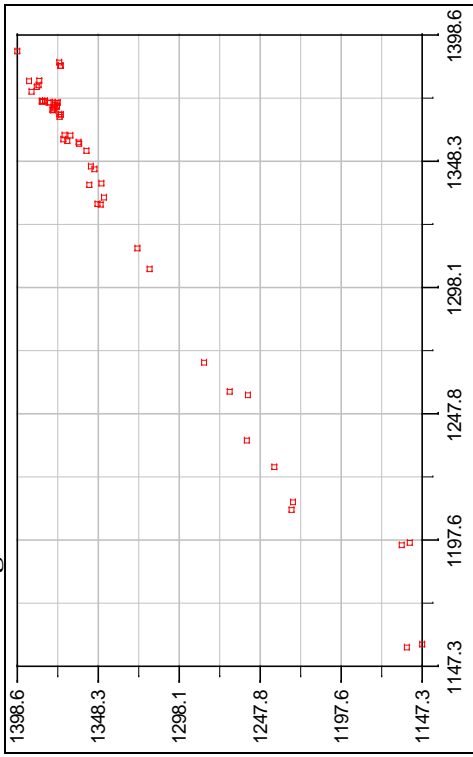
**MFRHighKHighRNoS**



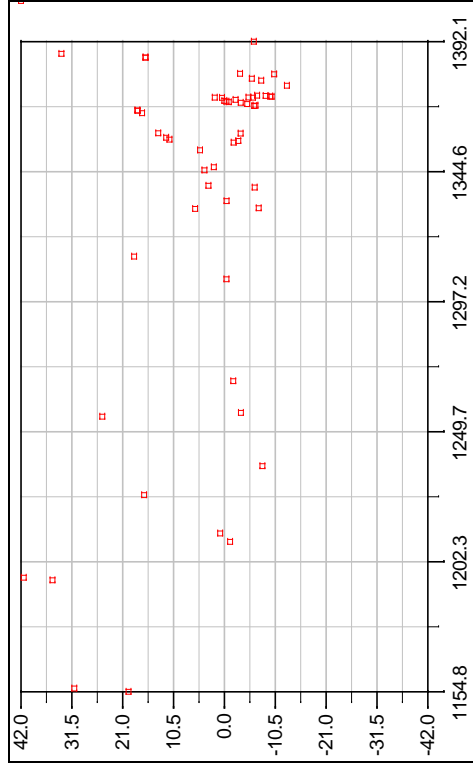
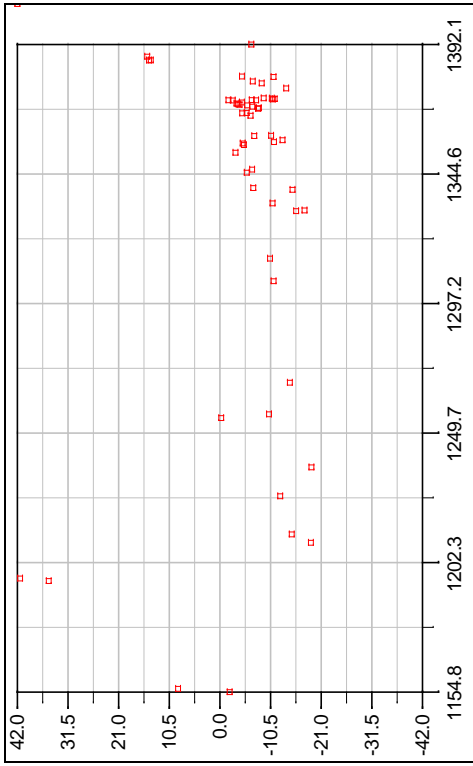
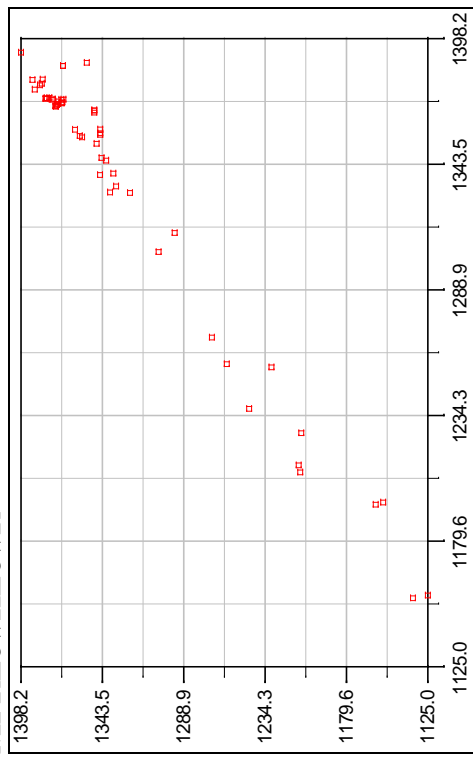
**MFRHighKLowRNoS**



**PrecLowKHighR**



**MFRLowKLowR**

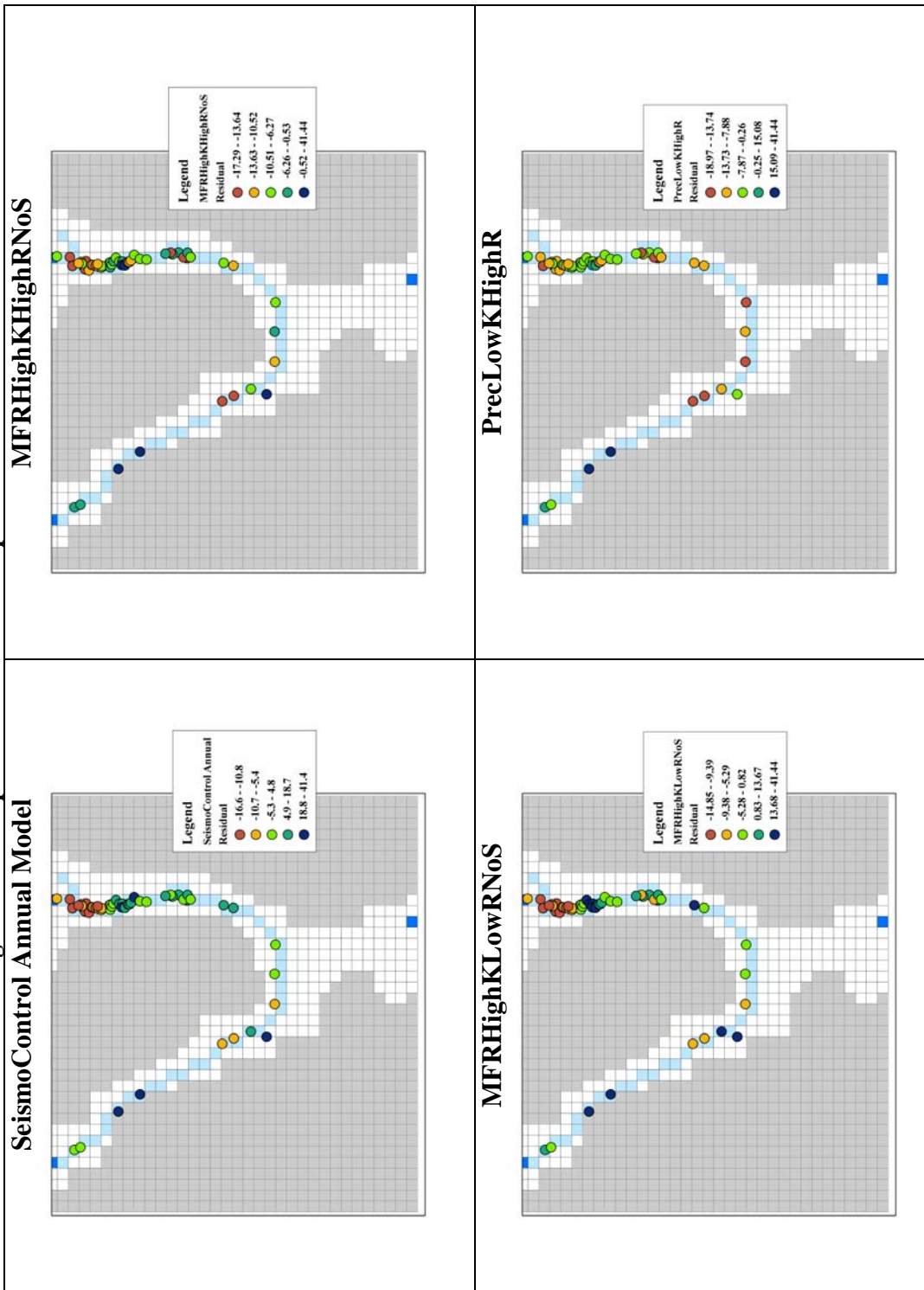




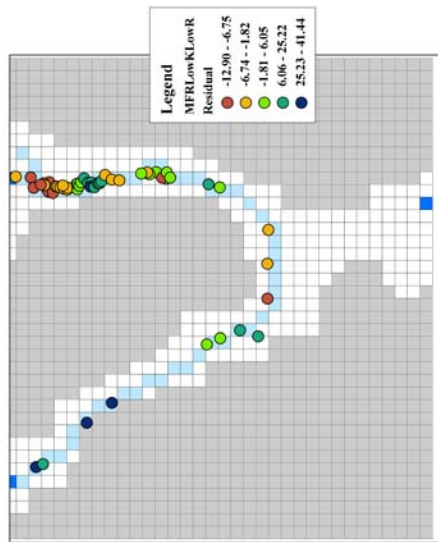
## 6.9.2 Residual Maps

Although some of the models tend to overestimate simulated heads more than others, and although there is variation in which parts of the modeled area the simulation best matches; there are four regions for which all of models consistently do not match target water levels. With the exception of the PreclowKhighR model, all models underestimate water levels at the southwest bend in the river (near Agua Zarca) and in the northwest (near Ejido Aldofo Lopez and Ejido Cadillal) and the models all overestimate head in the northeast portion of the aquifer (just after the river crosses into Mexico). Many of the models also have difficulty matching observed water levels just north of the southeast bend of the river (near Migel Hidalgo/San Lazaro); the models either overestimate the water levels at this point, or have one target over estimated by 10 m and a nearby target underestimated by 10m. Moreover, the largest residuals for all models are at Pozo Arroyo San Luis and Noria El Cadial. This across the board discrepancy between simulated and observed values likely points to errors in the representation of the aquifer geometry or soil properties in those areas. As resistivity logs exist for the region near Pozo Arroyo San Luis and Noria El Cadial, errors in measuring the head at those points may be more of an issue than model geometry.

Figure 6-9: Comparison of Residual Maps of Selected Models



# MFRLowKLowR



### 6.9.3 Contour Lines

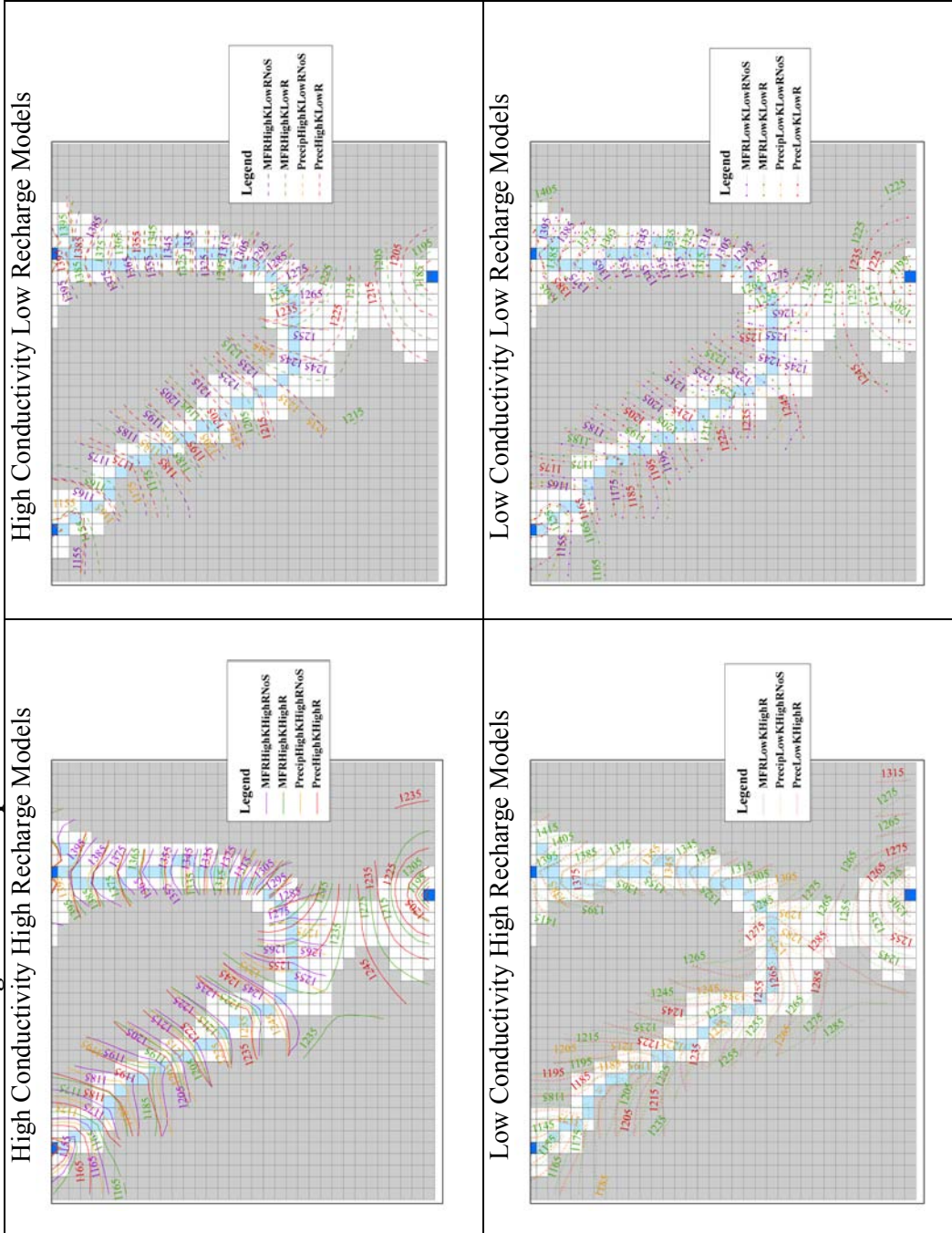
To understand the impact of assuming high and low conductivity and recharge values, I compared model fit across models with similar recharge mechanisms and assumptions about flow to the south. For models that assumed recharge occurred via precipitation, models that assumed high hydraulic conductivity values and low recharge consistently predicted lower heads than models that assumed low hydraulic conductivity and high recharge, regardless of whether or not there was underflow to the south. A combination of low hydraulic conductivity and low recharge lead to the lowest predicted contours. The difference between simulated contours between models could be up to 20 meters, and contours appeared to be most divergent towards the edges of the valley (i.e., near the mountain fronts). For models that assumed mountain front recharge occurred, high recharge models, irrespective of flow to the south or conductivity, lead to the highest predicted heads.

To understand the impact of assuming recharge occurs via precipitation vs. mountain front recharge or the impact of assuming underflow to the south, I compared model fit across models with similar conductivity and recharge values. Models that assumed high conductivity and high recharge models predict fairly similar contours, regardless of the recharge mechanism or flow to the south. Yet high recharge high conductivity models that assume no underflow to the south predict higher head levels than those that allow underflow south. Moreover, models that allow underflow to the south suggest the river is a losing stream where it runs east-west between San Lazaro and Paredes, whereas models that do not allow underflow to the south show the river as a gaining stream throughout. Among high recharge high conductivity models, those that assumed precipitation was the mechanism for recharge predict slightly higher heads (on the order of five meters).

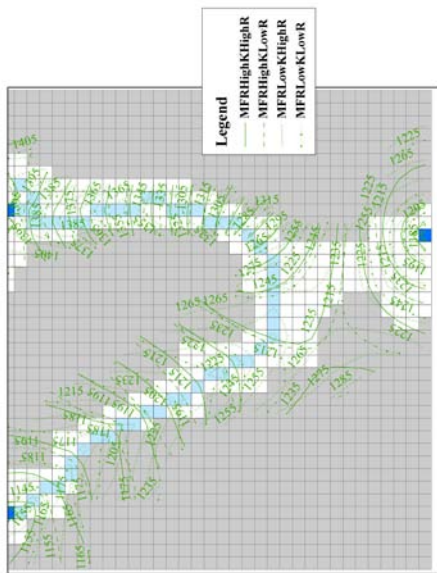
There is a larger variation among models that assume high conductivity and low recharge. Regardless of recharge mechanism, those high conductivity low recharge models that allow underflow to the south tend to estimated heads in the East-West segment of the river between San Lazaro and Paredes as 20-40 meters lower than those that do not allow underflow to the south. This result is highly sensitive to the value of the constant head assigned to the southern boundary. Similar to the high conductivity high recharge models, high conductivity low recharge models that allow underflow to the south also portray this east-west segment of the river as a losing stream.

Among low conductivity models, those with similar recharge amounts predict similar heads, irregardless of the recharge mechanism or whether or not there is underflow to the south. Contours predicted all have similar shapes and are within five or so meters. Figure 6-10 includes pictures of the simulated contour lines for overlaid on each other for comparison sake. The contours were drawn every 10 meters.

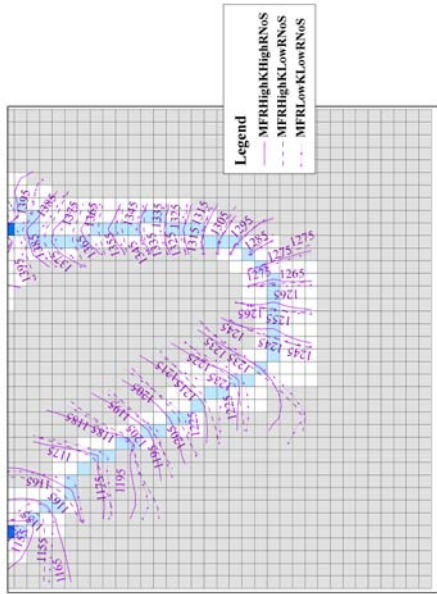
**Figure 6-10: Comparison of Piezometric Contours of Selected Models**



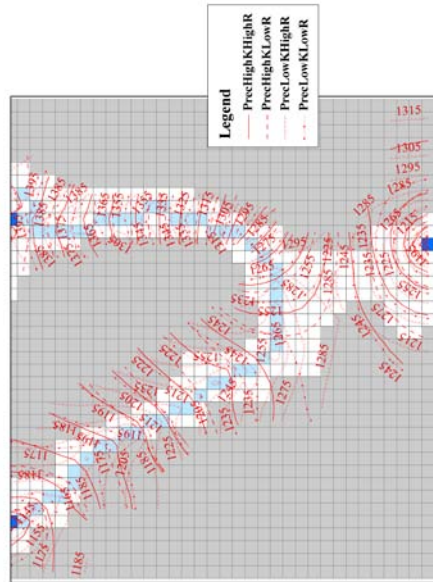
Mountain Front Recharge Flow South Models



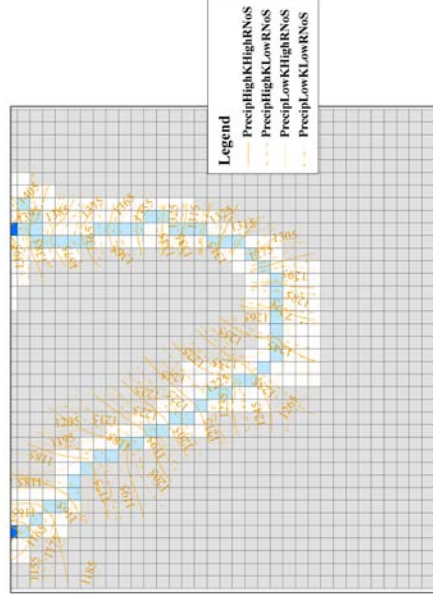
Mountain Front Recharge No Flow South Models



Precipitation Flow South Models



Precipitation No-Flow South Models



## 6.10 Sensitivity Analysis

I analyzed the sensitivity of the model fits to variations in the constant head boundary conditions, the river conductance, and the quantity of water abstracted via wells. As the impact of a small change in each parameter is likely to be different for each of the 17 alternative models (due to the complexity of the groundwater flows and the role of second order effects), rather than conduct a detailed sensitivity analysis for each parameter for each model, I semi-qualitatively looked at the impact of changes in the parameter on only a few selected models. The models I selected to use in the sensitivity analysis include the #1 Seismoasgiven, #6 MFRHighKHighRNoS, #10 MFRHighKLowRNoS, #11 PrecLowKHighR, and #17 MFRLowKLowR. These models cover the range of conductivity/recharge characteristics as well as variations in recharge mechanisms and underflow to the south.

Constant head boundaries were used in the model to describe flow into the modeled region at the northeastern portion of the aquifer, where the river crosses into Mexico, and flow out of the modeled area at the northwestern part of the aquifer, where the river crosses back into Arizona and the southern part of the aquifer, where there is possible underflow out of the river basin.<sup>168</sup> All of the models are quite sensitive to the constant head boundary conditions assumed, although the degree of sensitivity varies by model and by which boundary is being altered. Table 6-15 lists the head value ranges analyzed.

**Table 6-15: Values Constant Head Boundary Considered in Sensitivity Analysis**

Location of CHB	Range of Head Values Assigned
Northeast	1124 m – 1141 m
Northwest	1386 m – 1400 m
South	1156 m – 1204 m

For the northeast constant head boundary, lowering the head assigned improved RSS for all models, although lowering or raising the head more than 14 m would cause the low conductivity models not to converge. Reducing the head value by 2 m improved RSS for some models (MFRhighKlowRnoS, MFRlowKLowR) whereas for others, reducing the head value by 14 m lowered the RSS the most (Seismoasgiven, MFRhighKhighRNoS). Depending on the model, a decrease in the head value assigned of 2 meters could reduce flux into by 8 Mm<sup>3</sup> (Seismoasgiven) or increase flux by 5.9Mm<sup>3</sup> (MFRHighKHighRNoS). For the northwest constant head boundary, lowering or raising the constant head boundary by 5 m could have between an 0.5Mm<sup>3</sup>/yr and a 2Mm<sup>3</sup>/year effect. In general though, the current heads assigned appear best for reducing RSS. For the southern constant head boundary, increasing the assigned head reduced the RSS and flux out of the system for the Seismoasgiven and the MFRlowKlowR models, but reducing the CHB was most helpful in reducing RSS for the PreclowKhighR model. For the low conductivity models, reducing or increasing the head value assigned to the southern boundary only had impact on flux, of between 0.9 - 2Mm<sup>3</sup>/year. The impact on flux out of the system of changing the southern CHB was greatest for the Seismoasgiven model. The high

<sup>168</sup> Constant head boundaries represent an inexhaustible flow or sink of water into the system, the quantity of which is determined by the groundwater gradient and the aquifer properties. As the groundwater gradient is defined by the difference between the simulated heads just inside the boundary and the head value assigned at the boundary, the head value assigned plays an important role in determining how the model estimates flux.

sensitivity of the models to changes in the values assigned to the constant head boundaries indicates that better understandings of the model boundaries are needed to develop an accurate water-balance for the aquifer.

