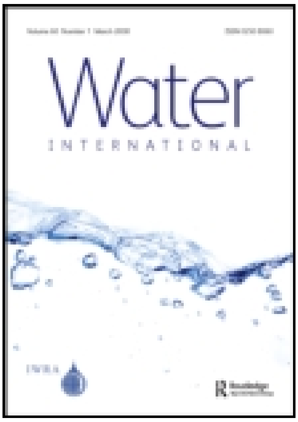

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Interpreting the unknown: uncertainty and the management of transboundary groundwater

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Interpreting the unknown: uncertainty and the management of transboundary groundwater

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This paper shows how uncertainty undermines collaborative transboundary groundwater management. Focusing on the Santa Cruz Aquifer, spanning the United States–Mexico border between Arizona and Sonora, the authors describe the uncertainties within the aquifer using interviews and hydrologic studies. We discuss how data requirements and ambiguous interpretations exacerbate these uncertainties, and explain how each country's water-management culture combines with this uncertainty to create contrasting views on groundwater availability and abstraction impacts. As a result, water managers in both countries predict different impacts from pumping and recharge, and each uses that information discursively to support unilateral policies rather than to promote collaborative management.

Keywords: transboundary groundwater; uncertainty; cooperation; United States–Mexico

Introduction

Many experts on cooperation over transboundary waters promote norms such as "equitable and reasonable use", "no significant harm" and "optimal basin development" (United Nations 1997, Wolf 2007); for a countering view see Wegerich and Olson (2010). To be useful, these norms require shared knowledge of hydrologic processes and shared understandings of "equity" and "harm". Our research in the transboundary Santa Cruz Aquifer, located along the United States–Mexico border, makes evident the difficulty of applying these norms to shared groundwater. Groundwater systems are characterized by inadequate information (epistemic uncertainty). Epistemic uncertainty can lead to framing uncertainty, or ambiguities in how a situation is understood and represented. We argue that poor data and clashing frames make it unclear how groundwater cooperation is to be achieved, if needed, or even how to determine the value (if any) to cooperative management.

Our research was conducted from 2005–2008 and included more than 40 key informant interviews, a detailed analysis of hydrogeologic data and groundwater simulation modelling. We begin with a discussion of the complexities of groundwater flow and their portrayal in the literature. We then describe the study region, explaining each country's perceptions of water availability and its conceptualization of the hydrology of the aquifer. We then show how inadequate data and institutional factors produce a poorly understood aquifer and explain how framing allows each country to hold different perspectives on the

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same aquifer. Each interprets information on the hydrologic processes via the lens of its own water-management paradigms and moves forward with its individual agenda. Lastly, we discuss the implications of our findings to the Santa Cruz aquifer and to transboundary aquifers more generally.

Uncertainty is inherent in transboundary groundwater

Uncertainty is characterized by the manner in which it can be reduced. Aleatory uncertainty refers to that which is stochastic in nature, and therefore cannot be reduced, although it may be described via probability-distribution functions. Epistemic uncertainty is due to insufficient knowledge of a system, and could be reduced, although the parties concerned may be unable or unwilling to do so (Oberkampf *et al*. 2004, de Rocquigney *et al*. 2008). In the international-relations literature, epistemic uncertainty is often called model uncertainty; this is contrasted with strategic uncertainty, referring to uncertainty on account of asymmetric information held by the bargaining parties (Iida 1993). Brugnach *et al*. (2008) add to this typology the concept of framing ambiguity, which refers to uncertainty arising from multiple concurrent framings or interpretations of a particular phenomenon.

Although all water-resource systems are characterized by aleatory uncertainty stemming from natural variability in climate, uncertainty in groundwater is also strongly epistemic. Groundwater systems are complex, open systems; therefore they are underdetermined (Oreskes *et al*. 1994). Data collection is expensive and requires technical expertise. Key features of the aquifer that impact flows, such as fractures, impermeable regions and high or low conductivity lenses, complicate measurement, as do stresses on the system that, by shifting gradients, may lead to induced recharge and capture of streamflow (Bredehoeft 2002). Transboundary aquifers are particularly difficult to characterize because information must cover the extent of the aquifer across multiple countries and data on piezometric levels, and flows taken from each side of the border should cover a similar timeframe and sampling frequency (see for example, Anderson and Woessner [1992]). But water agencies across a border operate independently, so such coordinated data usually do not exist. As a result, co-aquiferians do not have full (or even the same) understanding of how groundwater flows through the shared aquifer: they may hold different conceptual models of the aquifer, leading to different interpretations of water availability, and the impacts of groundwater use, recharge and protection activities. In the Santa Cruz, this epistemic uncertainty is amplified by multiple frames, as sparse data are interpreted via the lens of water-management paradigms.