The value of river bed conductance term<sup>169</sup> is an important element impacting estimates of flux between the stream and the aquifer. The SeismoControl model assumed the vertical conductivity of the riverbed was 1.0E-7 m/s (0.028 ft/day); however, the ADWR models used conductivities of between 6.06E-6 m/s (1.7 ft/day) and 1.07E-5 m/s (3 ft/day) depending upon the location along the river and the presence of floods.<sup>170</sup> The values used for riverbed conductivity in the sensitivity analysis are listed in Table 6-16. The model performed best when riverbed conductivity was decreased, thus reducing flux from the aquifer into the river. If riverbed conductivity is reduced to 5.0E-8 m/s, flux from the aquifer to the river for the MFRHighKHighRNoS model is estimated to be 7.7 Mm3/year less than is calculated using the base conductivity value of 1.0E-7. If riverbed conductivity is increased to 1.07E-5 m/s, flux from the aquifer into the river for the same model is 46.6 Mm3 more than calculated using the base conductivity value. This large variation in flux as riverbed conductivity is varied indicates that an accurate estimate of riverbed conductivity is also an important element in developing an accurate water-balance for the aquifer.

**Table 6-16: Riverbed Conductance Values Considered in Sensitivity Analysis**

m/s	ft/day
5.00e-8	0.0028
1.00E-8	0.014
1.00E-7	0.028
3.56E-7	1
6.06E-6	1.7
1.07E-5	3

Lastly, I compared how the models fared if the pumping rate assigned were 482 lps rather than 900 lps. This reduction in pumping increased RSS for all five models; this outcome should be expected, as the recharge rate assigned to each model was designed to minimize RSS under the assumption that pumping was 900 lps. Some drywell losses still occurred. Reductions in pumping caused evapotranspiration to increase by up to 7Mm3/year, flux from the aquifer into the river, and underflow to Arizona to increase by a few Mm3/year and increases contours by 2-3 meters for all but the MFRlowKLowR model. For this model, decreasing pumping had a much smaller impact on fluxes yet increased head by approximately 5 m. However, range of these changes is less than the variation across models, indicating that generating a clearer understanding of the other uncertain aspects of the aquifer may be more important to predicting aquifer behavior than having a more accurate estimate of the amount of pumping that occurred in the past.

<sup>169</sup> Riverbed conductance =  $(K_z * L * W)/M$  where  $K_z$  is the vertical conductivity of the riverbed material,  $L$  is the length of the river through a given grid cell,  $W$  is the river width, and  $M$  is the thickness of the river bed.

<sup>170</sup> Floods are thought to cause scouring of the riverbed, reducing clogging and increasing the conductance of the riverbed.



## **6.11 Conclusions**

Although I have explained in great detail how the conceptual model is incomplete and the uncertainties which exist, it should be noted that many groundwater models have been developed using less information. The question that most determines the amount of data that is needed, is how accurate does the model need to be. I would argue that for the USCRB, the model needs to be more accurate than allowed for by this amount of information. The upper layer of the aquifer is the most productive (in terms of extracting water) yet it is relatively shallow. Most recharge occurs during the late summer monsoons and the winter rains, so in between these periods, water levels can drop dramatically. Most of the models here, including the SeismoControl model, predicted heads that were 10 meters off many of observed water levels and some simulated values were even up to 40 meters off. Moreover, the water balances calculated by models differ at times by more than a factor of seven. Without sufficient information to more accurately simulate water levels and to corroborate the expected flows of water, choosing which of these models is most representative of aquifer behavior not possible. None-the-less, it is possible to glean some useful information about which aspects of this uncertainty have the greatest impact on the model simulations.

As expected, of the various aspects of the aquifer I explored, the combination of hydraulic conductivity and recharge applied to the model had the largest impact on model fit and the greatest influence on values estimated as part of the water balance. Models with different combinations of conductivity and recharge differed by at times up to 20 meters. Models that assumed higher recharge rates tended to have lower RSS (independent of conductivity values assigned); however those models also more systematically overestimated heads. Within models that assumed lower conductivities, there was less variation than within models that assumed higher conductivities – this suggests that the influence of errors in the values of the model parameters assigned on model predictions will be greater for higher conductivity models. In general, the combination of low conductivity and low recharge appears to lead to the most even distribution of residuals. None-the-less, given the amount of data available, it is impossible to say which model conceptualization most accurate.

The importance of choosing the model with combination of conductivity and recharge that best approximates aquifer behavior cannot be understated. As demonstrated by the models developed, a model that assumes high conductivity and high recharge might match head observations as well as a model that assumes low conductivity. Yet the high conductivity high recharge model will predict much larger fluxes of water. Use of the higher recharge and higher conductivity model for policy making, if it is incorrect, could lead to water management strategies that overestimate the availability of water and might have devastating side effects. Due to scaling effects (M. Anderson & Woessner, 1992; Beven, 1993), values of hydraulic conductivity that create the best groundwater models are not always the same as the values obtained from pumping tests. Thus, the best way to resolve the question of which conductivity and recharge values best predict aquifer behavior would be to develop better estimates of expected fluxes of water throughout the system (i.e., a more comprehensive water budget) as this information would narrow the combinations of recharge and conductivity that are considered acceptable.

Although the quantity of recharge applied to the model is important, relative to the importance of the hydraulic conductivity and recharge values assigned, the mechanism through which recharge occurs appears to be of little importance. The fit of models that represented recharge as occurring via the direct infiltration of precipitation did not appear systematically different than models that represented recharge as occurring along mountain fronts. Representation of the recharge mechanism may be unimportant due to the narrowness of the river valley or the low resolution of the model.

The possibility of underflow leaving the aquifer towards the south similarly seemed to have little impact on the ability of the models to match target observations. Nor did the possibility of underflow to the south have a large impact estimates of fluxes into or out of the system at the northern boundaries. Rather, total recharge was predicted to be greater for models that allowed flow to the south. However, much of that recharge stemmed from the areas near the southern boundary, and thus was not available to other areas of the aquifer. Flow to the south varied little with changes to the value assigned to the constant head boundary. Models that allowed flow to the south did indicate the river was a losing stream along the East-West reach between San Lazaro and Paredes, yet signs point to this as a gaining stretch. This points to it being unlikely that much water leaves the system to the south.

All of the models developed poorly matched head observations at the southwest bend in the river (near Agua Zarca), in the northwest (near Ejido Aldofo Lopez and Ejido Cadillal), and in the northeast portion of the aquifer (just after the river crosses into Mexico). Many of the models also have difficulty matching observed water levels just north of the southeast bend of the river (near Migel Hidalgo/San Lazaro) and at both Pozo Arroyo San Luis and Noria El Cadial. These results suggest there are either errors in how the model represents the geometry of the aquifer at these points, or there exist lenses, faults, and fractures that have a large impact on water levels at those points. As cross-sections of the aquifer have been developed using resistivity logs for the Pozo Arroyo San Luis and Noria El Cadial region, the large residuals calculated in all models may be due more likely to errors in measurements of head at those points than due to problems in the geometry of the area as assigned to the model.

Through the sensitivity analysis I performed, it also is clear that uncertainty in the model stems from aspects of the aquifer beyond four factors varied between the models. The high sensitivity of the models to changes in the CHB indicates that better understandings of the model boundaries are needed to develop an accurate water-balance for the aquifer. The large variation in flux as riverbed conductivity is varied indicates that an accurate estimate of riverbed conductivity is also an important element in developing an accurate water-balance for the aquifer. Finally, the low sensitivity of the models to changes in the pumping regime imposed, suggest generating a clearer understanding of the other uncertain aspects of the aquifer may be more important than improving estimates of the historic rates of groundwater abstraction.

## **6.12 Recommendations for Future Modeling Efforts**

A number of improvements could be made to my modeling efforts, some of which require the collection and analysis of additional data and some of which do not. Using the existing information, improved understandings of stream flow and recharge could be developed. Stream measurements from the El Cajon gauge between 1954 and 1974 could be compared with

measurements during the same time period at the Nogales and Lochiel gauges, as well as with precipitation measurements. Although this analysis would not fully capture the effects of stresses on the system on stream flow and recharge, because there is limited information on other system stresses that occurred during that time period, it would at least provide estimates of stream-aquifer flux and tributary in-flows. This information could also be useful in developing a better representation of the river in the groundwater model by using the MODFLOW stream package. Unlike the river package, the stream package allows the riverbed to dry out along certain reaches or during specific points in time. As observations show several parts of the river do not have perennial flow, this would be more accurate than the current representation. Precipitation measurements and water levels in carefully selected wells in Arizona could also be compared, to develop better understandings of the quantity of recharge that occurs. The wells would have to be selected to represent areas in Arizona that are most similar to Mexico (i.e., likely not the micro-basin area).

If the model is to be changed to represent a date beyond 1997 (to incorporate newer observation data or to calibrate a transient model), additional information on water abstractions and water level measurements should be included. The infiltration gallery located near Paredes should be incorporated into the model as a drain. In addition, pumping from wells that have been drilled post 1997 should be added (Santa Barbara III, Norias I and II in Mascareñas, Pozo 4, Pozo 7, and Buena Vista). Actual pumping data for these and all other municipal wells for Heroica de Nogales are available at OOMAPAS (Personal Communication, June 13, 2008, June 25, 2006).

The model could be calibrated as a seasonal-oscillatory (if not fully transient) model. To do so, estimates of seasonal changes in pumping will be necessary. OOMAPAS can estimate how its pumping varies by season (OOMAPAS, Personal Communication, June 13, 2008). Changes in seasonal patterns of agricultural water abstractions can be estimated using seasonal and irrigated crop data available from SAGARPA (2000-2005) Depth to water measurements for the eleven wells measured by Tapia and ADWR, as well as measurements from the August 2002 census, and data on precipitation at the Nogales weather station, could be incorporated to aid in the calibration of a seasonal-oscillatory model. Most useful, would be to clarify the methods used in obtaining the data in the well censuses, so as to have a better understanding of the exact location of the wells, if the measurements represent static or dynamic water levels, and from what reference the measurements were taken.

The collection of additional data would also greatly improve the model. If the eastern portion of the aquifer is of great interest, hydro-geologic testing should be performed to develop cross-sections of that area. If the eastern portion of the aquifer is not of great interest, perhaps there exists a location where water levels have been stable or fluxes and heads have been measured that might form a better model boundary could be selected. Additional hydro-geologic testing around the Santa Barbara well-field is essential in order to understand the role faults are playing in transmitting groundwater in that region. Pumping tests conducted for wells in the older alluvium or in the Nogales formation would also be helpful, and especially tests in the Nogales formation may lead to insights regarding fractures in the material. Piezometric head measurements taken for each of the layers in the aquifer would be exceedingly useful in determining flow through the aquifer in the vertical direction and understanding layer connectivity. Measurements taken in wells across the northwestern border would provide

valuable information regarding underflow at the international border, and measurements taken in the southern region could help to clarify the issue of the groundwater divide.

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## Chapter 7 : Polycentric and Evolving Institutions Ambiguity, Gaps, and Overlaps

### 7.1 Introduction

In Chapters 3-6, I explained the uncertainty which exists in the USCRB, how institutions serve to increase this uncertainty and the implications of it in the management of transboundary waters. In this chapter I return to my focus on institutions, analyzing the institutional environment in the USCRB to show how a country's internal institutional environment is a key determinant of the capacity of that country to negotiate, agree to, and implement collective action/cooperative management strategies.

The literature on transboundary water management overlooks the pivotal role played by the structure of national water management institutions in the development of cooperative management strategies. This disregard for internal institutional water management arrangements is largely due to the implicit underpinning of the literature in international relations (IR) theories, and in particular, as Du Plessis (2000) elucidates, the rationalist IR approaches of realism, neo-realism, and liberalism.<sup>171</sup> Consequently, a 'state-centric perspective dominates' and the focus of analyses is on understanding and predicting how and why states act in an anarchical environment.<sup>172</sup> By 'state-centric perspective,' Du Plessis refers to the tendency of international

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<sup>171</sup> In rationalist theories of international relations, the international system (i.e., the world) is modeled as sovereign states operating in an anarchical environment. Thus 'structural' or 'systemic' factors refer to the characteristics of such an environment that influence the interactions between nation-states. For example, Dinar (2000, pp 380) uses the term systemic variable to refer to "the anarchical nature of the international system, the number of major powers in the system, the distribution of military and economic power among them, patterns of military alliances and international trade, and other factors that constitute the external environment common to all states." Only a limited number of transboundary water scholars recognize the widespread adoption of such framings, and as a result, few analyses address the limitations of such an approach. Furlong (2006) uses a case study of the Southern African Development Community to demonstrate the pitfalls of adopting an IR framework; she demonstrates how such framings conceals power and exploitation within a state as well as the socially constructed nature of resources. Similarly, Dinar (2000), argues we must look beyond the systemic factors typically considered in the field of international relations and instead adopt a 'process-oriented' approach. Such an approach would consider the interactions among states in combination with non-systemic factors (such as ethno-national communities, nationalism and nationalist appeals, bureaucratic politics, and interest groups) which impact the negotiation process. Lastly, Blatter and Ingram (2001) use the many case studies in their edited book to support their claim that we need to move beyond modern rationalist approaches to transboundary waters, which have focused on the nation-state, and instead adopt an approach that considers values, histories, networks, and culture.

<sup>172</sup> The use of an IR framework is evident in both quantitative and qualitative analyses of transboundary waters. Most quantitative analyses adopt the country as the unit of analysis. This includes large-n empirical (Espsey & Towfique, 2004; M. Giordano, Giordano, & Wolf, 2002; Hensel, Mitchell, & Sowers II, 2006; Song & Whittington, 2004; Spector, 2000; Yoffe et al., 2004) and game theoretic (Barrett, 1994; Dombrowsky, 2007; Eleftheriadou & Mylopoulos, 2008; L. Fernandez, 2002; Frisvold & Caswell, 2000; Just & Netanyahu, 2004; Netanyahu, Just, & Horowitz, 1998; Roger, 1969) studies that draw from realist theories which attribute conflict and cooperation to power dynamics (economic, geographic, military), relative gains, strategic behavior and linkages. It also includes optimization (Fisher et al., 2002; Küçükmehtemoglu & Guldman, 2004; Whittington, Wu, & Sadoff, 2005) and multi-criteria decision models (Ganoulis, Duckstein, Literathy, & Bogardi, 1996) that draw from liberal theories and seek to determine the joint-gains from cooperation. Qualitative analyses, such as case and comparative case studies, also treat countries as 'homogenous monoliths' and phrase their analysis as "Canada feels... or Jordan wants..." Wolf (2007, pp 253). These studies adopt descriptive approaches and seek to explain conflict, cooperation, or regime effectiveness either based on power dynamics or the collective action dilemma that arises from the lack of a

relations theories, and thus also studies of transboundary water, to take the nation-state as the unit of analysis. In the transboundary water literature non-state actors are not fully disregarded,<sup>173</sup> yet the primary actor in studies of transboundary waters is the nation-state and the focus of the literature is on what leads these nation-states to conflict or cooperation, how can their behavior can be predicted, and how structural or systemic factors<sup>174</sup> can be overcome via the development of norms (international law) and regime formation.

Insights from IR theory regarding the impact of structural characteristics (i.e., characteristics of nation-states and their relation to each other) are indeed important to understanding the management of transboundary waters. However, the problem with the commonly used IR framings is that, in taking the nation-state as the unit of analysis and in focusing on structural characteristics, the literature on transboundary water management assumes countries have an internal institutional environment that allows them to negotiate and implement cooperative water management strategies. Levy et al. (1995) call attention to the need for research on international regime formation to consider how the willingness of a country and capacity of member states influences the effectiveness of a regime. The corollary to this is a need to also develop better understandings of how a country's capacity influences its ability to negotiate and formulate an international regime.

The importance of the institutional environment in governance has been well documented in studies of public choice, federalism, collective action (Hall & Taylor, 1996; Hooghe & Marks, 2003; E. Ostrom, 1999). These studies demonstrate how institutions influence behavior by constraining the choice set and otherwise influencing the costs and benefits of behavior. Although the transboundary water literature recognizes the importance of supra-national institutions,<sup>175</sup> the role played by national and sub-national water management institutions is

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higher authority in the international realm (Elhance, 1999; Ganoulis et al., 1996; Milich & Varady, 1998; A. Wolf, 1997, 2002). Studies of international water law also adopt the nation-state as sovereign actor model, as do articles recommending best practices such as finding the pareto-optimal solution and sharing the gains from participation similarly treat the nation-state as an entity with defined preferences, capable of determining, acting, and distributing gains from cooperation (M. A. Giordano & Wolf, 2003; Grey & Sadoff, 2003; Jagerskog & Lundqvist, 2006; Klaphake & Voils, 2006; Sadoff & Grey, 2005; UNDP, 2006; A. Wolf, 1997; A. T. Wolf, 2007).

<sup>173</sup> Although the nation-state is the unit of analyses for the majority of transboundary water studies, the role of transnational networks and supra-national entities (Barrett, 1994; Biswas, 1999; Conca, 2006; Elhance, 2000; Frisvold & Caswell, 2000; Gerlak, 2007) and the influence of domestic interest groups has not been ignored (Feitelson, 2006; Frey, 1993; Furlong, 2006; LeMarquand, 1976; Sneddon & Fox, 2006; Trolldalen, 1992; Turan & Kut, 1997).

<sup>174</sup> In rationalist theories of international relations, the international system (i.e., the world) is modeled as sovereign states operating in an anarchical environment. Thus 'structural' or 'systemic' factors refer to the characteristics of such an environment that influence the interactions between nation-states. For example, Dinar (2000, pp 380) uses the term systemic variable to refer to "the anarchical nature of the international system, the number of major powers in the system, the distribution of military and economic power among them, patterns of military alliances and international trade, and other factors that constitute the external environment common to all states."

<sup>175</sup> The role of supra-national institutions is recognized in the branch of IR theory known as liberal institutionalism (Burchill et al., 2001), as evidenced by their championing the formation of international regimes. In the transboundary literature, this translates into the endorsement of international basin management institutions as key to prevention of conflict (Chitale, 1995; M. A. Giordano & Wolf, 2003; Hensel et al., 2006; UNDP, 2006; A. T. Wolf, 2007) and the focus of many studies on how to design basin-regimes so they are most effective (Dombrowsky, 2007; Draper, 2007; Milich & Varady, 1998; Rowland, 2005).

underappreciated.<sup>176</sup> My research indicates in the USCRB, national water management institutions are critical components of the competence and the capacity<sup>177</sup> of both the US and Mexico to manage their transboundary groundwater resources. More specifically, my research shows the institutions for water management within the US and Mexico are not well characterized using the state-as-container approach and the structure of those institutions hinders formation of formal agreements and constrains the water management activities possible.

In the USCRB, the institutional framework for water management within each country and, particularly the framework for groundwater management, is more realistically characterized as an evolving system of polycentric agencies, each of which governs various (and sometimes overlapping) aspects of water. By poly-centric,<sup>178</sup> I refer to the distribution of authority for policy and decision-making, implementation, and enforcement to multiple entities at different scales of governance. Water management encompasses a wide variety of activities and tasks and it is common for different aspects of water management to fall under the jurisdiction of different entities. By evolving, I refer to the fact that the institutional environment for water management is in a constant state of flux. New entities, laws, and regulations are formed and existing responsibilities and jurisdictions are modified to address emerging problems and as objectives and governance paradigms change. The value of viewing the institutional structure as such is it allows for a greater understanding that ambiguity, gaps, and overlaps in responsibility and

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<sup>176</sup> The role of the institutional arrangement for water management within a country is mostly overlooked in the literature on transboundary water management. Dinar and Dinar (2003) review 99 books and a large number of articles on transboundary waters, yet include no indication that any of these articles considers the role of national water management institutions. Nor are national water management institutions mentioned in other key works such as the chapter of the Human Development Report (UNDP, 2006) that focuses on transboundary waters; Dinar et al.'s (2007) textbook on understanding transboundary water conflict, negotiation, and conflict; and Wolf's (2007) well-known review of the state of conflict and cooperation over shared waters. This is not to suggest that the governance structures within countries have not been considered in the context of transboundary waters. Two articles, both of which were published more than twenty-years ago, comment on the impact of federalism on cooperation over shared waters (Alheritiere, 1976; Hayton, 1978). Similarly, two case studies of water management between the USA and Canada highlight the distribution of power between federal and state/provincial government. Barrett (1994) explains how ratification of the Columbia River treaty was delayed was due to conflict between the provinces and the federal government in Canada; while Norman and Bakker (2005) highlight discrepancies between the structure of Canadian water management arrangements and those in the USA and conclude that the 'scalar mismatch' between the resolution mechanisms, which occur at the national level, and problems, which occur locally, create barriers to cooperation. However, the distribution of authority created by federalism is just one aspect of the structure of national water management institutions and a more in-depth institutional analysis is needed that also considers existing laws and regulations, property rights, and governmental agencies.

<sup>177</sup> In his analysis of the role of institutions in addressing environmental change, Young (2002) explains how the effectiveness of an environmental regime is impacted by competence, compatibility, and capacity. Throughout this chapter, I draw on Young's concepts of competence and capacity to show how those affect not only just the effectiveness of an international environmental regime, but the formation of the regime in the first place. By 'competence', Young (pp 99-100) refers to the "authority necessary to implement commitment." He explains that due to the distribution of authority between national and sub-national units of government, there is no guarantee that legally binding conventions (i.e., international agreements) will take precedence over US domestic laws. By 'capacity', Young refers to "a measure of the availability of social and institutional capacity as well as material resources necessary to make good on commitments" Young explains how in the US, individual agencies are not always willing or able to take on the responsibility for enacting international commitments.

<sup>178</sup> Ostrom et al. (1961) use the term polycentric to refer to "many centers of decision-making which are formally independent of each other." In my use of the term, I broaden this term to also account for the fact that there also may exist centers of decision making that have inter-dependencies. An example of this would be the relationship between the US Environmental Protection Agency and the Arizona Department of Environmental Quality.



jurisdictional authority are intrinsic features of the environment. These gaps, overlaps and ambiguities serve to constrain the actions of both the US and Mexico with respect to their transboundary ground and wastewaters until institutional change occurs. Yet changing the structure of national water management institutions can be complex and may take time, as change is inhibited by dynamic transaction costs (Challen, 2000)<sup>179</sup> and is limited by culture, institutional nesting, and path dependencies (Livingston, 2005).

## **7.2 Institutional Analysis of the USCRB**

In the remainder of the chapter, I analyze how the institutional environment within each side of the border impacts the feasibility of each of management strategies suggested above. I describe the bi-national institutions operating in the study region and then delve into more details explaining the institutions for water management institutions within the US and within Mexico. Through my description, I explain the polycentric and evolving nature of the water management institutions within each country and analyze how this structure impacts decision making.

### **7.2.1 Bi-National Institutions**

Several ‘international’ institutions impact water management in the USCRB. In 1944, the US and Mexico signed a treaty governing the waters of the Colorado, Rio Grande, and Tijuana rivers (IBWC, 1944). The treaty also created the International Boundary Waters Commission (IBWC) and the Comisión Internacional de Limites y Agua (CILA) as the respective US and Mexican federal agencies charged with implementing the treaty and assuring each country meets its treaty obligations. These agencies have become the defacto agencies responsible for responsible for resolving water and boundary related disputes and conducting activities and agreements related to water along the border (Hardberger, 2004; Stephen Mumme, 2005).

Although the Santa Cruz River is a distant tributary to the Colorado, there are no stipulations for the management of the Santa Cruz in the 1944 treaty, nor does the treaty address groundwater (IBWC, 1944; S. P. Mumme, 2000). However, addendums to the treaty, which take the form of Minutes, expand the responsibilities of the IBWC and CILA and include provisions related to ground and waste waters (IBWC, n.d.). Minute 242 stipulates that both countries will inform each other of water development activities that might adversely affect the other, includes an agreement that both countries will limit pumping near San Luis, and suggests a commitment to seek a comprehensive groundwater agreement (IBWC, 1973; S. P. Mumme, 2000). To date, negotiations for such an agreement have not begun.

Wastewater in the USCRB is addressed in a number of treaty Minutes (IBWC, n.d.) including: Minute 206, the initial agreement to construct and jointly operate of the NIWTP; Minute 227, which provides for increasing the capacity of the NIWTP and ensures the right of Mexico to dispose of its wastewater within its territory at anytime; Minute 261, which recognizes the responsibility of the IWBC and CILA to address border sanitation problems; Minute 276, which

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<sup>179</sup> In his analysis of institutional change, Challen (2000) differentiates between two types of transaction costs. Static transaction costs, which institutional change aims to reduce, include the costs of administering the daily tasks of the institution such as collecting information, communicating, monitoring, and enforcement. Dynamic transaction costs conversely, place limits on institutional change. Dynamic transaction costs include the transition costs of formulating and implementing changes in the institutional structure as well as the inter-temporal costs which occur due to changes in the current period limiting or affecting the possibilities for future institutional change.

again addresses the need for capacity expansion of the NIWTP and reiterates the right of Mexico to return its sewage for use in its own territory; and Minute 294, which calls for development of facilities planning for wastewater infrastructure and led to the development of the Ambos Nogales Facility Plan (Camp Dresser & McKee, 1997).

Beyond the institutions related to the 1944 treaty, several intergovernmental agencies influencing water management in the USCRB have arisen in response to NAFTA. The North American Agreement for Environmental Cooperation led to the formation of the Commission for Environmental Cooperation and the La Paz Agreement led to formation of the Border Environmental Cooperation Commission (BECC), the North American Development Bank (NADBank) and the Border 2012 Program (Border 2012) (Linda Fernandez & Carson, 2002; Spalding, 2000). The CEC is a tri-lateral agency formed between the USA, Mexico, and Canada, whose mission is to improve the environment in North America and prevent potential conflicts between trade and environmental protection.<sup>180</sup> The CEC conducts investigations of environmental problems and hears citizen complaints about environmental violations (Donnell, 2003; Liverman, Varady, Chavez, & Sanchez, 1999; Wilder, 2000). The BECC is a joint US-Mexico agency responsible for evaluating and certifying that environmental infrastructure projects meet sustainability criteria.<sup>181</sup> The NADBank, which is funded by contributions from the US and Mexico federal governments, aids the BECC in arranging financing for certified projects via loans and grant programs (Donnell, 2003; Good Neighbor Environmental Board, 2005; Vazquez-Castillo, 2001).<sup>182</sup> Lastly, the Border 2012 program adopts a bottom-up approach and coordinates local and regional-work groups and taskforces focused on specific issue areas in identifying environmental problems, planning, and mobilizing local and national resources (S. Mumme, 2005).<sup>183</sup> Other bi-national institutions influencing water management in the USCRB, include the Arizona-Mexico Commission and the Border Governor's Association.<sup>184</sup>

### 7.2.2 USA

Water resources in the United States are managed under a policy of federalism. Responsibility for the management of water resources is allocated to the states; however, the federal government retains authority in circumstances that relate to international agreements, inter-state commerce, the public trust, and the management of public lands (Cox, 1982; Heinmiller, 2007; Sax, Thompson, Leshy, & Abrams, 2000). As a result, the federal government, through its executive agencies and legislative powers, has intervened in a variety of water management activities. This involvement includes the development of projects related to irrigation, flood protection, hydropower, drainage and urban water supply; the creation of programs to regulate water pollution, encourage conservation and protect wetlands protection; and the setting of national environmental policies and regulations, such as the Clean Water Act (Gerlak, 2005; Lepawsky, 1950; Rogers, 1993). With specific reference to the transboundary USCRB, at least five federal agencies play important roles in regulating, monitoring, or developing water resources. The U.S. Geological Survey (USGS) conducts hydrogeological investigations,

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<sup>180</sup>For more information, see <http://www.cec.org/>

<sup>181</sup> See <http://www.cocef.org/ingles.php>

<sup>182</sup> See <http://www.nadb.org/>

<sup>183</sup> See <http://www.epa.gov/Border2012/>

<sup>184</sup> For more information on the Arizona-Mexico Commission see <http://www.azmc.org/> For information on the Border Governor's Conference see <http://www.gobernadoresfronterizos.org/index.php?lang=en>

monitors surface flow, and maintains water availability data. The U.S. Environmental Protection Agency (EPA) issues regulations for water quality and implements border area programs for water conservation and pollution abatement. The U.S. Bureau of Reclamation (USBR) conducts collaborative water supply studies and funds infrastructure development. The U.S. Army Corps of Engineers (ACE) approves stream crossings (bridges and culverts) and has conducted flood studies for the Nogales Wash. Finally, although not an agency charged directly with water management, the Department of Homeland Security (specifically the Border Patrol), monitors border crossing through drainage culverts, etc.

None-the-less, state governments have been delegated responsibility for the management of water resources within their boundaries, including the allocation of water rights. States are also frequently responsible for the implementation of federally defined policies. The Arizona Revised Statutes designates the Arizona Department of Water Resources (ADWR) as the entity responsible for administering Arizona water law and ensuring long-term adequate supplies for the state (ADWR, 2002; Arizona State Legislature, n.d.)<sup>185</sup> and the Arizona Department of Environmental Quality (ADEQ) as the entity responsible for enacting pollution control measures and ensuring the quality of Arizona's waters.<sup>186</sup>

Although both these agencies are charged with managing waters within the state and developing and implementing policies, these agencies can be considered primarily regulatory agencies in that they do not own water resources, they do not create laws, and they do not directly undertake physical water management activities. Rather direct actions are undertaken by other entities such as the Arizona Water Bank, the Central Arizona Groundwater Replenishment District, municipal service providers, local governments, and individual water rights holders. ADWR and ADEQ affect their mandates by issuing permits, conducting studies, providing technical assistance, and developing and enacting programs and policies. New laws must be passed by the Arizona legislature or through the governor's office.

In Arizona, surface and ground waters are administered separately. Arizona surface water law is based on the legal doctrine of prior appropriation while Arizona groundwater rights are subject to reasonable and beneficial use (ADWR, 2001). The 1980 Groundwater Management Code restricts groundwater use, particularly in Active Management Areas (AMA), where groundwater users must either possess a grandfathered water right, a service provider right, or a withdrawal permit (ADWR, 2001).<sup>187</sup> A number of other laws relate to water use within Arizona including regulations on interbasin and out of state transfers, stipulations for artificial recharge and recovery, and water markets. Within AMAs two important regulations include mandatory conservation requirements and a prohibition on the sale of sub-divided land without demonstration of a 100-year assured water supply (Colby & Jacobs, 2007)

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<sup>185</sup> See <http://www.azwater.gov/>

<sup>186</sup> See <http://www.azdeq.gov/>

<sup>187</sup> Up to 10 AFA for domestic or stock use may also be extracted from "exempt wells" without a permit. Exempt wells have a pumping capacity of less than 35 gpm. See <http://www.azwater.gov/dwr/WaterManagement/Content/AMAs/default.htm> for additional details

### *7.2.2.1 Gaps, Overlaps and Ambiguities*

As can be intuited from the above description of the institutional environment, water management within the US side of the USCRB is not a centralized punctilious process. The USA does not have a coherent national water policy (Conca, 2008; Gerlak, 2005), nor a direct chain of command for water management. Instead water management occurs through an amalgamation of many diverse activities and policies designed and enacted at a variety of scales. A representation of these institutions, including a summary of their main responsibilities and their relationships as of 2008, is included in Figure 7-1. Moreover, the institutional environment is in flux, as new laws are passed, new institutions arise, and existing institutions evolve. This polycentric and evolving institutional structure leads to gaps, overlaps, and ambiguities in responsibility and jurisdiction.

Within the US side of the USCRB, there is no entity responsible for conducting comprehensive water planning and for implementing the water management activities required to enact such a plan. This responsibility does not fall to the IBWC nor does it fall to ADWR. The mission of the IBWC is to resolve issues related to boundary demarcation, water, sanitation, water quality, and flood control in the border region that are related to treaties between the US and Mexico.<sup>188</sup> Its mission does not include enacting water management activities within the US side of the border that are unspecified in treaty minutes. The IBWC has been known to interpret its directive narrowly (Stephen Mumme, 2005). Thus in practice, the IBWC negotiates agreements, monitors compliance, and only undertakes actions specifically allocated to it via the treaty minutes. Consequently, policy design, decision making, and implementation functions are primarily left to the purview of other state and federal agencies.

The Arizona Department of Water Resources is charged the mission of with ensuring “an adequate quantity of water of adequate quality for Arizona’s future” (ADWR, 2002). The SCAMA was developed to aid in achieving this goal by facilitating the coordinated management of surface and ground water users and the participation of local water users in binational coordination of water resources management (ADWR, 1997; Arizona State Legislature, n.d.).<sup>189</sup> Although this broad mission seemingly encompasses the responsibility to manage transboundary waters, in practice, the directive does not translate into jurisdictional authority and capacity. ADWR is limited in its water resources planning and management activities by the tools and authority allocated to it. ADWR’s main functions are to administer and enforce the Arizona groundwater code and surface water rights laws. It can conduct technical studies and develop water plans, however, its policy making activities are constrained to developing incentive systems and developing and enforcing regulations. As a result, ADWR does not have the direct ability to plan and implement transboundary water management activities.

Ambiguities exist regarding which entity is responsible for conducting planning and decision making also arise out of the polycentric nature of the institutional environment. For example, interviews with key informants in Arizona indicate at the local level there is the sentiment that, because addressing water management in the region requires international cooperation, the US federal government should adopt proactive stance to planning and implementing water management activities in the basin including coordinating cross border activities. However,

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<sup>188</sup> See <http://www.ibwc.state.gov/home.html>

<sup>189</sup> Arizona Revised Statute 45-411.04 creates the SCAMA.

concurrently, federal governmental employees viewed management of waters in the basin as primarily the responsibility of state and local entities, with federal assistance in negotiating and ensuring compliance with desired activities once local planning had occurred. This ambiguity between state/local and federal responsibility stems in part from what Norman and Bakker (2005) dub ‘scalar mismatch’ in that a problem or challenge occurs at the local level but the solution necessarily involves the federal level, as the authority to enact international agreements lies at the federal level. Thus both levels of government must be involved, yet the degree of involvement or the distribution of responsibility in developing the solution is not well specified.

As there is no entity in the SCAMA with the jurisdiction to conduct comprehensive water planning and implementation, various aspects of water management are delegated among a number of different governmental entities. This results in overlaps in the jurisdiction of agencies and ambiguity in responsibilities. Overlaps occur as there is interplay<sup>190</sup> between the objectives and policies of each agency. For example, in the SCAMA, one issue of concern is maintaining critical habitat for endangered species such as the gila top minnow and the southwestern fly catcher (USFWS, Personal Communication, October 12, 2007; Friends of the Santa Cruz River, Personal Communication, May 29, 2006). Both the US Environmental Protection Agency (EPA), through its enforcement of the Endangered Species Act,<sup>191</sup> and the Arizona Department of Fish and Game, through its Project Evaluation Program,<sup>192</sup> hold responsibility for ensuring federal or state authorized projects do not negatively impact critical habitat. Thus, through their regulatory powers, both have a say in water management activities that might change the instream flow regime, such as reclaiming or recharging effluent released from the NIWTP.

The many gaps, ambiguities and overlaps in the institutional structure within the US limit its capacity to develop a formal strategy for managing the shared groundwaters of the USCRB. As responsibility for comprehensive water management planning and implementation is fragmented, there must be a coming together of many diverse actors to instigate water management activities. Where responsibility is ambiguous or overlapping, these actors must work to redefine or converge upon workable arrangements. This entails high transaction costs, both in coordination, communication and negotiation as well as in bringing about institutional change. These processes determine to a large extent the degree to which and the ability of the US to agree to and to implement transboundary water management activities.

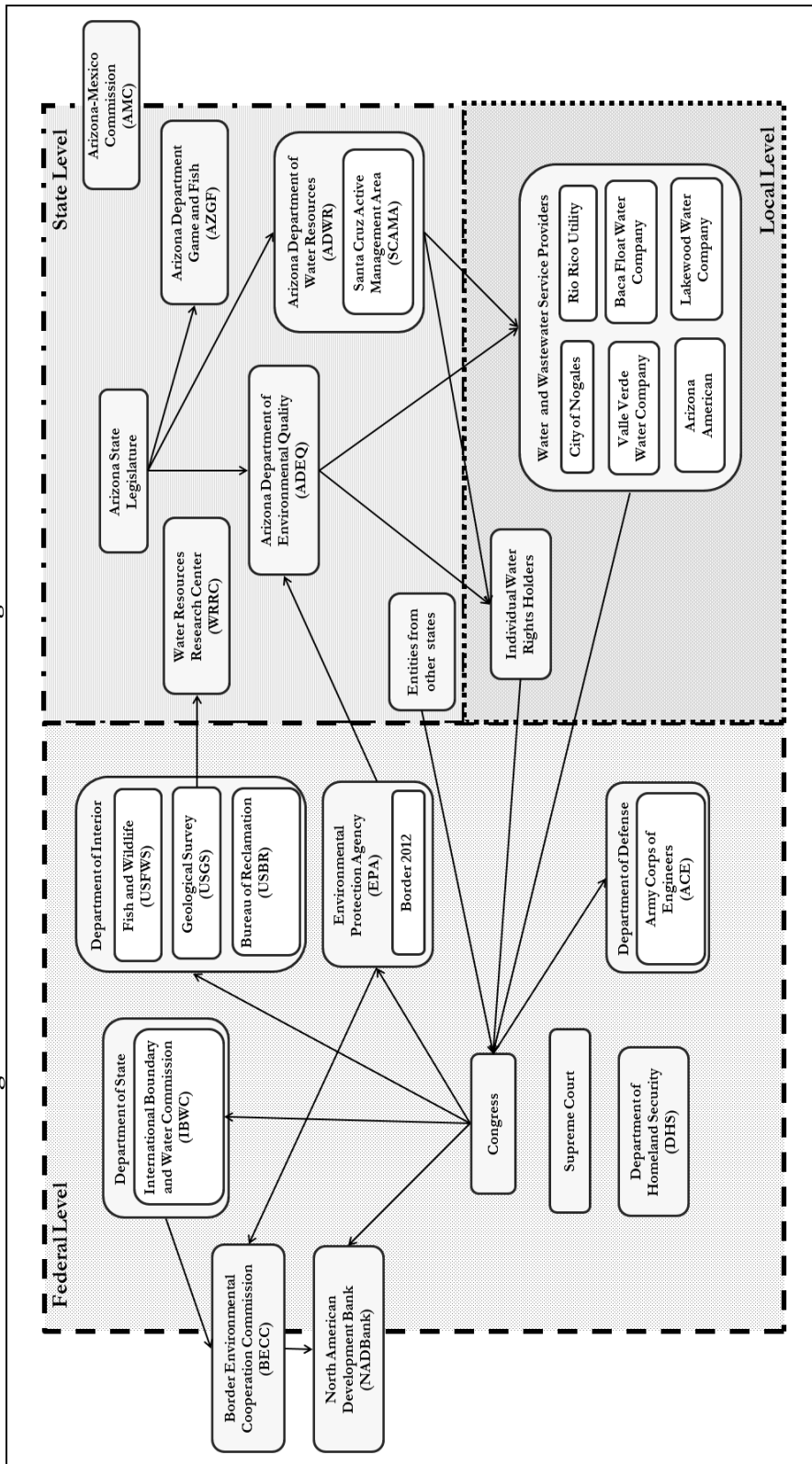
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<sup>190</sup> Oran Young (2002) explains the concept of interplay as interactions between agencies and entities within (horizontal) or across (vertical) a level of scale. Interplay can occur because two or more agencies have functional interdependencies, i.e., they are engaged in substantive policy areas that are linked due to their physical or socio-economic properties or because the agencies forge intentional links in order to work together.

<sup>191</sup> See <http://www.epa.gov/lawsregs/laws/esa.html>

<sup>192</sup> See [http://www.azgfd.gov/w\\_c/project\\_evaluation.shtml](http://www.azgfd.gov/w_c/project_evaluation.shtml)

Figure 7-1: Entities Related to Water Management in the SCAMA



<u>Entity</u>	<u>Synthesis of Mandate and Activities</u>
BECC	Certify proposed environmental infrastructure projects and provide technical assistance to entities seeking to develop such projects in the border region.
NADBank	Assist BECC in arranging financing for certified projects through loans and grants.
Department of State	Conduct foreign policy. Grant 'Presidential Permits' for infrastructure crossing the border.
IBWC	Ensure compliance with the 1944 treaty, negotiate treaty amendments, maintain hydrologic monitoring stations, manage joint infrastructure, and communicate information across the border.
EPA	Ensure pollution control and prevention by enforcing environmental legislation, develop water quality standards, and implement water conservation and pollution abatement programs.
Border 2012	Assist in environmental planning for the border region and finance related projects.
Supreme Court	Provide appeal mechanism for the regulation of water use that impacts interstate and foreign commerce.
USFWS	Protect endangered species
USGS	Conduct hydro-geological investigations, monitor surface water flow, maintain water availability data.
USBR	Conduct collaborative (inter-agency) water supply studies, fund infrastructure development.
ACE	Approve stream crossings (bridges and culverts) and conduct flood studies.
DHS	Monitor border crossing including through drainage culverts.
AMC	Provide a forum for advocacy and information sharing.
AZGF	Protect endangered species.
ADEQ	Develop, monitor and ensure compliance with pollution control measures including setting water quality standards, permitting discharge, reuse, and recharge activities.
ADWR	Conduct state-wide water resources planning, administer water rights, undertake hydrologic investigations and monitoring, permit water-related activities, and provide technical assistance to water users.
SCAMA	Develop management plans to achieve AMA goals, administer groundwater rights, monitor water use, and enforce conservation requirements.
WRRC	Implement the state's component of the Transboundary Aquifer Assessment Program, provide research and policy support for water resources planning and management in general.

### 7.2.3 Mexico

Management of water in Mexico is more centralized than in the USA (S. Mumme, 2004; Ramirez, 1967). Article 27 of the Mexican Constitution defines ‘national waters,’ i.e., waters that pertain to the nation, and places those waters under the jurisdiction of the Mexican Federal government (Brañes, 1991a, 1991b; Comisión Nacional del Agua & Salmon, 2008; Farias, 1993). Thus the federal executive branch, primarily via the Comisión Nacional del Agua (CONAGUA), is responsible for all activities related to the use, management, and protection of national waters. CONAGUA must coordinate with other executive agencies including the Secretaría de Relaciones Exteriores (Secretary/Ministry of Foreign Affairs) for matters related to transboundary waters, the Procuraduría Federal de Protección al Ambiente (PROFEPA) for safeguarding water quality; and the Secretaría de Agricultura Ganadería, Desarrollo Rural, Pesca y Alimentación (SAGARPA) on matters related to agriculture and rural development (Comisión Nacional del Agua & Salmon, 2008).

Mexico has been undergoing a process of decentralization, particularly in the water resources sector (Castro, 1995; Donnell, 2003; Gonzales-Villarreal & Garduño, 1994; Hearne, 2004) and as a result, thirteen deconcentrated (i.e., regional) offices of CONAGUA, known as Organismos de Cuenca (Basin Organizations) have been formed, based on hydrographic criteria (Garduño, 2005; Gonzalez & Magana, 2006; Hearne, 2004). The USCRB falls within the jurisdiction of Basin Organism Region II: Noroeste. Decentralization of water management in Mexico has been accompanied by efforts to increase water user participation. Thus, Consejos de Cuenca (watershed councils) and Comites Tecnicos de Aguas Subterráneas (COTAS – groundwater technical committees) have been developed to encourage private sector participation and increase coordination between governmental agencies, water users, academia, and other sectoral representatives (Tortajada & Contreras-Moreno, 2005). Consejos de Cuenca and COTAS act as advisory and coordinating units headed by a representative from CONAGUA, and do not have independent decision making or implementation authority (Brown & Mumme, 2000; Tortajada & Contreras-Moreno, 2005). The USCRB pertains to the Consejo de Cuenca Alto Noroeste; however a COTA has not been formed for the region (Comisión Nacional del Agua, 2008).

As the federal government regulates national waters, states in Mexico have limited jurisdiction over water resources management. The Comisión Estatal del Agua de Sonora (CEAS) is responsible for coordinating programs and resources related to water supply transferred to Sonora and its municipalities from the federal government; for establishing norms and standards related to water supply; for conducting water resource efficiency studies; and for assisting municipalities in providing water and sanitation services (Comisión Estatal de Agua Sonora, 2005).<sup>193</sup> CEAS supports municipal water providers through technical assistance and through the distribution of financial resources from both the state and federal governments.