The high degree of uncertainty associated with groundwater is well understood by hydrologists (Tsur and Zemel 1995, Beven 2000). Multiple working hypotheses are, in fact, fundamental to the science of hydrogeology (Chamberlin 1897, Bredehoeft 2005). Yet there is little explicit analysis of the role of uncertainty in studies of transboundary water management. Models of transboundary water management presume that countries share a common physical frame (hydrologic model), through which they know the quantity of water physically available as well as the impact possible water-management strategies will have on hydrologic processes. This assumption of shared and agreed-upon knowledge is especially common in economic approaches to transboundary waters, such as game theoretic (Frisvold and Caswell 2000, Dombrowsky 2007), optimization (Küçükmehmetoğlu and Guldmann 2004, Whittington *et al*. 2005), and benefit-sharing analyses (Sadoff and Grey 2005, Phillips *et al*. 2006). With few exceptions (for example, Fischhendler [2004]), variability in flows is rarely considered, and uncertainty of hydrologic processes has yet to be acknowledged in these policy-oriented literatures. This is especially true for ex-ante uncertainty that determines whether or not a collaborative treaty is possible, or even needed (as opposed to ex-post uncertainty that relates to treaty effectiveness.[1]

The clearest recognition of the role of ex-ante uncertainty in collaboration is by Lemarquand (1976) who suggested that when the consequences of a transboundary water-management strategy are not fully understood, countries may be reluctant or unwilling to reach an agreement. Zeitoun and Warner (2006) also suggest that ambiguity can be manipulated during the process of constructing "knowledge", a key mechanism leading to hydro-hegemony. Our research in the Santa Cruz highlights how multiple uncertainties brings to the fore extra-scientific considerations, such as equity, sovereignty, prestige and cultural ideologies. These considerations are, of course, known to influence the water-management strategies that countries adopt (Frey 1993, Wolf 1997, Bernauer 2002), but have been analytically sidelined by the emphasis on benefit sharing and Pareto-optimal basin management. We argue that these value-laden factors are key to interpretations of what benefits are to be shared or optimized, and thus influence the possibilities for collaboration over shared groundwaters.

The Santa Cruz Aquifer

The Santa Cruz Aquifer is located along the United States–Mexico border, spanning parts of Arizona and Sonora. There is a strong history of cooperation between the two countries over their shared surface waters, but little precedent for management of groundwater in the 17 aquifers that traverse the border (Mumme 2005). An addendum to the 1944 treaty that serves as the basis for water relationships between the two countries implied that a comprehensive groundwater agreement would be forthcoming (IBWC 1973), yet such an agreement has not been drafted.

The study region is defined by the path of the Santa Cruz River and the aquifer connected to it, as depicted in Figure 1. On the US side of the border, the region encompasses the area defined as the Santa Cruz Active Management Area (SCAMA). On the Mexican side it encompasses the municipalities of Nogales and Santa Cruz, Sonora. The region, which is part of the Sonoran Desert, is semi-arid and drought-prone (Morehouse *et al*. 2000, SAGARPA 2004). Precipitation is between 280 and 440 mm per year (Liverman *et al*. 1997) and occurs over two seasons, the summer monsoons (August/September) and the winter rains (December through February).

The aquifer is made up of 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. In several locations, outcrops of the Nogales Formation or bedrock constrictions create narrows, and pockets known as microbasins that act as mini-storage basins (Erwin 2007, geologist, pers. comm. 13 October 2007). The aquifer is characterized as unconfined or semi-confined and water-table levels fluctuate seasonally. There is a strong interaction between surface and groundwater, and the majority of water used in the region is withdrawn from wells located in the river valley.

Water availability and the impacts of use on water-table levels are primary concerns in the region. Up until the recent economic crisis (2007–2009), both sides of the border were experiencing rapid growth and that trend is likely to continue. While there is no immediate crisis, water agencies in both Arizona and Mexico recognize that the demands on the shared aquifer will intensify in the next few years. In Arizona, the priority is to meet increasing demands for housing and economic growth while protecting ecosystems and maintaining the aesthetic and cultural aspects of the community (ADWR 1997, Santa Cruz County 2004). Here water-management policies centre on preventing water-table

Figure 1. The Santa Cruz Aquifer: administrative boundaries and key features.
Source: Milman and Scott (2010, p. 530).

drawdown, maintaining safe yield and ensuring sufficient supply for growth. In Sonora, the priority is to improve and extend water-supply services; as of 2007, 13% of residents in the urban area of Nogales did not have access to piped water.[2] Sonora also wants to ensure that its burgeoning industrial sector continues to have its water needs met. Thus the focus is on transporting water from the aquifer to the population through infrastructure development. The potential forums for interaction over the aquifer include managing the timing, volume and location of groundwater abstractions, transfer of water across the border (likely from Arizona to Mexico) to mitigate the geographic impacts of pumping, and conducting artificial recharge of the aquifer.[3]