Municipalities in Mexico are responsible for the provision of water and sanitation services to their residents; however where they lack the capacity to do so, they receive assistance from the state (Comisión Estatal de Agua Sonora, 2005; Hearne, 2004). In the USCRB, ownership and operation responsibilities of the Heroica Nogales municipal water utility, the Organismo Operador Municipal de Agua Potable, Alcantarillado, y Saneamiento (OOMAPAS), was

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<sup>193</sup> See <http://www.CEAS.gob.mx/>



devolved to the municipality in June 2005. Thus the municipality is currently responsible for providing water, sewerage, and wastewater treatment and disposal services to its residents.

Concessions for the use of water in Mexico are granted by CONAGUA. Surface water users must obtain permission to divert and use national waters. Groundwaters, according to stipulations in the constitution, may be freely brought to the surface and used so long as such use is in the public interest. Where groundwater withdraw may impact public utility, CONAGUA has the authority to regulate abstractions, by declaring a “zona de veda” or restriction zone. Where veda has been declared, groundwater users ostensibly may not obtain new concessions from CONAGUA; where there are no restrictions, users may apply for time-bound volumetric concession titles in order to make use of the water (Farias, 1993; Manzanilla, Calleros, & Rodriguez, 1991; Zamora, Cossio, Pereznieto, Roldan-Xopa, & Lopez, 2004). All surface and groundwater users must report their water use to CONAGUA and pay usage fees.

#### *7.2.3.1 Gaps, Overlaps, and Ambiguities*

Although there are many differences between the system for managing water within the US and within Mexico, the institutional environment in Mexico can also be characterized as polycentric and evolving. It is polycentric, as within Mexico the authority for making decisions regarding the management of transboundary water resources is distributed between the OOMAPAS, CONAGUA, CEAS, and CILA (see Figure 7-2). The institutional environment in Mexico is best characterized as evolving, both because authorities and responsibilities for water management are shifting due to decentralization and because the institutional environment is adapting to accommodate emerging problems (such as increasing pressures on groundwater along the border) and unprecedented solutions (such as leases, artificial recharge, and water transfers). The result of the polycentric and evolving institutional structure is ambiguity and gaps in responsibility and jurisdiction, which hinders planning and decision making.

Unlike within the SCAMA where there are many large-scale water users, within the Mexican portion of the study region, the primary driver of water management activities is urban water use by the Municipio de Nogales. As per Article 115 of the Mexican Constitution (Farias, 1993) the municipality, through OOMAPAS, is responsible for planning and provision of water supply and sanitation services within its boundaries. However, the municipality does not have complete autonomy in this process; rather, CONAGUA, CEAS, and CILA each maintain some authority over the water management process. The result is jurisdiction over key planning decisions is ambiguous.

Although the municipality is charged with planning for the provision of water and sanitation services (WSS), allocation authority over supply sources, i.e., the aquifer and the river, falls to CONAGUA. CONAGUA conducts studies to determine water availability and it also administers permits for water abstractions and diversions aquifers and rivers. Not only is CONAGUA responsible for managing the water resources used as bulk supply by the municipality, it also regulates the release of wastewaters (treated or untreated), which impacts possibilities for aquifer recharge, as is discussed below. Thus, two key components of WSS planning are outside the jurisdiction of the municipality. Complicating the issue are recent decentralization efforts.

Since 2004, CONAGUA has undergone a process of devolving responsibilities to deconcentrated regional offices, the aforementioned Organismos de Cuenca. This has resulted in the transference of responsibility for determining water availability and issuing of permits from the central offices to regional offices. Interviews with key personnel indicate decentralization is very much still in process, as transfer of data, resources, and responsibilities remains incomplete. Thus even within CONAGUA, there is ambiguity regarding authority and jurisdiction. This detail is important; ambiguity even within a single agency is problematic as culturally, Mexican officials can be very conscientious about following set bureaucratic protocols and are cautious not to overstep boundaries.

The bi-national aspect of the USCRB also creates ambiguity with respect to jurisdictional authority, as here the responsibilities of CONAGUA, CILA, and OOMAPAS overlap. Although the municipality is responsible for the provision of water and sanitation services, CONAGUA is responsible for protecting and managing the nation's waters, and CILA is responsible for conducting and monitoring compliance with international agreements related to water, including managing infrastructure related to and promoting conservation of water resources falling under those agreements.<sup>194</sup> These three agencies must come together in decision making regarding transboundary water management activities. Until the early 2000's, CILA took a more proactive role in resolving border-related water issues; however, during the past years (2001 to the present), CILA has shifted its focus to communication and coordination, leaving other governmental entities to address water problems falling within their jurisdiction (CILA, Personal Communication, June 16, 2006). Thus CONAGUA, CEAS, and OOMAPAS must, as a group, reach a consensus in order for CILA to undertake negotiations or broker a formal international agreement.

Beyond creating ambiguities in responsibility and authority, the evolving nature of water management institutions in Mexico has also resulted in capacity gaps within governmental agencies. For example, OOMAPAS is charged with but does not have the capacity to conduct comprehensive planning. Historically, OOMAPAS has not conducted long term planning and what planning did occur was facilitated by the CEAS (OOMAPAS, Personal Communication, June 25, 2006). However, with the transfer of management from the state (COAPAES) to the municipality (OOMAPAS), responsibility for planning has been delegated to the municipality. Yet OOMAPAS is limited in its capacity to conduct planning activities, as, due to incomplete decentralization and existing administrative processes, it does not have access to necessary data and information to do so.<sup>195</sup> Moreover, staff turnover, particularly in the upper management of

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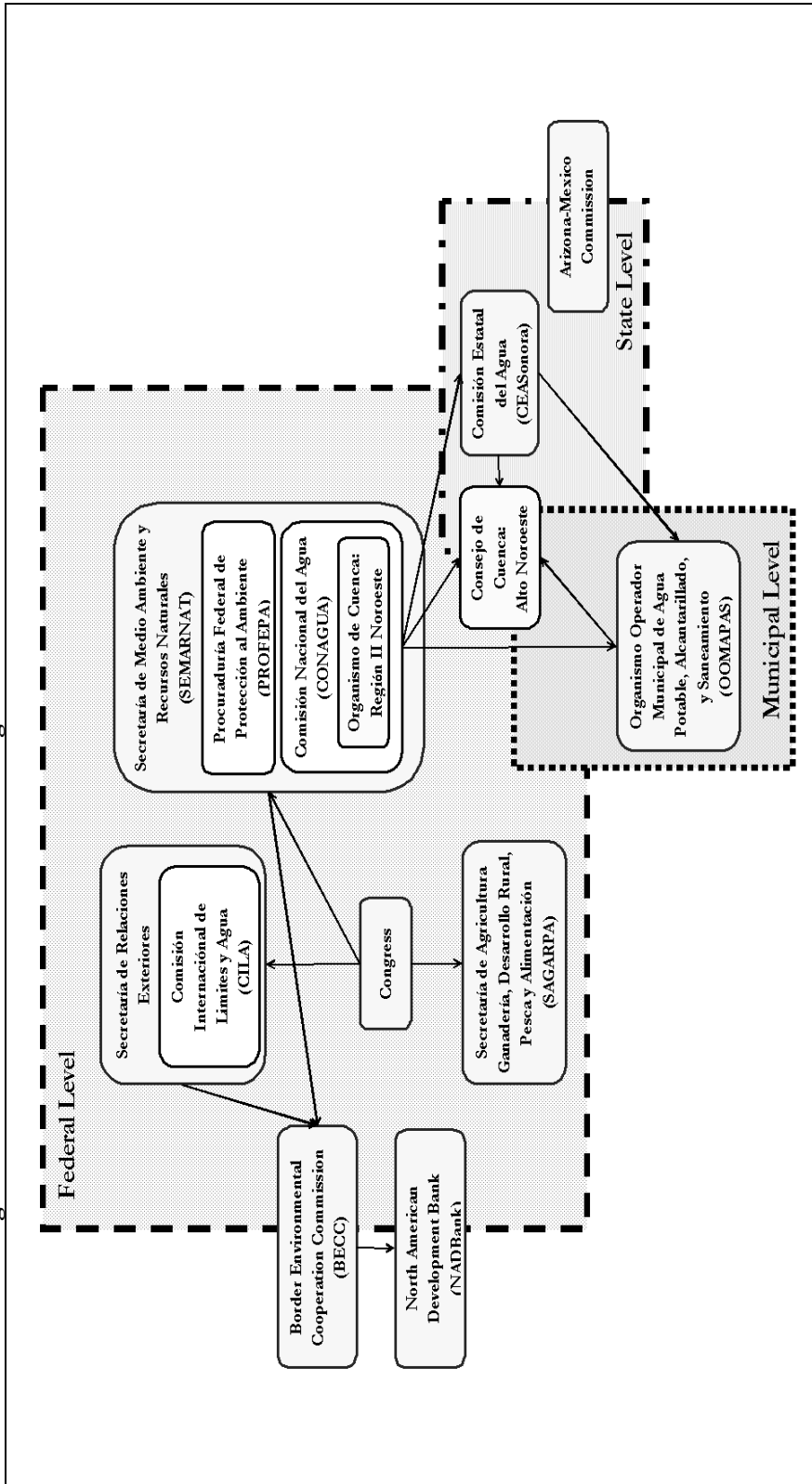
<sup>194</sup> See <http://www.sre.gob.mx/cila/>

<sup>195</sup> Data issues are three fold: i) Standards for WSS are set by CONAGUA and CEAS. These standards include not only engineering and water quality specifications, but also specifications regarding parameters for per capita water consumption and which statistics on population and population growth must be used for planning purposes (Martin Mexica, CEAS, Personal Communication, October 8, 2007). Thus, even if the OOMAPAS has knowledge or data indicating that these parameters do not well represent the municipality, it must use them for planning purposes. ii) Water availability studies and information on diversions and abstractions is under the purview of CONAGUA, and OOMAPAS does not have easy access to this information (Martin Navarro, OOMAPAS, Personal Communication, September 21, 2007) Thus OOMAPAS lacks essential information on supply availability iii) Even CONAGUA lacks complete information on existing water uses, as registration of water users (for assignments and concessions), which has been in process since 1992, is incomplete (Eduardo Robles, CONAGUA, Personal Communication, October 7, 2007, Martinez-Lagunes & Rodriguez-Tirado, 1998; Shah, 2002)

OOMAPAS is quite high. The director of OOMAPAS is a political appointee, and as a consequence, there were three different directors between 2005 and 2009. When a new mayor, or even when a new OOMAPAS director, takes office not only do water plans change, but institutional knowledge is lost. This capacity gap is problematic, in that it hinders formal decision making, as it leads to uncertainty regarding the usefulness of joint water management strategies.

In summary, within the Mexico, internal ambiguity is a product of both the incongruence between the strong regulatory and allocation decision-making role of the federal government with a mandate for local water service provision and the evolutionary nature of water institutions undergoing reform. These make the division of responsibility and authority between various governmental entities remains unclear. Where devolution of authority and responsibility has not been accompanied by devolution of power and resources, the changing institutional structure can result in insufficient capacity of local entities.

**Figure 7-2: Entities Related to Water Management on the Mexican side of the USCRB**



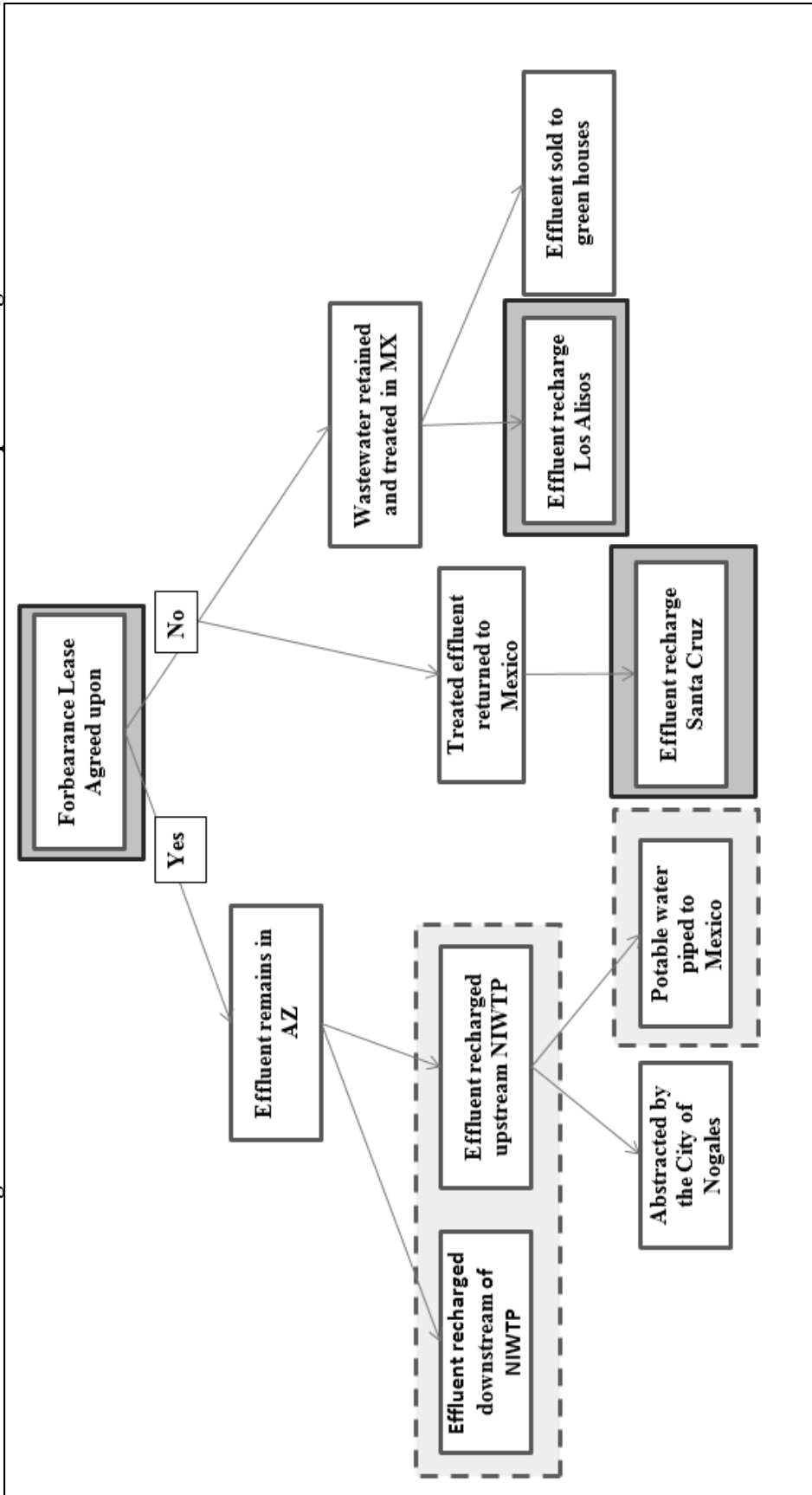
Entity	Synthesis of Mandate and Activities
CILA	Ensure compliance with the 1944 treaty, negotiate treaty amendments, maintain hydrologic monitoring stations, manage joint infrastructure, and communicate information across the border.
PROFEPA	Ensure pollution control and prevention by enforcing environmental (and water) quality standards.
CONAGUA	Administer and safeguard the nation's waters by establishing national water policies, develop standards and regulatory requirements, encourage water use efficiency, and support municipalities in the provision of water and wastewater services.
Organismo de Cuenca Región II Noroeste Consejo de Cuenca	Develop regional water plans, determine water availability, administer water concessions and discharge permits, and coordinate public and private sector activities. Assist in communication and coordination between government entities, water users, and other interests, especially with respect to defining and prioritizing specific actions in the basin.
SAGARPA CEAS	Coordinate water use policies and activities related to agriculture and rural development. Coordinate water-related programs and resources transferred to the state from the federal government, establish planning standards and regulations regarding the use and supply of water, conduct studies, assess, assist and provide technical and financial support to municipal water, sewerage, sanitation providers and provide those services in conjunction with municipalities when requested.
OOMAPAS	Provide water, sewerage and wastewater treatment services within the municipality, conduct long-range planning activities, construct and operate infrastructure, and regulate connections to services.

### **7.3 Evaluation of the possible management strategies**

Up to this point, I have demonstrated how the polycentric and evolving nature of the institutional structure for water management within each country impacts the capacity of each country with respect to general decision making. However, the gaps, overlaps and ambiguities inherent in the institutional environment have a greater impact, in that they also constrain the possible water management activities each country is capable of undertaking. To illustrate this point, I turn to an assessment of each of the possible transboundary water management strategies discussed in Chapter 2.

A flow diagram depicting the processes required for implementation of the first three management strategies is presented in Figure 7-3. Gaps in the institutional structure, which create barriers to implementing various steps in the process, are highlighted in the diagram and discussed in detail below. Highlighted with a solid line are steps in the process hindered by gaps in jurisdictional authority or regulatory mechanisms. Highlighted with a dotted line are steps in the recharge process for which formal agreements or permissions are required, and, although provisions for completing requirements do exist, these arrangements have not yet been completed.

Figure 7-3: Institutional Barriers to Possible Uses of the Effluent for Aquifer Recharge



### 7.3.1 Forbearance Lease

A forbearance lease would involve an agreement that Mexico would continue to send a specified quantity of wastewater to Arizona for treatment at the NIWTP in exchange for compensation. This compensation might include any combination of payment of the cost to treat that wastewater, other financial compensation, or supply of potable water across the border from Arizona to Sonora (Holub, 2001; Sprouse, 2003).

#### 7.3.1.1 USA

As mentioned previously within the US side of the border, there is no entity responsible for conducting comprehensive water management planning and for enacting the activities needed to realize such a plan. This lack of authority encompasses the decision to enter into a forbearance agreement with Mexico, as it is unclear what entity would take the initiative and assume responsibility for entering into such an agreement. The IBWC would be responsible for brokering and ensuring compliance with a forbearance lease; however, another entity would first have to request a lease, as the IBWC does not have the responsibility for or the authority to make decisions regarding local/state water management activities. Additionally, an entity would need to assume responsibility for implementing the terms of the lease (raising funds for payment, allocating water, etc). Although many individual entities could benefit from continued flow of effluent into Arizona, there is no centralized entity to allocate or distribute those benefits.<sup>196</sup>

In 2002, Arizona Senate Bill 1410 was proposed, which would allow for the formation of a Water Management and Importation Authority (WMIA) in the SCAMA. This bill would have created a legal entity in the SCAMA with the authority to construct and operate water augmentation projects (including underground storage and recovery), to acquire and exchange water, water rights, and water credits; to enter into agreements with governmental agencies; and to raise funds to pay for its activities (Arizona State Senate, 2002). Thus the bill would have created the institutional structure required to enact a forbearance lease with Mexico. However, the bill was not passed, primarily due to concerns that it might have unintended impacts on other AMAs and it might negatively impact DWR activities and funding sources (Arizona Municipal Water Users Association, 2002).

Significant transaction costs must be overcome for the IBWC to undertake negotiations to sign a forbearance lease and for the Arizona State Legislature to approve formation of a WMIA. Both processes require building agreement, if not consensus, among numerous diverse interests. In the case of the involvement of the IWBC, transaction costs arise both in generating awareness of the need for as well as in garnering approval for a forbearance lease. The IBWC's jurisdiction encompasses the entire border region, and the Santa Cruz River Basin comprises a small, less salient portion of the border. The attention of governmental officials is often elsewhere, as they must address a myriad of issues and responsibilities at the same time. In order to enact a forbearance lease, the need to do so must be raised to a level of visibility such that resources (time, energy) can be directed to the task. In addition, the approval of the many other entities acting along the border is required. The IBWC's budget is subject to congressional approval, and thus any action the IBWC takes is subject to at minimum indirect oversight by the many (8 senators and 96 house representatives) congressmen from the four border states (Stephen

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<sup>196</sup> Currently the City of Nogales has the greatest ability to benefit from and pay for such an agreement (ADWR, Personal Communication, June 9, 2006) and has been a leader in promotion of signing the lease.



Mumme, 2005). If other entities along the border view the lease as problematic (for example, if there is the fear it might set an undesirable precedent), it may be difficult to gain their backing. Similarly, in the case of the WMIA, there are a number of transaction costs involved in garnering the approval of diverse state interests, including bureaucratic interest groups concerned about secondary impacts of the legislation (Arizona Municipal Water Users Association, 2002). These transaction costs, which result directly from the polycentric structure of the institutional environment, impact the feasibility of decision making and directly influence the capacity of the US to manage its transboundary waters.

### **7.3.1.2 Mexico**

Although the institutional environment is not as fragmented as it is in the SCAMA, in Mexico it is similarly unclear which agency has the responsibility and authority to decide to whether or not to enter into a forbearance agreement with the US. CILA does not have jurisdiction to make decisions regarding the management of waters; however, once a decision is made, CILA would be responsible for brokering an agreement and monitoring compliance with its terms.

OOMAPAS, which as mentioned previously is responsible for providing WSS services within the municipality of Nogales, is the entity that theoretically makes decisions regarding how to provide those services. However, as soon as a pipes cross the international border or wastewaters are released from those pipes, water falls under the jurisdiction of CONAGUA. Moreover, if any financing of such activities is to be provided by the State of Sonora, the activities must be in compliance with the Sonoran State Hydrologic Plan. As OOMAPAS, CEAS, and CONAGUA jointly hold responsibility and authority for aspects of the forbearance lease, and as CILA plays a critical communication and compliance role, these four entities must work together to enact the lease.

### **7.3.2 Recharge of the Aquifer**

Recharge of the aquifer using treated wastewater is another potential strategy which could improve water supply availability in the USCRB. Effluent could be used to recharge the aquifer at variety of key locations in both Arizona and Mexico. Within Arizona the effluent could be piped upstream from the NIWTP and used for recharge in the Kino Springs, Guevavi, or Potrero Creek regions (ADWR, 1997; Camp Dresser & McKee, 1997). Alternatively, the effluent could be used to recharge the aquifer downstream of the NIWTP. The treated wastewater could instead be returned to Mexico and used for recharge within the Santa Cruz basin, in the Paredes, Mezquital, or Mascareñas areas. Lastly, rather than treat the wastewater at the NIWTP, Mexico could instead capture wastewater flows, pump them for treatment in the Los Alisos Basin, and use them for recharge of the Los Alisos well fields (Camp Dresser & McKee, 1997).<sup>197</sup> Although preliminary evaluations of these potential recharge sites have been conducted, more technical investigations are required to understand the effectiveness and the benefits of using each site.

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<sup>197</sup> Chapter 2 contains a more detailed explanation of the two primary sources of water for Nogales, SO, i.e., the Santa Cruz and Los Alisos Rivers, as well as an explanation of the design in progress for a wastewater treatment plant in the Los Alisos basin.

### 7.3.2.1 USA

Similar to the situation with a forbearance lease, the lack of a centralized planning and implementation authority means there is no entity responsible for managing the aquifer by implementing artificial recharge of aquifers recharge in the SCAMA. Thus water management activities occur in a bottom-up fashion; incentives and regulations can encourage individual entities to initiate recharge activities, but no governmental entity directs the process. Beyond this gap in planning and implementation responsibility, there also exist gaps within the institutional environment that impede use of the effluent for recharge. Within the SCAMA, approved mechanisms for recharging the aquifer and for issuing and monitoring of recharge credits do not exist. Furthermore, institutional provisions do not currently enable the most likely beneficial uses of recharging the aquifer.

To date, there are no certified or operational storage and recovery facilities in the SCAMA. Chapter 3 of Title 45 of the Arizona Revised Statutes contains laws governing underground storage and replenishment in the State of Arizona (Arizona State Legislature, n.d.). These laws include provisions for storage of water in an aquifer (via recharge) and extraction of water at a later time. Recharge credits, which grant permission to recover stored water, are issued based on the amount and type of water stored in the aquifer and assumptions regarding loss due to seepage or underflow out of the aquifer. Water does not have to be recovered at the same location it was stored. Storage facilities must be certified and permits are -required for all stages in the storage and recovery process including: operation of the storage facility,<sup>198</sup> storage of water in that facility, and recovery of stored water or long-term storage credits (ADWR, n.d.-b; Colby & Jacobs, 2007). No such facilities have been permitted within the SCAMA and the suitability of such facilities, including the use of the Santa Cruz as a managed (in-channel) facility, has not been evaluated (ADWR, 1997). Without a certified recharge facility, there is no mechanism for determining the quantity of water stored and recoverable in the aquifer, and therefore, recharge credits cannot be issued.

Recharge credits would be key to the usefulness of the Mexican effluent as recharge credits would serve as proof of both physical water availability and the legal right to use such water. Demonstration of both physical availability and the legal right to water is important in the SCAMA because, as per Arizona Law A.R.S. S 45-576, part of the Arizona Groundwater Management Code, proof of a 100-year assured water supply (AWS) is required in order to subdivide and sell land within an Active Management Area. Certification or designation of an AWS requires demonstrating physical, legal, and continuous availability of water for 100 years; that the water is of sufficient quality; that the water use is consistent with the AMA goals and the AMA management plan; and that the entity applying for the AWS has the financial capability to construct any infrastructure necessary (ADWR, n.d.-a). The Arizona Administrative Code, Title 12 Natural Resources Chapter 15 (Arizona Secretary of State, n.d.) includes several provisions for the use of effluent, storage credits, and water exchange agreements for demonstrating an assured water supply. Use of the Mexican effluent could fall under any and all of these categories. However, under the AWS rules, three barriers to the use of the effluent exist.

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<sup>198</sup> Two types of underground storage facilities exist: constructed facilities, which recharge the aquifer using constructed devices such as injection wells or percolation basins, and managed facilities, which make use of naturally transmissive areas to convey water from the surface into the aquifer (ADWR, n.d.-b).

First, the AWS rules require that water use be consistent with the management goals of the AMA. The management goals of the SCAMA include maintaining safe-yield and preventing long-term decline of local water table levels (ADWR, 1999). The SCAMA is in the process of refining its AWS requirements; as a result, what constitutes safe-yield and local water table decline has not yet been fully defined. This lack of definition presents a barrier to aquifer recharge using the effluent, as it remains unclear what the requirements will be enacting recharge and recovery activities. None-the-less it is clear if the effluent is used to recharge the aquifer, recovery of stored water must occur in accordance with the geographic distribution of recharge benefits, so that water table levels are not impacted. Due to the hydrogeology of the region this means the City of Nogales, one of the entities most likely to be interested in and capable of paying the forbearance lease, would have to transport the treated effluent south to its well fields in order to be able to use recharge credits. It would not be able to use credits accrued from recharge downstream to augment its pumping upstream.<sup>199</sup>

Secondly, the one hundred year timeframe of the AWS rules places constraints on the usefulness of recharge using Mexican effluent. In order for an entity leasing the effluent to demonstrate an AWS using recharge, it will have to either negotiate a 100 year lease or develop a mechanism for accruing storage credits by storing extra effluent in the aquifer during earlier periods. The long-term accrual of storage credits will require the development and approval of accounting mechanisms specific to the hydrogeology of the region.

Lastly, one of the most likely mechanisms for recharging the aquifer using the effluent would be to conduct managed recharge using the Santa Cruz River bed downstream from the NIWTP for infiltration (Camp Dresser & McKee, 1997). As a result water would be stored where the aquifer widens and deepens, north of Tubac and farther north. Recharged water could be recovered either by developments in the northern end of the SCAMA or across the SCAMA boundary, in the Tucson Active Management Area. However, there currently are no provisions for accruing, transferring, or selling recharge credits outside the boundaries of an Active Management Area. Thus institutional arrangements would need to be developed which allow the recharge of water in one Active Management Area and withdrawal of that water in another.

### **7.3.2.2 Mexico**

Within Mexico, use of the effluent to recharge the aquifer is constrained both by ambiguity in decision making authority as well as by gaps in the institutional environment at the operational level. The decision to reclaim and use treated wastewaters for artificial recharge falls jointly to OOMAPAS and CONAGUA. OOMAPAS holds the jurisdiction to decide how it wants to dispose of its wastewaters, in terms of sending it (or some portion of it) to the NIWTP or treating it at newly constructed wastewater treatment plant within the Mexican side of the border. However, it cannot decide to use of that water for recharge purposes without approval from CONAGUA. Moreover, CONAGUA, not OOMAPAS, is responsible for protection of aquifers from both over-exploited and contamination. Thus CONAGUA regulates the injection of water and the decision to inject water into the aquifer. As a result, the decision to artificially recharge

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<sup>199</sup> Although this institutional requirement is a barrier in that it increases the costs of aquifer recharge, the physical reality is such that the City of Nogales would concurrently benefit the most from enacting recharge at its own well fields as the City is currently not only constrained by legal water rights; it is also constrained by physical availability.

the aquifer falls to both agencies simultaneously. Yet neither can make this decision, as currently legal provisions for enacting recharge are lacking.

Standards regulating aquifer recharge and mechanisms that accounting for recharge activities have yet to be developed. The 1992 Ley de Aguas Nacional designates CONAGUA as responsible for establishing conditions and issuing permits for the discharge of wastewater and recharge of the aquifer infiltrated wastewaters (Estados Unidos Mexicanos, 1992; Farias, 1993). Although regulations (NOMS) for the quality of wastewater discharged to a national water way or on national property have been established (SEMARNAT, 1996), no regulations exist that specify water quality requirements for injection or infiltration of treated wastewaters into an aquifer.<sup>200</sup> (K. Rodriguez, 2008; SEMARNAP, 2008; Simon, 2007). This regulatory gap prevents use of effluent for artificial recharge, as such activities cannot be undertaken until a permit is issued from CONAGUA, yet there is no process for issuing a permit.

Not only is there no legal framework stipulating water quality parameters required for aquifer recharge, there are also no mechanisms for benefiting from such recharge once it has occurred. Unlike Arizona, which has developed provisions for underground storage and recovery, water management institutions in Mexico include no provisions for recharging the aquifer and recovering that water for use at a later date. As mentioned above, groundwater abstractions are only regulated in “zonas de veda,” i.e., zones the federal government has declared as restricted in order to prevent or remedy over-exploitation, to restore the ecosystem, to protect potable water supplies against contamination, to preserve water quality, or in the case of scarcity or extraordinary drought (Farias, 1993).<sup>201</sup> In order to extract groundwater within a zona de veda, a concession (for a private entity) or assignation (for a governmental entity) must be obtained from CONAGUA. A concession/assignation stipulates the volume of water the concessionaire is entitled to withdraw. The volume of water allotted is determined by CONAGUA. However, there are no provisions in the concession process that increase the quantity of water a concessionaire is allowed to withdraw if that entity conducts artificial recharge of the aquifer. Moreover, even the newly formed Mexican Water Bank (Comision Nacional del Agua, 2009; F. Rodriguez, 2008), which was created to promote more efficient and rational use of water, does not include provisions for underground storage and recovery. Thus within Mexico, institutional arrangements impede artificial recharge of the aquifer and the beneficial use of the resulting augmented supply.

### 7.3.3 Transfer or Sale of Water

One alternative that would allow for recharge of Mexican effluent in Arizona yet would still serve to augment the availability of water in Mexico would be if the effluent is used to recharge

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<sup>200</sup> Projects for both NOM-014-CONAGUA-2003, “Requisitos para la Recarga Artificial de Acuíferos”, and NOM-015-CONAGUA-2005, “Requisitos para la Disposición de Aguas al Suelo y Subsuelo” were created but the regulations have not been published. (K. Rodriguez, 2008; SEMARNAT, 2008; Simon, 2007) (Lawyer, Personal Communication, January 22, 2009) The problems stemming from a lack of regulations stipulating water quality parameters for artificial recharge of aquifers can be clearly seen through Mexico City’s attempts to use treated wastewater for aquifer recharge (“Anulan ley para recarga de los mantos freaticos,” 2005; “En manos de la Corte, la decision de que se reinyecten aguas residuales al acuífero,” 2005)

<sup>201</sup> All wells for groundwater abstractions must be registered with CONAGUA, as water users pay use fees “contributions”; however, groundwater use by the overlying property owner outside of a zona de veda is not restricted.

the City of Nogales, AZ well field in Guevavi and the City of Nogales returns a portion of the recovered potable water to Nogales, SO through its piped water supply network (Sprouse, 2003). This arrangement might be a more cost effective scenario than if wastewater is used to recharge the aquifer on the Mexican side of the border.

In practice, the transfer of potable water from Arizona to Sonora is not unprecedented. A number of times the City of Nogales, Arizona has provided emergency potable water to Nogales, Sonora via a fire hose during the weeks preceding the start of the summer monsoons (Wright, 2005). Moreover, three permanent connections conduct water from the City of Nogales, AZ piped water system to Nogales, Sonora (Ingram, Laney, & Gillilan, 1995; Sprouse, 2003). Yet none of these activities have been formally sanctioned by the federal or state governments of either country (ADWR, Personal Communication, July 18, 2005) and several features of the institutional environment in the USA may inhibit such an agreement.

Within Arizona, several laws limit the transport of water both out of an AMA and out of state. Arizona Revised Statutes title 45 section 543, which regulates the transport of water away from an Active Management Area, stipulates circumstances by which water may be transported from an AMA. Allowable transport scenarios include if the water is withdrawn pursuant a Type 2 non-irrigation grandfathered right; if the water is withdrawn within a service area and transported to another part of that same service area (either by an urban water provider or an irrigation district); pursuant a groundwater withdraw permit,<sup>202</sup> or via an exempt well (Arizona State Legislature, n.d.). However, transport of water across the border to Mexico would not fit into the scenarios outlined. In addition, Arizona Revised Statutes 45-291 to 45-294 stipulate water may not be transported from the state without approval from the ADWR director, unless required by interstate compact, federal law, or international treaty.

Federal institutional arrangements may restrict formation of a formal agreement to transfer water to Mexico. A 'Presidential Permit' is required for all infrastructure that crosses the border (U.S. Department of State, n.d.; IWBC, Personal Communication, June 23, 2005). Such a permit will be subject to approval by the executive office and, as such, must also meet requirements related to the Endangered Species and the National Environmental Policy Acts. If the abstraction of or transfer of water, including the construction and operation of necessary infrastructure is somehow deemed to negatively impact the critical habitat for endangered species in the region, such as the gila top minnow or the southwestern fly catcher, this permitting process may form a barrier to cross-border water transfers.

Lastly, even if both Arizona and federal law allow for the transfer of water to Sonora, the Arizona Groundwater Code does not include provisions for the abstraction of the water for such purposes. The City of Nogales maintains both service provider and surface water rights.<sup>203</sup> In

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<sup>202</sup> Groundwater withdraw permits are granted for a specified period of time for eight possible water uses: to fill or refill a body of water, for dewatering, for mineral extraction and metallurgical processing, for general industrial use, for poor quality groundwater, for temporary dewatering purposes, for drainage purposes, and for hydrologic testing purposes. See [http://www.azwater.gov/dwr/Content/Find\\_by\\_Category/Permits\\_Forms\\_Applications/default.htm](http://www.azwater.gov/dwr/Content/Find_by_Category/Permits_Forms_Applications/default.htm) for more information.

<sup>203</sup> The City holds service area rights for 7,300 AFA for water abstracted from its Potrero well fields and surface water rights for 5110 AFA for water abstracted from its Guevavi, Kino Springs and SR 82 well fields (City of Nogales, 2000).

order to pump additional water, for the purpose of transferring such water to Mexico would require the development and assignment of a different type of water right, for which, as of the moment there is no process. If a water transfer is conducted as part of recharge activities, it is possible that a system could be developed that would allow the water to be abstracted under provisions for using recharge credits even if the abstracted water is used outside of the AMA.

#### 7.3.4 Restrictions on Groundwater Abstractions

Restrictions on groundwater abstractions are frequently imposed to prevent the negative externalities associated with over-exploitation of an aquifer. Due to the hydrogeology of the region, the aquifer in the USCRB does not fit the typical 'bathtub' or 'reservoir' model of an aquifer; rather because of the microbasin formations (Halpenny & Halpenny, 1991), the transboundary impacts of groundwater abstraction are thought to be uni-directional: Mexico to the US. Although there remains much uncertainty, it is thought that groundwater pumping in Mexico may negatively impact Arizona by capture of baseflow in the river, which is key to aquifer recharge in Arizona (ADWR, 1995) and through possible reduction of underflow thought to occur through fractures and faults in the lower stratigraphic unit of the aquifer. Thus, it is likely that restrictions on pumping in Mexico would benefit Arizona, but the reverse may not hold. None-the-less, an analysis of how the institutional environment impacts possibilities for restricting groundwater abstractions in the region is useful in illustrating the challenges which might arise in joint management of transboundary aquifers.

Within the SCAMA, abstraction of groundwater is already constrained by provisions of the Arizona Groundwater Code. Yet, due to the existing institutional arrangements, further restrictions may be difficult to achieve. The right to use groundwater has already been allocated to many water users in the region, and although according to Sax (1989), the federal government has the authority to restrict those rights if it is in the interest of the public trust, attempts to constrain abstractions by individual users who have historically made use of these water rights may prove challenging. Individual water users may contest such an effort and the policy makers may not have the political capital needed to overcome such dissent (Burchi, 1999). The difficulty in instituting institutional reforms once property rights have been devolved is illustrated in Challen's (2000) analysis of the Murray-Darling Basin.

The challenge of restricting pumping occurs not only when property rights have already been allocated, as in the SCAMA, but also when informal institutional arrangements have historically allowed for unregulated abstraction of groundwater. In Mexico, the right to freely abstract and make use of groundwater was granted in the 1917 Constitution. The federal government has the right to limit groundwater use when it impacts the public trust (Farias, 1993); however it does so through regulation of concessions. Since 1992, CONAGUA has been developing a registry of water users, which forms the basis for allotting concessions. However, registration of water users is incomplete (Martinez-Lagunes & Rodriguez-Tirado, 1998); moreover, domestic water users obtaining their water from individual private wells are not required to register. As a result, groundwater abstractions can go unregulated and additional restrictions may be difficult to impose.

In both cases, the US and Mexico, the challenge to instituting further restrictions on groundwater abstractions is the outcome of the very decentralized nature of groundwater use, both in terms of

physical activities and in terms of governance. Attempts to restrict pumping would require reclaiming of jurisdiction or authority that has been granted to individual users, a task which could be quite formidable. Given that in a great many of countries, the right to use groundwater has been granted to the overlying property owner (either through tradition or official policy) (Hodgson, 2006) it is likely a country's capacity to enact a transboundary water management strategy that restricts groundwater use will be constrained by its ability to reclaim this authority.

#### **7.4 Impact of the Institutional Environment in the USCRB**

In summary, throughout this chapter I have made the case that the tendency of analyses of transboundary waters to adopt a state-as-container approach is problematic in that it ignores the capacity of a country to conduct transboundary water management activities, and particularly activities related to groundwater. I also contended that the institutions for water management within a country are an important determinant of the capacity of that country to conduct transboundary water management, as these internal institutions both define responsibility and authority for planning and decision making and constrain the choice set.

Findings from the institutional analysis of the USCRB indicate the institutional environment for water management on both the US and the Mexican sides of the border is best classified as polycentric and evolving. Within the SCAMA, responsibility and jurisdiction over water management and planning is dispersed among a wide array of agencies and individual property rights holders. The relationship between these entities, and the powers and authorities each holds, changes over time. Within the Mexican portion of the basin, water management institutions are undergoing a process of decentralization and redefining of governance paradigms. As a result, there are gaps, overlaps, and ambiguity in the institutional environment of both sides of the border.

This polycentric and evolving institutional structure impacts the capacity of each country to enact transboundary water management activities in that inhibits leadership, increases transaction costs, and constrains possible actions. The lack of an entity responsible for comprehensive planning and implementation of water management activities in the SCAMA and the overlapping assignment of such responsibilities within Mexico translate to an ambiguous process for planning and decision-making. Moreover, coordination among the many agencies, within and across scales, can be time-consuming and costly. Lastly, mechanisms that would provide for the implementation of certain water management activities are lacking, which hinders possibilities for recharge, the transfer of water across the border, and placing additional restrictions on pumping. One possible explanation for these gaps, overlaps, and ambiguities is that water management institutions within a country are devised in a piecemeal fashion. Institutions emerge and change to address current or near foreseeable needs and problems. In the USCRB, both sides of the border are currently facing relatively new management challenges and are seeking novel solutions to these problems. The existing institutional environment was not designed to address these issues, and thus in order to address them, the institutional structure will need to adapt and change.

In Chapter 8, I extend this institutional analysis to the decision-making process. There I explain how the uncertainty discussed in Chapters 2 through 6 combines with the polycentric and

evolving structure of the institutional environment to obviate the thesis of countries as 'rational-utility maximizing actors.' Rather, I demonstrate that water management decisions and actions are most determined by the ethos of water a country holds and immediate incentives it country faces.

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## **Chapter 8 : Transboundary Ground- & Waste- Water Management in Practice**

### **8.1 On the Ground**

In Chapters 3 through 6, I demonstrated how in the USCRB, neither the US nor Mexico have complete understandings of the costs and benefits that will be achieved by enacting any specific transboundary groundwater or wastewater management policy, and knowledge of hydrologic processes in the region is fraught with uncertainty. Then, in Chapter 7, I established the capacity of a country to undertake those strategies is also constrained by its intra-national institutional regime for water management. The combination of uncertainty with an institutional structure characterized by gaps, overlaps, and ambiguity in responsibility and authority serves to inhibit adoption of the four possible transboundary water management strategies discussed in Chapters 2 and 7 (forbearance lease, recharge of the aquifer, transfer of water across the border, restrictions on pumping). Although actions addressing the cross-border implications of groundwater use or capitalizing on possible bi-national synergies from aquifer recharge using treated wastewater are not forthcoming, both countries are engaging in activities related to water management within their respective borders. Below, I delineate the ground and waste water management activities currently being undertaken in the USCRB and discuss the motivation behind them.

Interviews with the governmental officials charged with managing water resources in the region suggest they selected which water management strategies to adopt based on their paradigm for water management and funding opportunities available. The explanations of interviewees are consistent with my claims from previous chapters, as given the high degree of uncertainty and the fragmented institutional environment, decision making cannot be based on optimizing outcomes. This contrasts with rational IR perspectives that hold economic rationality or power positioning as the primary determinants of a country's approach to transboundary water management.

In my research I did not explore in-depth the motivations of individual decision makers; thus the true impetus for each decision must be relegated to future research. During my research, I saw little indication that interest groups and political maneuvering played salient roles in decision making processes in the USCRB. None-the-less, the possible influence of lobbying, politics, and the self-interest of officials within each country should not be obviated. My claim in this chapter represents a plausible hypothesis: when faced with a high degree of uncertainty and fragmented institutional authority, the ethos of water held by a country and the immediate incentives it faces become the de facto basis for decision making. This premise is not incongruent with theories of planning that emphasize how normative ethics influence planning (Howe, 1990) or that explain how short-term financial incentives can lead to myopia in natural resources management.

#### **8.1.1 Activities within the SCAMA**

The ground and wastewater management activities occurring in the SCAMA are discrete efforts, being undertaken by both governmental agencies and individual water rights holders. These actions, which focus on the management of waters internal to the SCAMA, are primarily directed at increasing knowledge (decreasing uncertainty). They reflect an ethos of management based

on scientific analysis and risk aversion, as well as the enticement of economic incentives from outside the AMA.

The SCAMA division of ADWR is taking steps to clarify its management goals of preventing long-term decline of local water table levels and maintaining safe yield. In conjunction with the Groundwater User Advisory Council (GUAC), ADWR is in the process of defining mathematically what constitutes acceptable drawdown, both in terms of depth to water and frequency of occurrence. In addition, AWS rules have been updated to require applicants run one-hundred stochastic model simulations of 100 years for demonstrations of water availability (ADWR, 2007). ADWR has also stipulated effluent from the NIWTP must be excluded from water models or estimates that are part of studies of water availability (Corkhill, 2006; Corkhill & Dubas, 2007; Corkhill, Swieczkowski, Morris, & Kurtz, 2008). These new rules require applicants for AWS support their proposals with substantial data and complex analysis methods; this is indicative of an ethos for water management that privileges quantitative analysis and expert knowledge. Moreover, the new rules point to risk aversion, as excluding wastewater recharge and conducting stochastic analyses will, in theory, lead to conservative estimates of water availability.

An ethos of basing decisions on scientific understandings is also reflected in the many efforts being undertaken to improve knowledge of the hydrology of the SCAMA. ADWR is using recently developed groundwater simulation models (see Chapter 5) to conduct stochastic simulations aimed at improving understanding flow patterns and the expected affects of water use activities. In addition, ADWR is coordinating with researchers from other institutions, to conduct further studies in the region. Researchers from the University of Arizona are investigating stream-aquifer interactions,<sup>204</sup> the value of the effluent released from the NIWTP,<sup>205</sup> and causes of tree-die off in the region.<sup>206</sup> The City of Nogales, the US Bureau of Reclamation, and ADWR are partnering to study the feasibility of conducting aquifer recharge and storage.<sup>207</sup> ADWR, in conjunction with the Arizona Water Resources Research Center and the USGS, have also hosted workshops related to the Transboundary Aquifer Assessment Program (United States Senate, 2006), a congressionally funded effort designed at increasing scientific knowledge of the shared aquifers along the US-Mexico border. Many of these research activities were developed in response to funding opportunities from outside of the SCAMA, including grants from the University of Arizona and federal agencies.