Views differ on water availability and impacts of use

From conversations with water managers on each side of the border and observation of water-planning meetings it is evident that perspectives on water availability and the impacts of pumping differ. Within Arizona, it is widely commented that groundwater pumping in Mexico adversely impacts both water availability and stream flow in Arizona. In 1995, an Arizona Department of Water Resources (ADWR) evaluation of future Mexico well-field expansion reported: "Increased pumpage of the Mexican well fields on the Santa Cruz River will have a detrimental effect on the ability of wells on the US side of the border to obtain water" (ADWR 1995a, p. 1). The same report suggested that increased pumping in Mexico could result in future supply shortages and damage to the riparian ecosystem, including habitat for several endangered species. Interviews[4] with large water-rights holders, developers and environmentalists indicate that they concur with this negative assessment. They expressed concern about the future, about the rapidly increasing demands for water within Mexico and the impact that meeting those demands could have on their water supply and ecosystems. As one interviewee describes the situation: "We've got to come to some sort of agreement with Mexico, the SCAMA cannot go on a lot longer with the dark cloud of what is going to happen hanging over our heads" (10 October 2007).

Water specialists in Arizona also acknowledge uncertainty in the conceptual model[5] of the aquifer. One interviewee, widely known to be an expert on the hydrogeology of the Santa Cruz, explained that the role of fractures in the bottom layer of the aquifer (the Nogales Formation) in conveying water was unknown, and could greatly influence estimates of underflow across the border. Moreover, although (observed) declines in the summer base flow at the Nogales stream gauge (Shamir *et al*. 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, pers. comm. 28 April 2007). Despite the general belief in the negative impact of pumping in Mexico, the complexity of the aquifer is well recognized in Arizona.

Water managers in Mexico express a different perspective: they assert that additional water can be abstracted from the aquifer and this abstraction will have minimal impact on the United States. Although residents on the Sonora side of the border experience water shortages,[6] water managers explain this not as a result of insufficient water but rather of insufficient funding for the construction and repair of conveyance infrastructure (OOMAPAS[7], pers. comm., 14 July 2005, 21 and 22 September 2007). The view that there is additional water available for withdrawal is supported by a study of the aquifer by the Mexican National Water Commission (Comisión Nacional de Agua, hereafter CONAGUA), which determined that current withdraws are less than annual average recharge (CONAGUA, n.d.). Overall, Mexican officials believe that the cross-border effect of their water use, if any, is minimal. Interviewees stated they expect no significant impact on Arizona because the aquifer is shallow, has a high conductivity and the Santa Cruz River is (and remains) a gaining stream. These factors imply that there may be physical limits to the potential impact of pumping across the border, but they do not rule out negative cross-border impacts of increased groundwater use.

The differing perspectives each country holds regarding the availability of groundwater and the impacts of its use could stem, in part, from its water-management priorities and its national self-interests. At the same time, these divergent perspectives are a result of (and subsequently bolstered by) incomplete understandings of the hydrologic processes combined with ambiguity regarding the concept of safe or sustainable yield. As is discussed below, the determination of safe or sustainable yield has been a topic of much debate by hydrogeologists (Bredehoeft 1997, Zhou 2009). Consequently, safe or sustainable yield is itself subject to interpretation via the lens of each country's water values and self-interest.

Data sparseness allows for divergent perspectives

In the Santa Cruz, there is insufficient empirical data to characterize the hydrogeologic properties of the aquifer and to describe flow processes. The lack of data sharing across the border augments this uncertainty. Even were information sharing to be the norm, the frequency and timing of measurements (piezometric data, abstractions) on each side of the border are uncoordinated, so using that information would be challenging. As result of sparse data (and the subjectivity of its interpretation), the conceptual models of the aquifer that were developed independently by each country contain gaps and do not match.

In the conceptual model developed by Arizona, 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). A paucity of measurements, missing or "ambiguous" (Erwin 2007, p. 84) drilling logs and insufficient testing mean they have no information on how water levels vary between the hydrogeologic layers of the aquifer, and limited knowledge of the thicknesses and extents of the three hydrogeologic units (Erwin 2007, Nelson 2007). Recharge and evapotranspiration values are uncertain on account of scarce and unreliable pumping data (Nelson 2007), and mountain-front recharge processes are similarly uncertain (Wilson and Guan 2004).