Individual water rights holders are also taking actions to reduce uncertainty regarding their water allotments. More water rights have been granted than physical water exists in the basin. The entire Gila River, to which the Santa Cruz is a tributary, is undergoing an adjudication process. Although adjudications typically involve surface water rights, due to the existence of dual rights (see Chapter 4), these water rights holders possess both surface water and grandfathered irrigation water rights (groundwater rights). In an effort to secure their water rights in a more timely fashion (the Gila River adjudication is expected to take many years), thirteen of the largest holders of water rights in the SCAMA initiated a study comparing historic irrigated

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<sup>204</sup> See Tom Meixner et al <http://www.uwater.arizona.edu/grants/grants07.html>

<sup>205</sup> See Frisvold & Sprouse <http://cals.arizona.edu/AZWATER/research/trifgrant.html>

<sup>206</sup> See McCoy [www.uwater.arizona.edu/documents/Fellowship200607/McCoy.pdf](http://www.uwater.arizona.edu/documents/Fellowship200607/McCoy.pdf)

<sup>207</sup> See Nogales Area Water Storage Project description <http://www.usbr.gov/lc/phoenix/programs/progdescon.html>



acreage and water use patterns; the goal is to use this information as the basis for an agreement amongst themselves regarding the volume of water allotted to each. In addition to clarifying water rights, as part of the settlement, the large water rights holders continue advocating for the formation of a Water Importation and Management Authority (see Chapter 7), which would aid in comprehensive water management and planning in the region (Lawyer, Personal Communication, October 18, 2007; Lawyer, Personal Communication, October 17, 2007; Lawyer, Personal Communication, October 5, 2007; ADWR, Personal Communication, October 3, 2007).

Risk aversion, both with respect to negative environmental outcomes and to financial losses is also manifest in the decision to upgrade the NIWTP. The City of Nogales and the IBWC, with assistance from the EPA, the Border Environmental Cooperation Commission, and the North American Development Bank, finalized designs and have begun construction on improve the quality of effluent released from the plant.<sup>208</sup> Although nominally the new treatment plant retains the same treatment capacity as prior to the upgrade, in actuality the design includes extra capacity to allow for surges in peak flow or leeway if construction of PTAR Los Alisos Mexico is delayed (NADBank, Personal Communication, May 31, 2006). While the NIWTP remained out of compliance with ADEQ Aquifer Protection Permit Program standards, the City of Nogales risked fines of up to \$25,000 per day (Sprouse & Villalba Atondo, 2004). The City of Nogales also risked losing \$59.5 million in grant funding from the EPA Border Environmental Infrastructure Fund (BEIF), due to its long delay while negotiating treatment alternatives with Mexico (Gelt, 2006). Thus the decision to go ahead with the upgrade, without a firm commitment from Mexico, was in a large part a response to immediate financial incentives.

### 8.1.2 Activities within Mexico

Within the Mexican side of the border, a number of water management activities are also in processes, primarily directed at improving water supply services and wastewater treatment. These efforts reflect not only Mexico's intention to improve access to basic services, but also a strong ethos of water as patrimony and management at the basin scale. Beyond management paradigms, the activities underway also are indicative of how immediate incentives, such as funding opportunities, influence planning processes.

As discussed in Chapters 3 and 7, OOMAPAS has been making a substantial effort to address wastewater treatment needs in Nogales, Sonora. OOMAPAS has begun a pre-treatment program, is implementing improvements to the wastewater collection system, and is in the process of designing a new wastewater treatment plant (PTAR Los Alisos). All wastewaters generated south of two planned lift stations (Rastro-Tecnológico and Virreyes) will be collected and transmitted to PTAR Los Alisos, which will have the capacity to meet wastewater treatment needs beyond the 9.9 MGD allocated to the NIWTP through the year 2026 (Caro Camacho, 2006).<sup>209</sup> However, given the large uncertainty in population estimates and location

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<sup>208</sup> The project is expected to be completed on June 23, 2009 <http://www.nogaleswastewater.com/>

<sup>209</sup> The capacity of the collectors and PTAR Los Alisos will be approximately 10 MGD (Caro Camacho, 2006), the same capacity also allocated to Mexico at the NIWTP.

of growth,<sup>210</sup> it is unclear how much wastewater will be treated at PTAR Los Alisos and whether or not this will reduce flows to the NIWTP below 9.9 MGD.

The decision to construct PTAR Los Alisos stems from an ethos of water as patrimony and basin-water management. When asked about building a new wastewater treatment plant in Mexico rather than to treat additional wastewater in Arizona, officials responded that water pertains to the Mexican people and they (the officials) cannot relinquish it to another country. Interviewees also stressed the principle that wastewater should be treated and released in the Los Alisos basin because water should remain in the basin of origin.<sup>211</sup> These responses reflect both strong nationalism within Mexico and the current water management paradigm in Mexico, which emphasizes integrated basin management (Martinez-Lagunes & Rodriguez-Tirado, 1998; Tortajada & Contreras-Moreno, 2005).<sup>212</sup>

In choosing to construct PTAR Los Alisos, OOMAPAS also took advantage of external funding opportunities<sup>213</sup> that would not have been available should OOMAPAS instead have selected to treat all of its wastewater at the NIWTP. Due to expected growth in the southern part of the city, OOMAPAS needs either to construct wastewater treatment facilities in the south or a pump station to transport wastewater over the topological divide so that it could be treated at the NIWTP. In choosing to convey flows exceeding treaty limits to PTAR Los Alisos, rather than building additional capacity in Arizona, OOMAPAS was able to link wastewaters generated in the southern part of the city with the international border and thus access NADBank and BEIF financing for that project. Moreover, in constructing the new wastewater treatment facilities within Mexico, OOMAPAS could also take advantage of funds from CONAGUA designated to support compliance with NOM-001-ECOL-1996<sup>214</sup> and it could also recapture some of its concession fees.<sup>215</sup> Thus there were strong financial incentives for OOMAPAS to construct Los Alisos.

In addition to plans to address wastewater collection and treatment, Mexico is also undertaking efforts to improve water supply services throughout the city and to regulate water use. OOMAPAS continues construction of its “Acuaferico” project, which aims to improve and extend water system services via the drilling of new wells, construction of new pumping stations, water tanks and distribution lines. Smaller projects have also focused on connecting several smaller neighborhoods to the city-wide piped water network. OOMAPAS is also working to

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<sup>210</sup> It is expected that the majority of new housing will be developed in the southern end of the city; thus wastewater from those developments would be treated at PTAR Los Alisos.

<sup>211</sup> As mentioned in Chapter 2, approximately half the water supplied to Nogales, Sonora is abstracted from wells in the Los Alisos basin.

<sup>212</sup> This paradigm that water is best managed at a basin level is also manifest in the development of Basin Organizations and watershed councils, as discussed in Chapter 6

<sup>213</sup> Design of the treatment plant is being undertaken by CONAGUA and design of the pump stations and conveyance lines by the Border Environmental Cooperation Commission. Construction will be funded by a combination of federal, state (CEAS), and municipal sources, as well as BEIF grant funding and a loan by the North American Development Bank to OOMAPAS.

<sup>214</sup> This CONAGUA regulation stipulates the dates by which all cities with populations greater than 50,000 must have a wastewater treatment facility (Comisión Nacional del Agua, 2008).

<sup>215</sup> Through the PROAGUA program, CONAGUA allows water and sanitation providers to forgo paying fees for water concessions if the utility reinvests those funds in infrastructure and infrastructure improvements (Hearne, 2004; CONAGUA, Personal Communication, October 7, 2007).

install water meters, repair leaks, rehabilitate wells, and educate the public regarding water conservation. With respect to supply regulation, CONAGUA has also been active in registering and regulating concessions of water, especially those providing water to water delivery tanker trucks. These activities represent efforts on part of both agencies to improve the services they provide to the population, and to better manage public resources.

### 8.1.3 Collaboration in the USCRB

From the activities described above, it can be seen that in the USCRB neither country is taking direct action to address the transboundary aspects of the Santa Cruz aquifer or to explore possible synergies from collaborative activities such as aquifer recharge or water transfers. Rather, both countries are primarily acting (unilaterally) to address water management concerns within their own borders. Activities being undertaken in the US center on reducing uncertainty and improving scientific understandings and regulatory processes. Activities in Mexico are directed at improving water and sanitation services and taking advantage of any funding sources available.

The greatest movement towards collaboration over groundwater in the USCRB has been through activities associated with the Transboundary Aquifer Assessment Program. The Santa Cruz aquifer is one of four priority aquifers listed in the TAAP (United States Senate, 2006). Since November 2007, the University of Arizona Water Resources Research Center, in conjunction with the US Geologic Survey, have conducted a number of bi-national informational and planning workshops in the USCRB. The goal of these workshops has been to synthesize data from both sides of the border and to develop a list of research priorities.

The TAAP is not, and does not aim be, a formal agreement regarding transboundary groundwater management; rather it is an effort to engender bi-national cooperation for data and information sharing, including joint studies of the aquifer. As knowledge of hydrologic processes is essential for effective groundwater management, this effort will support each country in the management of its portion of the shared groundwater resources. The extent to which TAAP goals will be achieved, and whether or not the TAAP will be able to bridge the gaps, overlaps, and ambiguity in the intra-institutional environments of both countries remains an empirical question, as the TAAP is still in its nascent stages and has yet to receive the full funding authorized.<sup>216</sup>

## 8.2 Conclusions

Throughout this dissertation, I have made the case that the physical and institutional characteristics of transboundary ground and waste waters are different than those of surface waters. As a result, templates from research on cooperation over transboundary rivers are likely not applicable to those resources. More specifically, due to the high degree of uncertainty associated with ground- and wastewaters, and due to the complexity of the intra-national institutional regime governing those resources, I challenged the application of rationalist approaches to cooperation.

In Chapters 3-6, I argued that because transboundary ground and waste waters are characterized by both analytic and strategic uncertainty, in the USCRB neither the US nor Mexico is well

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<sup>216</sup> Although Senate Bill 214 authorized \$50 million for the TAAP during the years 2007, to date, only \$500,000 has been allocated, and there are no allocations for it in the 2010 federal budget.

approximated as a rational utility maximizing actor. The utility functions of both countries are poorly defined due to contested visions, ill-defined management goals, an inability to quantify water needs, and incommensurability between outcomes. Moreover, physical processes are not well understood, due to incomplete conceptual models, insufficient data, and subjectivity in interpretation. As a result, it is unclear what either side of the border stands to gain or lose from enacting transboundary water management activities. This uncertainty leads each country to adopt differing interpretations of the need for or benefits from cooperation.

Campbell (2003) explains how disputes that are characterized by complexity, in which basic values are contested, or that are based on conflicting world views or ontologies are particularly intractable. The USCRB fits this description: the flow of water in the region is complex; each side of the border holds differing world views (as witnessed by differences in prioritization of human vs. environmental water needs, see Chapters 3 and 4); and each country holds divergent perspectives of water availability (see Chapter 4). This last point, that, despite access to relatively similar information regarding the aquifer, hold differing views of water availability, serves to highlight my claim that rationalist IR models do not well match the empirical situation, as those presume countries hold a similar (objective) analytic model of the world (Rathbun, 2007).

Beyond pointing out how the uncertainty characterizing transboundary ground and wastewaters makes moot rationalist assumptions, I also contested the representation of the US and Mexico as monolithic actors. Through the institutional analysis in Chapter 7, I exposed the fragmented nature of ground and wastewater governance within each country. The polycentric institutional regime within both the US and Mexico leads to gaps and overlaps in authority while concurrently the evolving nature of those institutions leads to ambiguity in authority. Young (2002), in his analysis of the role of institutions in international environmental agreements, explains how the effectiveness of an environmental regime is impacted by competence, compatibility, and capacity. Gaps, overlaps, and ambiguity in the authority of national and sub-national institutions in the USCRB reduce the competence and capacity of each country to enact transboundary groundwater management activities. They also cause incompatibility between proposed management strategies and existing arrangements.

Reflecting upon these results, my initial research questions appear incongruous; the questions themselves stemmed from the very rationalist perspective my findings refute. In an environment characterized by contested visions and ill-defined management goals the management objectives of each country are unknowable. Moreover uncertainty and incommensurability make paradoxical the determination of the benefits that can be derived from transboundary ground and wastewater management strategies and the impacts of each country's water use on one another. None-the-less, I am able to directly respond to my last question of what drives decision making. My research findings suggest that, rather than being driven by economic rationalism or international power positioning, the water management activities taking place in the USCRB are motivated by a combination of the ethos of water held by each country and immediate financial incentives.

The value of my research extends beyond the USCRB, as there is reason to believe my findings are representative of how ground and waste water management occur in a number of other

countries around the world. Due to the large quantity of data required to determine flow processes and the subjectivity of interpretation of this information, groundwater availability and the impacts of groundwater use are inherently uncertain (Kalf & Woolley, 2005; Narasimham, 1998). In many countries, little data is available, as water levels and water abstraction rates have not systematically been measured, nor has hydrogeologic testing been undertaken. Wastewaters too, are fraught with uncertainty, as although their supply is more predictable, the demand for those waters is mutually dependent on the availability of other water supplies.

Not only can we expect most transboundary ground and wastewaters to be characterized by high degree of uncertainty, they are also likely governed by polycentric and evolving institutional arrangements. Intra-national institutions are changing, as countries respond to the relatively recent (post-1950's) surge in the use of groundwater and urbanization leading to greater and more concentrated volumes of wastewater. Thus for groundwater, control has gone from predominately in the private (individual) realm to a more fragmented system of governance consisting of regulation on the local, state, and national levels. Concurrently, paradigms for governance are shifting; within the water sector, there has been a global movement towards decentralization of management, private sector participation, and allocation of marketable property rights (Easter & Hearne, 1995; Saleth & Dinar, 2000; Tortajada, 2001).

Recognition of uncertainty and the polycentric and evolving nature of national water management agencies is important not only for understanding how transboundary ground and wastewater management occurs and the obstacles to cooperation, but also because it points to policies that might improve the potential for cooperation and collaboration. Given the high degree of uncertainty and how it can lead to intractability, transboundary ground and wastewater management might be best addressed using an incremental approach. Rather than seeking cooperative solutions that maximize benefits or commit to long-term actions, it might be best to begin with mechanisms designed to reduce uncertainty, such as data collection, monitoring, and scientific investigation. The TAAP program aims to do just this. The data and information collected could then be used in shared vision modeling and scenario workshops (Kallis, et al., 2006; Lund & Palmer, 1997; Palmer, Werick, MacEwan, & Woods, 1999), reducing both analytic and strategic uncertainty. Where uncertainty cannot be minimized, stepwise solutions that allow for adaptation as water management objectives are defined or shift and as knowledge of hydrologic processes, costs, and benefits increase may serve to make cooperation more tractable.

In addition to addressing uncertainty, intra-national institutions governing transboundary ground and wastewaters need to be strengthened. Waterbury (1997) claims cooperation begins at home; this should be extended to include not only the need to efficiently and effectively manage water resources but also the need to develop institutions with the authority, capacity, and responsibility for comprehensive planning and for implementing water management activities. To do so, countries can take steps to clarify jurisdiction and provide mechanisms to increase communication, coordination, and collaboration across fragmented institutions. Institutions also need to be endowed with the ability to adapt and respond to new challenges in a timely manner.

Lastly, if countries plan to decentralize water management, institutional changes should be designed to avoid scalar-mismatch problems and to reduce dynamic transaction costs which

might be incurred should centralized management be required in the future. To avoid scalar-mismatch, governments could create mechanisms that allow for the enactment of binding international agreements at the local level.

History has demonstrated that we are able to devise and cooperatively manage our shared surface water resources; with careful attention to the unique characteristics of ground and wastewaters, effective solutions for those transboundary resources can also be found. International cooperation requires intra-national capacity, which is built by improving knowledge (reducing uncertainty) and bridging of gaps, overcoming overlaps, and clarifying ambiguity in jurisdiction and authority. If we take steps to address these, the next inventories of international water agreements will be rife with examples of countries working together to manage transboundary ground and wastewaters.

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## **Appendix A : Physical and Institutional Characteristics of Water Resources**

### **A.1 Introduction**

Transboundary surface, ground, and waste waters are often grouped together into a single category; yet each has unique characteristics that influence the types of challenges that occur in managing it and constrain the solutions available for resolving those problems. In this appendix, I compare and contrast the physical and institutional attributes of surface, ground, and waste waters and then explain how these differences need to be considered in theories of transboundary water management.

### **A.2 Physical Attributes of Surface, Ground, and Waste Water Resources**

Surface, ground, and waste<sup>217</sup> water resources have distinct physical properties. They differ in their flow processes, geographical configuration, temporal characteristics, visibility, and reliability. They also differ in terms of the infrastructure needed to access or use them and the types of information needed to characterize them. A summary comparison of the physical characteristics of these resources is included in Table A-1.

#### **A.2.1 Surface water**

The focus of the literature on transboundary waters has been on shared river basins, lakes, and reservoirs. These water sources are highly visible and flow patterns (volume and timing) are primarily driven by precipitation, although in the colder climates, run-off maybe delayed until snow and ice melt. Base-flow in a stream is also supported by discharge of percolated waters from the aquifer.

Surface water flows are linear. In rivers, water flows from upstream to downstream. In lakes and reservoirs, flow is driven by hydraulic head, yet is relatively straightforward to determine based on inlets and outlets. Utilization of surface water quickly impacts downstream users, and as a result, the effect of changes in surface water use and management are rapidly identified. Uncertainty arises primarily due to climatic variability, although changes in surrounding land uses may also impact flows. Management concerns for shared surface water resources include the timing and quantity of diversions, flood protection, pollution prevention and control, navigability, and ecosystem preservation.

#### **A.2.2 Groundwater**

The characteristics of groundwater are quite different from those of surface water. Groundwater flows underground and as such, the physical and chemical processes of groundwater flow and transport are unseen (Burke, Moench, & Sauveplane, 1999; Jarvis, Giordano, Puri, Matsumoto, & Wolf, 2005; Mechlem, 2003) Consequently, the boundaries of the aquifer, inflows and outflows of water, and the impact of utilization may be difficult to determine. Furthermore,

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<sup>217</sup> Although technically the term wastewater refers to all water that has been used and discharged, in this thesis, by wastewater I refer to waters that have been used and the return flow captured and conveyed through a pipe. This water can thus be easily transferred and accessed. Through this definition, dispersed discharges of wastewater would instead be viewed as pollution.



because it is closely linked with surface water and land use, groundwater cannot be understood independently of those resources.

Unlike rivers, which are characterized primarily by the timing and rates of flows, aquifers are characterized by both flows and storage. These qualities are determined by the physical properties of the aquifer. Groundwater flow rates are limited by the conductivity of the aquifer material and the hydraulic gradient whereas groundwater storage is determined by the properties of the soil matrix and the aquifer's physical expanse. Soil and rock formations and hydrogeologic properties vary dramatically within any given aquifer, thus aquifers are inherently heterogeneous and groundwater flows and storage will vary throughout the aquifer (Schwartz & Zhang, 2003).

Unlike rivers, which flow from upstream to downstream, groundwater flows both vertically and horizontally. The direction of flow may vary with time and depth. Depending on the configuration of hydraulic heads and soil conductivity, groundwater may also flow in multiple directions simultaneously within a given aquifer or a hydrostratigraphic layer. Recharge and abstraction influence hydraulic heads and may completely reverse the direction of flow. In fact, the aggregated effect of dispersed abstraction can have a significant impact, even at far away distance. Even under pristine natural conditions, groundwater flow directions have been shown to vary seasonally by up to 40 degrees (Cleary et al., 2008).

The temporal characteristics of groundwater also differ from those of surface water. Groundwater flows at rates much slower than surface waters. Groundwater generally moves between zero to ten feet per day (Cleary et al., 2008). The average residence time of water in river channels is two weeks; in lakes and reservoirs it is two to ten years, and for groundwater it ranges between two weeks to 10,000 years (Shiklomanov, 1999). Recharge is also slow, as precipitation and surface runoff take time to infiltrate. Furthermore, in arid climates, evapotranspiration may exceed recharge and thus recharge may only occur during widely spaced storm events (Foster, 1999). As a result of groundwater's slow velocity and the time it takes for recharge to occur, there may be a delay between use and when the impacts of groundwater utilization on water table levels are experienced.

This four-dimensional nature of groundwater (3-dimensional flow plus the time element) makes it difficult to determine precisely the availability of water or the impacts of water use. This uncertainty is exacerbated by geological heterogeneity and meteorological variability. Large amounts of data must be collected in order to reasonably estimate groundwater availability, drawdown, and contaminant flows; yet frequently such data does not exist and when it does, it is incomplete or unreliable (Mechlem, 2003; Moench, 2004). Consequently, there are often "substantial error bands on the prediction of the impact of given scenarios of groundwater abstraction and contaminant loading" (Foster, 1999, pp 20).

Issues related to transboundary groundwater resources are similar to those of surface waters and revolve around the allocation of water, timing of use, pollution, and environmental protection. In addition, transboundary groundwater management must take into consideration the impact of declining water table levels that can cause vegetation to die off, land to subside, flow directions to change, salt water intrusion, reductions in base flow in streams, and higher extraction costs.

Unfortunately, some of these problems are irreversible. Aquifer storage capabilities can be permanently reduced by land subsidence and contamination may be impossible to fully remediate.

### A.2.3 Wastewater

Wastewater differs from both surface and groundwater in that it is both a resource to be used and a risk or hazard which must be addressed. Wastewater is produced through human use of other water sources and therefore the timing, quantity of flow, and location of discharge is well known. Beyond quantity and timing, wastewater is characterized by its water quality parameters.<sup>218</sup> These include physical and chemical characteristics as well as the degree of treatment it has received. Temperature, color, odor, and total dissolved and suspended solids are some of the most common physical characteristics considered. Chemical characteristics include pH, nutrient loading, biological oxygen demand, and concentrations of toxics and bacteria. Treatment can occur at many different levels, ranging from simply removing solids, to biological degradation, to chemical treatment (Crites & Tchobanoglous, 1998).

As a dual nature resource, there are two sets of concerns related to transboundary flows of wastewater: those related to negative impacts due to contamination and those related to use of the resource as a water supply. Exposure to un-treated or improperly treated wastewater presents human health risks, as wastewater may contain pathogens and toxins. Ecosystems may also be endangered if the wastewater released contains excessive levels of nutrients, heavy metals, or salts. With respect to transboundary flows of wastewater, the degree of treatment necessary and the entity responsible for treating the wastewater are issues which must be resolved (Angelakis, Bontoux, & Lazarova, 2003; Asano, 2002).

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<sup>218</sup> The water quality parameters of surface and ground water are also important; however, these resources are much more commonly described by quantity characteristics rather than quality characteristics.

Table A-1: Comparison of the Physical Characteristics of Surface, Ground and Waste Waters

	Surface Water	Ground Water	Waste Water
Properties used to Characterize	<p>Rate and frequency of flows</p> <p>Streambed width</p> <p>Streambed slope</p>	<p>Depth to water</p> <p>Underflow/flux</p> <p>Permeability</p> <ul style="list-style-type: none"> <li>- Conductance</li> <li>- Transmissivity</li> </ul> <p>Storativity</p> <ul style="list-style-type: none"> <li>- Specific yield</li> <li>- Specific storage</li> <li>- Storage coefficient</li> </ul>	<p>Rate and timing of flows</p> <p>Physical properties</p> <ul style="list-style-type: none"> <li>- Temperature</li> <li>- Total solids</li> <li>- Color</li> </ul> <p>Chemical properties</p> <ul style="list-style-type: none"> <li>- Concentrations</li> <li>- BOD</li> <li>- pH</li> </ul>
Geographic Expanse	River bed from headwaters to outflow	Delineating boundary can be complex	Location of discharge
Direction of Flow	<p>Linear</p> <ul style="list-style-type: none"> <li>- Upstream to downstream</li> </ul>	<p>Non-Linear, 3-dimensional</p> <ul style="list-style-type: none"> <li>- Horizontal and vertical flows</li> <li>- Flow direction linked to                             <ul style="list-style-type: none"> <li>o Usage</li> <li>o Recharge</li> </ul> </li> <li>- May change over time</li> <li>- May flow in multiple directions at different levels simultaneously</li> </ul>	<p>Linear</p> <ul style="list-style-type: none"> <li>- Based on infrastructure and release location</li> </ul>
Temporal Aspects	Rapid flow	Slow movement	Flow rates based on usage patterns of other water resources

	<b>Surface Water</b>	<b>Ground Water</b>	<b>Waste Water</b>
	Residence time: weeks Impact of use quickly felt downstream	Residence time: weeks to thousands of years, Slow replenishment Time lag between use and effect of impact	Residence time: hours to months <sup>219</sup>
Visibility	Highly visible	Low profile	Medium visibility
Infrastructure	Mostly centralized – Reservoirs – Canals – Pipelines	Decentralized – Wells	Centralized – Treatment plants – Sewage and drainage network
Reliability	Medium – Dependent on nature – Impact of upstream consumption	Medium – Time lag before effects of climate or use are felt	High – Predictable due to its anthropogenic origins
Uncertainty	Medium – Inherent climatic variability	High – Inherent climatic variability – Heterogeneity of aquifer properties	Low
Data Requirements	Medium Historical record – Climate – River gage data	High Historic record – Climate – Water table levels	Low Historic Record Chemical Analyses

<sup>219</sup> Residence time for wastewater treatment vary, depending upon the type of treatment provided and the volume of flows through the facility. For a conventional activated sludge treatment plant, the residence time may be at most eight hours, whereas for a pond or wetland system residence time may be several months. (Ashley Murray, UCB, Personal Communication, February 10, 2008)

	Surface Water	Ground Water	Waste Water
		<ul style="list-style-type: none"> <li>- Pumping rates</li> </ul> Aquifer characterization data <ul style="list-style-type: none"> <li>- Pumping Tests</li> <li>- Geophysical Tests</li> </ul>	
Factors which impact water availability	Land Use Precipitation Diversions	Land Use Precipitation Stream flow (if alluvial aquifer) Abstractions Induced recharge	Human activity
Concerns	Water quantity <ul style="list-style-type: none"> <li>- Diversions</li> <li>- Hydroelectric generation</li> <li>- Instream flows</li> </ul> Water quality Flooding Navigability Riparian ecosystems	Water table levels <ul style="list-style-type: none"> <li>- Reductions in baseflow</li> <li>- Dry wells</li> <li>- Salt water intrusion</li> <li>- Land subsidence</li> <li>- Damage to ecosystems and wetlands</li> <li>- Increased concentrations of arsenic or fluoride</li> <li>- Increased pumping expenses</li> </ul> Water Quality	Public health Environmental protection
Management Decisions	Determining timing and quantity of <ul style="list-style-type: none"> <li>- Diversions</li> <li>- Reservoir releases</li> </ul>	Definition of safe yield Determining timing and quantity of	Acceptable treatment levels Location of release

	<b>Surface Water</b>	<b>Ground Water</b>	<b>Waste Water</b>
	Determining impacts of utilization <ul style="list-style-type: none"> <li>- Instream flows</li> </ul>	<ul style="list-style-type: none"> <li>- Abstractions</li> </ul> Determining impacts of utilization <ul style="list-style-type: none"> <li>- Drawdown</li> <li>- Changes in direction of flow</li> <li>- Reduced baseflow</li> </ul>	Prevention of untreated spills

### **A.3 Institutional Attributes of Surface, Ground, and Waste Waters**

Not only do surface, ground, and waste water resources have very different physical characteristics, the institutional environment governing their management and use is also quite diverse. These resources differ in the history of how they have been managed and in the institutional arrangements that have been devised to control or regulate water use. They also differ in the extent to which monitoring and enforcement of their use can occur. A summary comparison of the institutional characteristics of these resources is included in Table A-2.

#### **A.3.1 Surface water**

Regulation over uses of surface waters dates to Roman times, when water was considered part of things held ‘common to all mankind’ (Narasimham, 2008, pp 127). As such, usufruct rights were granted that allowed for the use of surface waters; however, the government retained the ability to regulate such use to prevent over-exploitation (Hodgson, 2006). This system of usufructory rights remains part of English Common law, the Napoleonic code, and Spanish law which form the basis of water law in much of the world and currently the two most common water rights systems are riparian rights and prior appropriation. Riparian rights, which exist through land ownership, allow adjacent landowners to make use of rivers and streams so long as they do not interfere with the rights of other proprietors (Cox, 1982; Hodgson, 2006; Sax, Thompson, Leshy, & Abrams, 2000). In the late 1800’s, the doctrine of appropriative rights was developed in the western United States. Appropriative water rights are not attached to the land and are allocated on a first in time first in right basis. Lastly, surface water rights might be centrally controlled, with use concessions or permits allocated by governmental agencies according to governmental priorities or plans. More recently, the environment is being recognized as a legitimate user of surface waters.

#### **A.3.2 Groundwater**

Historically, water management institutions have focused on surface waters (Hodgson, 2006; Nanni et al., n.d.), in part because groundwater abstraction was limited in scope, as large scale pumping did not begin until diesel pumps became readily available. In addition, gaps in technical understandings lead to the perception that groundwater was perceived to be unlimited in supply and un-connected with other groundwater or surface water (Cleary et al., 2008; Foster, 1999).

Under Roman law, and similarly under both English common law and Spanish law, groundwater was considered part of the overlying soil and pertained to the overlying property owner. A majority of countries, including much of Europe, Latin America, and Africa, follow this rule (Narasimham, 2008; Salman, 1999; Shah, 2002; Wegerich, 2006). In countries governed by Islamic law, groundwater belongs to all beings, and, even though people may own individual wells, water is to be shared (Hodgson, 2006). In the United States groundwater use is governed by a variety of legal principles, and groundwater is subject to the rule of capture, correlative rights (California only), or beneficial use, depending upon the location.

In recent years, as groundwater use has increased, new institutional arrangements have been developed to regulate abstractions, particularly in countries in which groundwater pumping is subject to the rule of capture, i.e., unrestricted use by the overlying property owner. For

example, in the 1980's and 1990's, South Asia, China, Spain, and Mexico implemented groundwater management plans and instated groundwater permitting systems (Shah, 2002). None-the-less, these institutional arrangements are still evolving. New groundwater regulations often face resistance, because due to the historic linkage of groundwater to land ownership, imposing new regulations is viewed as interfering with private property rights (Burke et al., 1999). As a result, many countries still lack policies and institutions for the governance of groundwater (Sagala & Smith, 2008).

Unlike surface water use, which can easily be identified as diversions occur along the length of the river or lake, groundwater use is more dispersed. Monitoring water use is not only complicated by this geographic decentralization, but also because the quantity of water abstracted is unknown to all but the user. Limitations in monitoring capacity also constrain possibilities for enforcement, as non-compliance is difficult to spot.

### A.3.3 Wastewater

The institutions which govern wastewater management arrangements stem from individual country policies rather than the long tradition law that accompanies the management of ground and surface waters. As a result, these institutions vary widely from country to country. In accordance with the dual nature of the resource, wastewater management institutions fall into two categories: those related to the discharge and quality of wastewater and those related to ownership of return flows.

Many wastewater management requirements stem from the public trust doctrine; however in the US and Europe, tort law also provides a forum for resolving grievances (Narasimham, 2008; J. Sax, 1989). Wastewater regulations may take the form of requirements stipulating water quality standards or requirements stipulating the technologies or best practices which must be used to treat the wastewater. In many countries, wastewater discharge is regulated through permit systems. Wastewater is also frequently governed indirectly by environmental protection laws, health regulations, and other non-water-specific regulations (Tchobanoglous, Burton, Stensel, & Metcalf & Eddy, 2003; von Sperling & Augusto de Lemos Chernicharo, 2002).

Ownership over wastewater flows is not well stipulated and may fall under institutional restrictions over the rights of water in artificial water courses. In many places, wastewater remains under the jurisdiction of the water appropriator who created the flows until it is released. In the US, wastewater belongs to the producer, yet others may appropriate the water once it has been released. However, the producer of an artificial flow is not obligated to maintain this flow (Sax et al., 2000). In Mexico, wastewater pertains to the entity creating it (usually the municipality) until it is discharged into a natural water course, at which point, control over the resource returns to the National Water Commissions (CONAGUA, Personal Communication, October 8, 2007).



**Table A-2: Comparison Institutional Characteristics Surface, Ground and Waste Waters**

	<b>Surface Water</b>	<b>Ground Water</b>	<b>Waste Water</b>
Water Management Systems	Riparian rights Prior appropriation Centralized control	Right of capture by overlying land owners  Correlative rights	Environmental Regulatory Agencies
Users	Easily identified	Dispersed	Few and easily identified

#### **A.4 Impact of Resource Characteristics on Transboundary Water Management**

The different characteristics of surface, ground, and waste waters have implications for the study of transboundary water management. Below I explain how differences between surface and groundwaters relate to several dominant theses stemming from the transboundary literature on surface waters including: principles for the allocation of water rights; the role of geography; monitoring and enforcement capacity; time considerations; and uncertainty and data requirements. In particular, I explain how the complexity of groundwater flow, including the high degree of uncertainty, the slower time frame, and the decentralized nature of both its physical and institutional properties, may serve to increase intractability in the management of transboundary groundwaters.

##### **A.4.1 Determining or Allocating Ownership or Water Rights**

The allocation and ownership over shared water resources is a primary focus of the literature on transboundary waters. Four main mechanisms for dividing shared waters are discussed in the literature: the doctrine of absolute sovereignty, the doctrine of absolute territorial integrity; division based on equitable and reasonable use; and needs based allocations (Barrett, 1994; Dombrowsky, 2007; Giordano & Wolf, 2003; McCaffrey & Benvenisti, 2001). The doctrine of equitable and reasonable use has come to be considered the best mechanism to allocate shared water resources (UNDP, 2006). Exactly what constitutes reasonable and equitable use is debatable, and is particularly difficult to determine for groundwater resources.

Article 6 of the ILC agreement on the management of non-navigational international water courses includes seven factors to help determine equitable and rational use, the first of which is “geographic, hydrographic, climatic, ecological, etc. factors of a ‘natural character’” (Wolf, 1997). For the case of surface waters, this includes consideration of the portion of runoff that can be attributed to each country. Unfortunately, for groundwater, there is no easy corollary. The amount of recharge contributed to the aquifer by each country is more difficult to determine. Neither the amount of recharge contributed to, nor the amount of water that can be withdrawn from, an aquifer is a function of land expanse; rather both depend on both the hydrogeology of the region and groundwater abstraction patterns. Thus even were the hydrogeology to be well understood (and it frequently isn’t) the quantity of recharge apportioned to each country will vary over time and space, depending upon where and what quantity of water is being pumped.

Hence for groundwater, ‘factors of natural character’ takes on a nature more ambiguous than it is already critiqued to be (Waterbury, 1997).

#### A.4.2 Geography

Studies of transboundary rivers have often looked to geography as a determinant of cooperation over shared water resources (Dinar, 2006; Dombrowsky, 2007; Espey & Towfique, 2004; Gleditsch, Furlong, Hegre, Lacinda, & Owen, 2006; Song & Whittington, 2004). Most commonly these studies distinguish between uni-directional and common-pool externalities. Uni-directional refers to upstream-downstream situations, where one country has, due to geography, a different power positioning than another. Common-pool, conversely, refers to where each country’s action affects (more-or-less) equally on the other. More specifically, any country’s action is supposed to have an impact not only on its co-riparian but also upon itself. The transboundary literature theorizes that different geographical positioning influences both the likelihood of formulating and the nature of a cooperative solution. Cooperation is thought to be more common in the case of uni-directional externalities because the outcome of non-cooperation, i.e., the default payoff, will differentially affect one player over the other. Cooperation is thought to be more difficult to achieve in the case of common-pool geographies, and more likely to fall into the ‘tragedy of the commons’ (Barrett, 1994; Bernauer, 2002; Dinar, 2006).

Uni-directional vs. common-pool externality characterizations can also be applied to ground and waste waters, with waste water being considered a uni-directional problem and groundwater a common-pool problem. This suggests cooperation over transboundary groundwaters will be more difficult to achieve than cooperation over surface waters. The literature on common property management supports this theory, as the issue of transboundary groundwater management is a collective-action dilemma. Collective action is theorized to be successful when, among other factors, there is a small group of homogeneous actors, boundaries are clearly defined, and there exist mechanisms for monitoring and sanctioning of behavior (Ostrom, 1990). However, as described above, transboundary groundwaters do not generally fit these stipulations. Countries sharing aquifers are likely to have diverse interests and preferences; due to the dispersed nature of groundwater resources, monitoring is difficult; and both because the resource is decentralized and due to the lack of history/control countries have over their groundwater resources, enforcing and sanctioning compliance, even within the level of a country is likely to be difficult. Thus the physical and institutional characteristics of groundwater may serve to hinder the joint management of shared groundwater resources.

#### A.4.3 Monitoring and Enforcement Capacity

Another key theme in the transboundary literature is the issue of monitoring and enforcing transboundary water agreements (Barrett, 1994; Just & Netanyahu, 1998). Domestic water management structures influence both the authority a nation has in developing international agreements that allocate or control water use and the ability of that nation to meet enforce, internally, its treaty agreements. The authority the national government has over its own water resources and its ability to enforce water use policies varies from country to country and is different for surface, ground, and wastewaters.

In the case of groundwater, the national government may not have much control over usage, because as mentioned previously, as until recently most countries did not regulate groundwater use, rather the right to use it lay with the overlying property owner. In order to reach an agreement on groundwater use, countries would need to at minimum, place some restrictions on pumping, and at maximum develop clearly defined groundwater rights. Yet the national government may not have the authority or the political capital to limit groundwater use by its own constituency. The links between groundwater and property ownership make implementation of new regulations all the more difficult. Individuals within the country may reject regulations as infringement upon their private property. Or, at a larger scale, the country may view entering into an international agreement that restricts pumping or regulates land use<sup>220</sup> as ceding sovereignty over its own natural resources

#### A.4.4 Temporal Aspects

With the exception of several commentaries on the need to address variation in climate (Draper & Kundell, 2007; Fischhendler, 2004; Morehouse, Carter, & Sprouse, 2000), studies of transboundary water management do not consider the temporal nature of water flows. Yet surface, ground, and waste waters have different temporal characteristics, which impact influence the types of problems that arise and the types of management activities that need to be undertaken. Surface water is for the managed on a seasonal or annual basis, as precipitation, snowmelt, and runoff occur at this temporal scale. Wastewater resource temporal patterns are generally quite well understood, as the generation and disposal of wastewater stems directly from human use and disposal. Conversely, groundwater resources operate along a different time scale. Unlike stream flow, where run-off is experienced relatively quickly, aquifer recharge may occur over an extended period, ranging between weeks to thousands of years. Water in aquifers may have been accumulating for many years. Additionally, there may be a lag between when groundwater is abstracted and the impacts of those actions are felt. Thus unlike surface water resources, which are typically managed on an annual or seasonal basis, the temporal slowness of groundwater calls for a longer management cycle. Failure to do so may result in agreements that are not sustaining over the long term or that do not achieve their intended water management goals.

#### A.4.5 Uncertainty, Data and Information Requirements

The role of uncertainty is another theme overlooked by the transboundary water literature. Studies of transboundary waters tend to assume countries have complete knowledge of their water resources, their water resource management objectives, and the utility of various water management strategies. In addition, many articles include normative statements recommending data and information sharing across the border (Sadoff & Grey, 2005; Timmerman & Langaas, 2005; UNDP, 2006; Wolf, 1997).<sup>221</sup> Yet surface, ground and waste waters are characterized by different levels of uncertainty. The variability associated with surface waters can usually be reasonably well characterized given a historic record of sufficient length. However, due to

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<sup>220</sup> Land use patterns impact both aquifer recharge and pollution, two issues of concern in transboundary water management. Thus one country may wish to regulate the land use practices of its neighbor in order to secure the desired state of the aquifer.

<sup>221</sup> Normative studies of transboundary water management recommend data sharing as a best management practice and a mechanism for increasing goodwill between countries.

geological heterogeneity and the interaction effects of dispersed users, groundwater flows are significantly more difficult to understand. Moreover, a much larger dataset is needed to generate understandings of groundwater flows, and this data is frequently non-existent. This uncertainty may impede management activities, as countries may be hesitant to make decisions (LeMarquand, 1976).

### **A.5 Concluding Comments**

The above comparison demonstrates the very different physical and institutional characteristics of surface, ground, and waste waters. Surface water has a more linear structure, groundwater is more dispersed, and wastewater is usually being restricted to a single discharge location. Surface waters have a clearly defined direction of flow and move relatively rapidly, groundwater moves in multiple directions and responds to stresses more slowly, and wastewater flows can be fairly regularized. Surface water is more visible and its infrastructure often involves large scale constructions, whereas groundwater is more hidden and relies on dispersed infrastructure and the visibility and infrastructure associated with wastewater depends on the location and level of treatment provided. It is also easier to quantify the availability of and to predict the impacts of the use of surface and waste waters than it is for groundwater. With respect to management, the use of surface waters has been regulated for longer than ground and waste waters, and thus countries have more developed systems for allocating surface water rights and controlling use. Lastly, due to the decentralized nature of the resource, monitoring and enforcement of activities is more difficult for ground than for surface and waste waters. These different characteristics of surface, ground, and waste waters have implications for the study of transboundary water management, in that, not only are management challenges and solutions different across the resources but also understandings derived from research on one type of transboundary water resource may not be directly transferable to the others.

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## **Appendix B : Calculation of Water Needs and Values**

### **B.1 Introduction**

This appendix elaborates on the water needs and value analysis presented in Chapter 3. Here I include details on the data sources, assumptions, and calculations used to determine the amount of water currently used in the SCAMA and in the Mexican portion of the basin, as well as similar information on how I calculated the fees currently paid for water in both regions.

### **B.2 SCAMA Water Needs**

Table 3-3 in Chapter 3 included a summary of my estimates of current and future water use in the SCAMA. This section provides more information on how I arrived at those values.

My estimates for municipal water needs (i.e., residential, commercial, and governmental water use) is based on estimates of the 2005 population (Arizona Department of Commerce, 2008)<sup>222</sup> and ADWR estimates of per capita daily water consumption (ADWR, 1999).<sup>223</sup> To make predictions of future municipal water needs, I translated population estimates into an estimate of the current housing stock<sup>224</sup> and then developed future scenarios of housing development. My calculations of future water needs are predicated on the number of households rather than estimated population for two reasons: i) water connections tend to be made at a household level (except in the case of multi-family residences) and ii) this allows me to use zoning and permitting processes to understand projected growth and limits to growth that exist for the county.

Information on the number of existing houses in the SCAMA is not readily available,<sup>225</sup> thus my calculation is based on the number of single and multi-family connections served by each of the five major water providers in the SCAMA: the City of Nogales, Valle Verde, Rio Rico, Tubac,

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<sup>222</sup> The exact 2005 population of the SCAMA is unknown, as a census is only taken every ten years. Moreover, SCAMA is comprised of a part of western Santa Cruz County as well a portion of southern Pima county but population statistics are aggregated by county and by census division (Arizona Department of Commerce, 2008) and these boundaries do not exactly coincide with the geographical extent of SCAMA .

<sup>223</sup> The SCAMA Third Management Plan (ADWR, 1999) estimates per capita municipal water use for 2025, averaged across all providers in the region, will be 180 gallons per day. This value accounts for both residential and non-residential municipal uses.

<sup>224</sup> I use a rate of 2.3 persons per house, based on data provided to ADWR by the City of Nogales. This information includes the number household connections served by the City Utility, the total amount of water provided to residential customers, and an average per capita water consumption. Other estimates for household size in Santa Cruz County include 3.23 persons per household (U.S. Census Bureau, 2000)

<sup>225</sup> Although estimates exist for the total number of houses per county, as mentioned in a previous footnote, SCAMA encompasses land in both Santa Cruz and Pima Counties. Each county has planning and tax information on all parcels within the county; however, this information is not identified in relation to the SCAMA boundaries. In Santa Cruz County, this information has not yet been compiled into a computerized format, and to sort through the paper files so as to determine the status of each property would be an enormous task. Furthermore, as land is subdivided and developed, land titles transfer hands frequently. Following this web of transactions, especially in a non-electronic form, would be near impossible. (Real Estate Developer, Personal Communication, September 20, 2007) Adding to this complexity is the fact that Santa Cruz County has been developing at a rapid pace (Headwaters Economics, 2007), although there were signs of a slowdown in 2007 and the current mortgage and credit crisis is sure to take its toll on development.

and Lakewood. I added to this an estimate of the number of houses served by small providers or exempt wells<sup>226</sup> to arrive at an estimate of the current housing stock.

Future growth scenarios are based on zoning for Santa Cruz and Pima Counties. Using GIS and zoning regulations, I determined the maximum number of houses that could be built according to existing zoning. This represents the “Full Development” scenario. If population growth continues at the current growth rate,<sup>227</sup> full build out will occur in 2114.<sup>228</sup> I also developed a “Medium Development” scenario which, using the current growth rate, represents development that might occur by 2050. This scenario assumes full development of sub-divisions in the Northwest Character Area of the County (Santa Cruz County, 2004) already permitted or with permits in process are fully built out and 50% of the remaining houses platted in Rio Rico and in the zone residential areas immediately surrounding the center of the City of Nogales are also built out.

In determining agricultural water needs, I assumed current agricultural water use represents an upper bound on future agricultural water needs in the SCAMA. Arizona law prohibits irrigation of land in the SCAMA not actively irrigated between January 1975 and January 1980 (ADWR, 1999).<sup>229</sup> Moreover, agricultural water use is likely to decline, due to increased efficiencies in the application of water as well as a movement to use water previously used in agriculture for municipal and other uses. My estimate for agricultural water use is based on the number of irrigated acres and the number of head of livestock in the county, as listed by the 2002 Agricultural Census (National Agricultural Statistics Service, 2004). Crop water use was calculated by multiplying irrigated acreage by evapotranspiration rates estimated by Unland et al (1998) and livestock water use was calculated by multiplying the number of heads of livestock by 15 gallons per head per day (Conley, Eakin, Sheridan, & Hadley, 1999; Lardy & Stoltenow, 1999). The amount of irrigated acreage listed in the census is comparable to that cited in Liverman et al (1997). As the Agricultural Census uses Santa Cruz County as its unit of analysis, and as the portion of the SCAMA that lies in Pima County is quite small, this is likely to be an overestimate of agricultural water use in SCAMA.

Industrial water needs in the SCAMA are relatively small and are primarily landscape watering and sand and gravel operations. Water use for industrial manufacturing or processing is negligible in SCAMA (ADWR, 1999). ADWR (1999), estimates that if the current ratio of industrial water use to population remains constant, industrial water use will increase to 3000 AF

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<sup>226</sup> By multiplying the number of connections served by the major water providers times average household size, I developed an estimate of the population served by those water providers. Subtracting this population from my population estimate and dividing by average household size lead to an estimate for houses served by small providers and exempt wells.

<sup>227</sup> Using Arizona Department of Commerce (2008) population estimates for Santa Cruz county in 2000 and 2005, I calculate the population of Santa Cruz County grew at a rate of 2%. I consider this to be a conservative estimate, as Rio Rico expects to grow at a rate of 7% (Rio Rico Utilities, Personal Communication, June 27, 2006).

<sup>228</sup> Patterns of growth and development are unlikely to continue along the same path during the next 100 years. However, despite the inherent uncertainty and likely error in this estimate, it does represent one constraint on the maximum amount of water needed for municipal use within the SCAMA, and therefore places a sort of upper bound on my estimate. Moreover, as the Arizona Groundwater Code requires consideration of a 100 year time horizon, this metric is not fully unconceivable.

<sup>229</sup> Refer to the SCAMA Third Management Plan Chapter 4 for details regarding Arizona Law, A.R.S. Section 45-452.



annually by 2025. However, as industrial water use currently represents a small fraction of total water use in the SCAMA, I assume industrial water use remains constant for my future scenarios.

The most difficult water needs to evaluate in the SCAMA are related to environmental uses, namely the riparian flora and fauna. Evapotranspiration by riparian vegetation is the largest current use of water in the SCAMA (ADWR, 1999). As mentioned in Chapter 3, the extent of riparian vegetation that should be preserved is a contested issue, with some residents wanting to preserve the current expanse and with others who are more inclined to reduce the size of the riparian corridor. Resolving the question of how much vegetation should be preserved is key to determining how much water is required. Water needs of riparian vegetation need to be considered along two scales: a consumable quantity of water is needed for plant sustenance and growth and a non-consumable amount of water is needed to maintain groundwater levels above a certain depth, so that plant roots can access groundwater. I used ADWR estimates of current riparian evapotranspiration (ADWR, 1999) as my estimate of riparian consumptive water needs. However, the amount of water needed to maintain the water table at a given height is difficult to estimate, as it depends on a variety of other factors such as soil properties, recharge and abstraction rates, among others. A detailed discussion on the complexity of aquifer behavior and how this leads to uncertainty regarding water needs is included in Chapters 5 and 6.

Water is also needed to maintain instream flows, which provide valuable habitat for riparian fauna such as the endangered Gila Top Minnow and other native fish populations (USFWS, Personal Communication, September 17, 2007). However, the amount of flow needed to support fish species is unknown. Desert fish are accustomed to drought cycles (Friends of the Santa Cruz River, Personal Communication, May 28, 2006; USFWS, Personal Communication, September 17, 2007) but still require enough water to survive. According to USFWS, “Less water would be an issue, but to quantify it [i.e., the minimum before a problem] would be very difficult.” Excessive abstractions of groundwater or diversions of surface waters would not only decrease instream flows, but they might also lower the incidence of flooding. Flooding also plays an important role in the protection of native fish species in the region, as it tends to wash out non-native species, which are not as well adapted to extreme events (USFWS, Personal Communication, September 17, 2007). Even if instream flow requirements could be quantified, in terms of a flux of water that must remain in the stream at any given time, it would still be quite difficult to translate these into an amount of water needed. This is because, similar to water table levels, instream flows cannot be thought of as a fixed quantity of water, because they are the outcome of stream-aquifer interaction, recharge processes and other stresses on the system.

### **B.3 Sonora Water Needs**

Table 3-5 in Chapter 3 included a summary of my estimates for current and future water use in the Mexican portion of the basin. In estimating those ‘water needs’, I adopted a similar approach as used for determining SCAMA water needs.

To calculate residential water needs, I used a per capita water requirement and estimates of the population. A recent study surveyed households in several neighborhoods throughout Nogales, Sonora and estimated per capita water use to be 173 lpcd (OOMAPAS, Personal Communication, June 13, 2008). However, OOMAPAS estimates that, due to system losses,

35% more water needs to be provided from the source than is consumed by households.<sup>230</sup> Consequently, I estimated per capita water needs as 262 liters per day. Although this rate of water use is likely to change over time, I assume it remains constant for the purposes of this analysis.

I include the entire populations of both the municipality of Nogales and the municipality of Santa Cruz in my estimate of the population in the Mexican portion of the USCRB. The actual population of Nogales, Sonora (and the surrounding areas) is not well known, primarily due to the large number of “guests” in the city. Official statistics list the 2005 population as 193,517 (INEGI, 2005); however, OOMAPAS, the city water utility, estimates the population to be approximately 350,000<sup>231</sup> (OOMAPAS, Personal Communication, October 4, 2007). Table 3-4 in Chapter 3 listed the range of estimates for the 2005 population. As I included in my population estimates the entire population of both municipalities, some residents that are unconnected to the Santa Cruz watershed are included. Given those included are small populations relative to the size of Heroica Nogales<sup>232</sup> and given the large uncertainty in the estimate of the population in Heroica Nogales, it seems this is a reasonable accounting mechanism.

Not only are there discrepancies between official estimates of the current population, the rate at which growth is expected to occur also differs from document to document. OOMAPAS estimates approximately a 2% annual growth rate (BECC/COCEF, 2006) whereas the Municipal Plan estimates almost a 5% growth rate (H Ayuntamiento de Nogales Sonora, 1997). According to the Subdirector of Urban Infrastructure and Public Works for Nogales, Sonora, the municipality plans to construct approximately 30,000 new houses during the next 5-10 years (Ayuntamiento de Nogales, Sonora, Personal Communication, October 16, 2007), increasing the number of houses in the city by approximately 50%. This represents a rate of growth in the number of households of between a 4 and 8%. However, the addition of new residences does not necessarily mean the population will increase at the same rate as houses are constructed. Rather these new homes may simply mean that part of the existing yet uncounted population will be legitimized. If all of the new homes are provided with piped water service, it is likely water use will increase; yet it is also true that some of this water may already be in use and, due to unofficial population estimates and illegal connections the water is simply unaccounted for.

It reasonable to assume that growth will not occur in the region indefinitely, as both economic and resource constraints exist.<sup>233</sup> The Municipio de Nogales master plan zoning, including both

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<sup>230</sup> This estimate for system losses is lower than the 50% overall losses thought to exist in the piped water system. One explanation for this difference is OOMAPAS believes 35% of all losses occur within the household, due to leaky faucets and pipes. As control over these losses is outside of the domain of the water provider, these losses are attributed to the water user as part of their consumption.

<sup>231</sup> The OOMAPAS population estimate is in agreement with their current pumping rates, as assuming 35% losses, the amount of water they abstract from wells would provide 148 lpcd to 350,000 people.

<sup>232</sup> In 2000, only approximately 4000 residents in the municipality of Nogales lived outside the city limits; this number is quite small compared to the between 156,854 and 350,000 people thought to reside within the city center. Moreover, in 2000, the entire municipality of Santa Cruz was home to only approximately 1628 people. (INEGI, 2000)

<sup>233</sup> There are natural physical limits to growth that should be taken into consideration, for example, the city is surrounded by quite steep and hilly terrain and thus only a portion of the land is suitable for development.

the current zoned and the reserve area, only provides for a maximum population of 285,890 (H Ayuntamiento de Nogales Sonora, 1997), which is insufficient to house the OOMAPAS estimate for the existing population.<sup>234</sup> Thus, unlike in the SCAMA, I cannot use land-zoning documents to place a bound on development. Rather than arbitrarily impose limits to growth, my future water needs scenarios consider the uncertainty in estimates of the current population and increase those at high and low rates of growth to arrive at a range of possible future population scenarios.

As there is such large uncertainty in the current population and the amount and rate of growth that is expected to occur, I developed two water use scenarios: a high scenario and a low scenario. The high scenario takes as its starting point the OOMAPAS estimate of 350,000 people, combined with the 1728 persons estimated to reside in the municipality of Santa Cruz in 2005 (INEGI, 2005). I then assume the population in Nogales then increases at a rate of 2.6% annually, whereas the population in Santa Cruz increases at a rate of 1%.<sup>235</sup> My low water use scenario uses the CONAPO estimate (BECC/COCEF, 2006) for the current population of Nogales and assumes that population grows at a rate of 2.1% annually. The low water use scenario includes the same population estimates for the municipality of Santa Cruz as used for the high water use scenario. As mentioned in Chapter 2, I do not expect my assumed growth rates nor my total population estimates are correct; in fact, in my subjective opinion, they are likely all overestimates. None-the-less, these estimates provide some initial bounds on the amount of water that might be needed for municipal water use in the Mexican portion of the basin.

Given not all commercial water use is metered and I was unable to obtain information on other municipal non-residential water use (such as governmental use and services), I had to make a number of assumptions about current non-residential water use. To arrive at a ball-park figure, I assumed non-residential municipal use was equal to 15% of residential municipal water use.<sup>236</sup> I also assumed this ratio stays constant over time. I include both a high and a low estimate for non-residential municipal water use, based respectively on my high and low residential water use scenarios.

Current industrial water use was based on 2005 OOMAPAS billing to industrial customers<sup>237</sup> plus information on water rights allotments to industry from the Registro Publico de Derechos de

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<sup>234</sup> This result is not counter-intuitive, as interviews with the municipal government indicate there is currently a housing shortage in Nogales (Ayuntamiento de Nogales, Sonora, Personal Communication, October 16, 2007). The OOMAPAS population estimate is the highest, and includes approximately 35,000 as a transient population (BECC/COCEF, 2006). Furthermore, land use planning is a relatively new practice in the city. Zoning has not been adjusted to conform with existing land use practices and has only recently begun to be enforced for new development (Juan Baena, Ayuntamiento de Nogales, Sonora, Personal Communication, July 19, 2005)

<sup>235</sup> Between 1990 and 2000, the population of the municipality of Santa Cruz, Sonora grew at a rate of 1%. See (Gobierno del Estado de Sonora, n.d.). I assumed this growth rate remains constant.

<sup>236</sup> The CDM (1996) Facility Plan for Ambos Nogales calculates that in 1995 non-residential municipal water use was equivalent to is 15% of residential water use. The basis for this assumption is not well documented in the Facility Plan. Moreover, it is unclear if the current ratio of non-residential to residential water use is the same, as the maquiladora industry has grown considerably since 1995.

<sup>237</sup> One hundred percent of industrial water use provided by OOMAPAS is metered.

Agua (REPDA).<sup>238</sup> I assume the ratio of industrial to residential water use remains constant over time.

My calculations of agricultural water needs include both water used for crops and water used for livestock. Crop water use was based on the average number of hectares of crops planted in both the municipality of Nogales and Santa Cruz between 2000-2004 (SAGARPA, 2000-2005) and empirical estimates of evapotranspiration for agriculture in the region (Unland et al., 1998). This is likely to be an overestimate of agricultural water use in the basin, as this number includes acres planted outside the basin. Livestock water use is based on the SAGARPA (2005) livestock inventory times and a rate of 15 gallons per head of livestock per day (Conley et al., 1999; Lardy & Stoltenow, 1999). Given the number of acres planted does not appear to have changed much during the several years for which I have data (2000-2004), I assume agricultural water use will remain the same over time.

Lastly, my estimates of evapotranspiration by riparian vegetation are quite coarse. Unlike the ADWR estimates for the SCAMA, which used aerial photography to determine vegetation density and extent (ADWR, 1999), little information is available on vegetative cover in the Mexican portion of the basin. Although satellite images exist for the region (Dohrenwend, Gray, & Miller, 2001; Google, n.d.; USGS, 2008), it is difficult to distinguish between agricultural water use and riparian vegetation (Hutchins et al., 2006). Thus to estimate the extent of riparian vegetation, I assumed it covered the length of the river times an area of 0.16 kilometers (0.1 miles) on either side of the river. This is likely to be an over-estimate, as visits to the region<sup>239</sup> indicate in most areas, vegetation is sparse.

Similar to in the SCAMA, the water needed to maintain water table levels and instream flows cannot be identified.

#### **B.4 SCAMA Water Values**

Table 3-6 in Chapter 3 summarized my estimates for the fees paid for water in the USCRB. This section explains how arrived at those estimates.

The amount paid for water used in the USCRB can be viewed as a lower bound estimate for the economic value of water in the basin, as consumers were willing to pay at least that amount in order to obtain that water. For water provided by utilities, this value is a function of the tariffs were charged by the utility. For water extracted from private wells in the SCAMA, this value is the result of both groundwater withdrawal fees<sup>240</sup> paid to ADWR as well as by the cost of extracting and conveying well water (electrical costs, etc.). The cost of groundwater extraction varies tremendously, due to differences in the depth to water level and the pumping system

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<sup>238</sup> Companies that use their own private wells for their water supply are required to register their wells with the CONAGUA and are allotted a concession that is recorded in REPDA. Industrial users are required to report their water use and pay groundwater extraction fees to the CONAGUA. It is believed that conformance with this regulation among industrial users is high (CONAGUA, Personal Communication, October 8, 2007).

<sup>239</sup> I toured the length of the river up to San Lazaro during Summer 2006, various spots in 2007, and through Paredes during June 2008.

<sup>240</sup> ADWR charges all non-exempt water users in Active Management Areas to file a water withdrawal and use report and to pay an annual groundwater withdraw fee of \$3 per acre-foot. (ADWR, Personal Communication, September 21, 2006;ADWR, n.d.)

installed in each well. Rather than address this complexity, for water not provided through one of the five water utilities in the SCAMA, I use simply the fees paid to ADWR as my lower bound estimate.

For each of the five main utilities (City of Nogales, Rio Rico, Valle Verde, Tubac - now Arizona American, and Lakewood) I calculated, on average, the total annual residential and commercial tariffs charged.<sup>241</sup> To determine the residential fees charged, I used data provided to ADWR by the utilities that includes information on the amount of water provided monthly and the number of connections between 2000 and 2005. First, I calculated average monthly use per connection. Then, using tariff schedules either obtained directly from the utilities themselves or via the Water Infrastructure Finance Authority of Arizona (2005), I calculated the average annual tariffs paid per connection. This value was then multiplied by the number of connections in 2005 to estimate the total annual average residential tariffs paid to each utility. Non-residential<sup>242</sup> municipal water tariffs charged were calculating using a similar process, only due to a paucity of data, I used the amount of water provided to connections in 2005 rather than the average of 2000 to 2005.

Unfortunately, my calculation of the amount of water reported as provided by the large water utilities to water users in 2005 did not match the total amount of water abstracted for municipal purposes as reported to ADWR for that year. This is likely due to the facts that i) I did not include information on connections to industrial facilities or governmental facilities (such as hospitals and schools) , ii) some municipal users are served by small providers or private wells rather than the large water providers, iii) some water is extracted by utilities and used for their own purposes (such as checking pressure, cleaning pipes, etc), and iv) average 2000 – 2006 monthly water use may have been different than actual water use for 2005. As I do not have access to sufficiently disaggregated data to accurately account for each of these possibilities, I cannot assess tariffs charged to consumers other than the averages I calculated. However, at minimum, for all water extracted and reported to ADWR, the ADWR groundwater withdrawal fee was charged. Thus, to my estimate of the sum of the fees charged by the large providers, I added the amount that would have been charged as groundwater extraction fees for this amount of unaccounted for municipal water use. To finalize my estimate of the fees charged for water in the SCAMA, I added the fees that would have been charged for groundwater extracted from private wells for irrigation and industrial use.

## **B.5 Sonora Water Values**

Table 3-7 in Chapter 3 summarizes my estimates of the fees paid for water in the Mexican portion of the USCRB. Similar to my efforts for the SCAMA, I developed a lower bound estimate for the value of water in the Mexican portion of the basin based on the amount users

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<sup>241</sup> I use tariffs charged to users as my proxy rather than tariffs paid by users for two reasons. The first, is that I do not have access to payment information from the water utilities. The second is that customers may be late on payments or have made alternative payment arrangements and thus using payments rather than charges would require addressing this issue.

<sup>242</sup> Non-residential municipal water use includes water provided to commercial, governmental, and turf facilities. My calculation includes only commercial and turf facilities, as I have no information on the number of governmental connections nor the tariffs charged to them. Only the City of Nogales has a separate category and listing for turf facilities (golf courses or other areas, such as parks, that might have large irrigation needs). These facilities are charged a different rate for water than other municipal connections.

currently were charged for water. This estimate includes tariffs charged to customers by OOMAPAS, the Heroica Nogales municipal run water utility; concession charges to industrial users to the Comision Nacional de Agua (CONAGUA); as well as low and high estimates of the cost of water purchased from pipas (water trucks) and garrafones (bulk bottled water).

My estimates of fees charged for water only include the municipality of Nogales; the municipality of Santa Cruz is not included for several reasons. First, I have no information on water tariffs charged in for the municipality of Santa Cruz and the population reached by the piped water system in Santa Cruz, is quite small, on the order of less than 1000 residents. Secondly, there is little to no industry in the municipality of Santa Cruz, and thus no concession payments are made to the CONAGUA. Lastly, the provision of water via pipa to rural areas such as Santa Cruz is rare.

I calculated the tariffs charged by OOMAPAS using information provided to me by the OOMAPAS (OOMAPAS, Personal Communication, June 28, 2006) on the number of connections by category and the total amount of water billed by category (residential, small commercial, large commercial, and industrial) for July 2006. From this information, I determined the average amount of water billed per connection, and, combined with the tariff schedule, calculated the average monthly bill per connection type. I then multiplying the average monthly bill per connection type by the number of connections in each category and summed to obtain and estimate total annual tariffs charged by OOMAPAS for 2006.

My estimate of CONAGUA concession charges of industrial water users was based on the amount of water assigned to industrial users in the CONAGUA Registro Publico de Derechos de Agua (REPDA) and the annual concession fee of \$7 MX pesos per m<sup>3</sup> (CONAGUA, Personal Communication, October 8, 2007).

Beyond the piped water network and private wells, pipas are another key source of water for many residents and business in Nogales. An estimated 25,000 residents live in housing not connected to the piped water system (OOMAPAS, Personal Communication, October 4, 2007). Additionally, many residents and businesses require more water than can be delivered to them via the piped network, due to poor quality service, disruptions in service, and other factors. A pipa contains approximately 5000 liters of water and is sold, on average, at a cost of 350 pesos (Ayuntamiento de Nogales, Sonora, Personal Communication, October 16, 2007; OOMAPAS, Personal Communication, October 4, 2007). My low estimate for the amount of money spent on pipa water per year is based on the assumption that the entire population without access to piped water purchases on average, 50 liters of pipa water per person per day. My high estimate for the fees paid for pipa water assumes on average, 170 liters per day (the average amount of water used per capita by piped water customers). Although assuming all residents without piped water use pipa water may be incorrect, this assumption is balanced by the fact that many residents with piped water also used pipa water. Thus I expect both my low and my high estimates for pipa water use are on the lower end of the spectrum.

The most expensive, on a per liter basis, water purchased in Nogales is purified bottled water. Since the early 1990's, the Mexican Government has engaged in a very active public awareness campaign focused on educating the population about the importance of safe drinking water

(IFPRI, n.d.; SEDESOL, n.d.). As a result, a large portion of the population, especially in urban areas, relies on bottled water for drinking water.<sup>243</sup> My low estimate for garrafone purchases assumes half the population of Nogales consumes half a liter of garrafone water per day. My high estimate assumes 0.7 percent of the population consumes 1.5 liters of garrafone water per day. I believe these estimates are within the correct order of magnitude, given my low estimate for garrafone consumption in Heroica Nogales represents only approximately 0.1% of the national total bottled water consumption and my high estimate would represent 0.6%. In comparison, the population in Heroica Nogales forms 0.3% of the total Mexican population. Furthermore, one might expect bottled water consumption to be higher in urban areas and in more touristy areas, such as Nogales, than in the remainder of the country. Without access to data on total garrafone sales in Nogales or without conducting a statistically valid survey, it is difficult to corroborate or improve upon these estimates.

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<sup>243</sup> According to the International Bottled Water Association and Beverage Marketing Corporation (Beverage Marketing Corporation, 2007) Mexico has the second highest per capita bottled consumption rate in the world. In 1997, more than 5 billion gallons of bottled water were consumed in Mexico, approximately 3.6 billion gallons (13.8 billion liters) of which was from garrafones. (Llopis & Garcia, 1997) In 2007, more than 5.9 billion gallons (22.3 billion liters) of bottled water were sold in Mexico. (Beverage Marketing Corporation, 2007).

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