The conceptual model developed for the Mexican side of the border is fraught with even more gaps, as data is extremely limited; see Table 1 below for a summary of those gaps. There is little historical data on piezometric head, flux into and out of the aquifer, or tributaries and stream flow. The only data on water levels is from three well censuses (which were taken several years apart and during different seasons: November 1989, December 1997 and August 2002) and from measurements of water levels in seven of the wells operated by OOMAPAS in May and June 2005.[8] Measurements of flux between the river and the aquifer do not exist; the only stream gauge on the Mexican side of the border was damaged by flooding in 1974, repaired in 2000, and destroyed shortly after by vandals (Comisión Internacional de Límites y Aguas (CILA), pers. comm. 2 October 2007). Historical groundwater abstraction information is limited to estimates from the well census for 1997.[9] Data on well construction also does not exist (see Milman [2009, ch. 5]) and hydrogeologic data on aquifer properties and geometry is similarly sparse (SeismoControl 1995, SeismoControl 1996, Milman 2009).[10]

Not only are there gaps in the conceptual models developed within each side of the border, but those models also differ dramatically. Figure 2 shows the conceptualization of the aquifer at the international boundary developed by ADWR (Erwin 2007) for the US side of the border, and the model developed by a sub-contractor for CONAGUA for the Mexican side of the border. Both countries agree that the aquifer is made up of three hydrogeologic layers, yet the conceptualization in the Arizona model is of shallower, less conductive layers whereas the Mexican model depicts a deeper aquifer with greater conductivity. No hydrogeologic tests have been conducted at this point, so the conceptualization is based on interpolation of data by each country. In addition to differences in transmissivity,[11] the model developed for the Mexican side of the border estimates a recharge rate equivalent to 19% of annual average precipitation, while the model for Arizona estimates a recharge closer to 4% (SeismoControl 1996, Milman 2009).

In groundwater-simulation modelling, conductivity parameters are most frequently calibrated to account for uncertainties arising from heterogeneity in the soil and interpolation of aquifer layer thicknesses. Given equifinality,[12] it is not unusual that the models have differing depths and conductivities; what is unusual is in this case is the magnitude of these differences. The aquifer as conceptualized in the Mexican model is nearly twice the thickness of that in the ADWR model and contains a higher conductivity. The Mexican groundwater-simulation model also assumes the aquifer is in steady-state equilibrium, whereas the ADWR simulation model is a transient model. The conceptualization from the Mexican side suggests an aquifer through which a larger quantity of water can flow more easily, reflecting the perspective of water managers that water availability is not the problem.

Table 1. Epistemic uncertainty: gaps in the conceptual model of the Santa Cruz Aquifer for the Sonora side of the border.

Aquifer system property	Uncertainties in the conceptual model
Estimates of underflow at system boundaries (into and out of the aquifer)	Estimates only exist for the top layer of the aquifer at the northern model boundary (international border). 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. No information exists regarding layer thicknesses or groundwater gradients for the southern model boundary.
Inter-connections between aquifer layers	Limited piezometric head observations exist from which to determine the presence (and direction) of vertical flow between the layers. Pumping tests do not extend to the older alluvium or the Nogales formation. Reports and models are incongruent in their characterization of the lower layers of the aquifer as unconfined or confined. Studies indicate possible fractures within the Nogales formation. The Santa Barbara well field was drilled on a fault, but this fault and other potential faults are not included in the conceptual model.
Streams and stream–aquifer interaction	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. No measurements of tributaries exist, nor is it clear if any are perennial.
System geometry	Cross-sections only exist for the western portion of the aquifer and do not include the boundaries of the region to be modelled. Microbasins are known to exist in the region yet may not be accurately depicted due to the limited cross-sectional data available.
Historical water levels and fluxes	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. The 2002 water-level observations occurred in the middle of the summer monsoon season, and due to seasonal variation in the aquifer, comparing those with the 1989 or 1997 values would provide little information.
Historical abstraction rates	Data reports listing historical abstraction rates are inconsistent.
Recharge mechanisms and quantities	Studies of recharge in the arid US southwest suggest mountain-front recharge may be the dominant recharge mechanisms in the region. 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. Conceptual estimates of tributary recharge do not exist, nor is there sufficient data on tributaries and flow to develop such estimates. The lack of estimates for underflow into and out of the older alluvium and Nogales formation, combined with unknown historical pumping rates and tributary flows, makes it difficult to estimate recharge inversely though a water-balance calculation.

Note: See Milman (2009, chapter 5) for a complete analysis. Data from: Erwin (2007); SeismoControl (1995, 1996); Padilla (2005); CONAGUA (2009, nd); Shamir *et al.* (2005); and personal communications including raw data from CONAGUA, OOMAPAS, ADWR and local geologists.

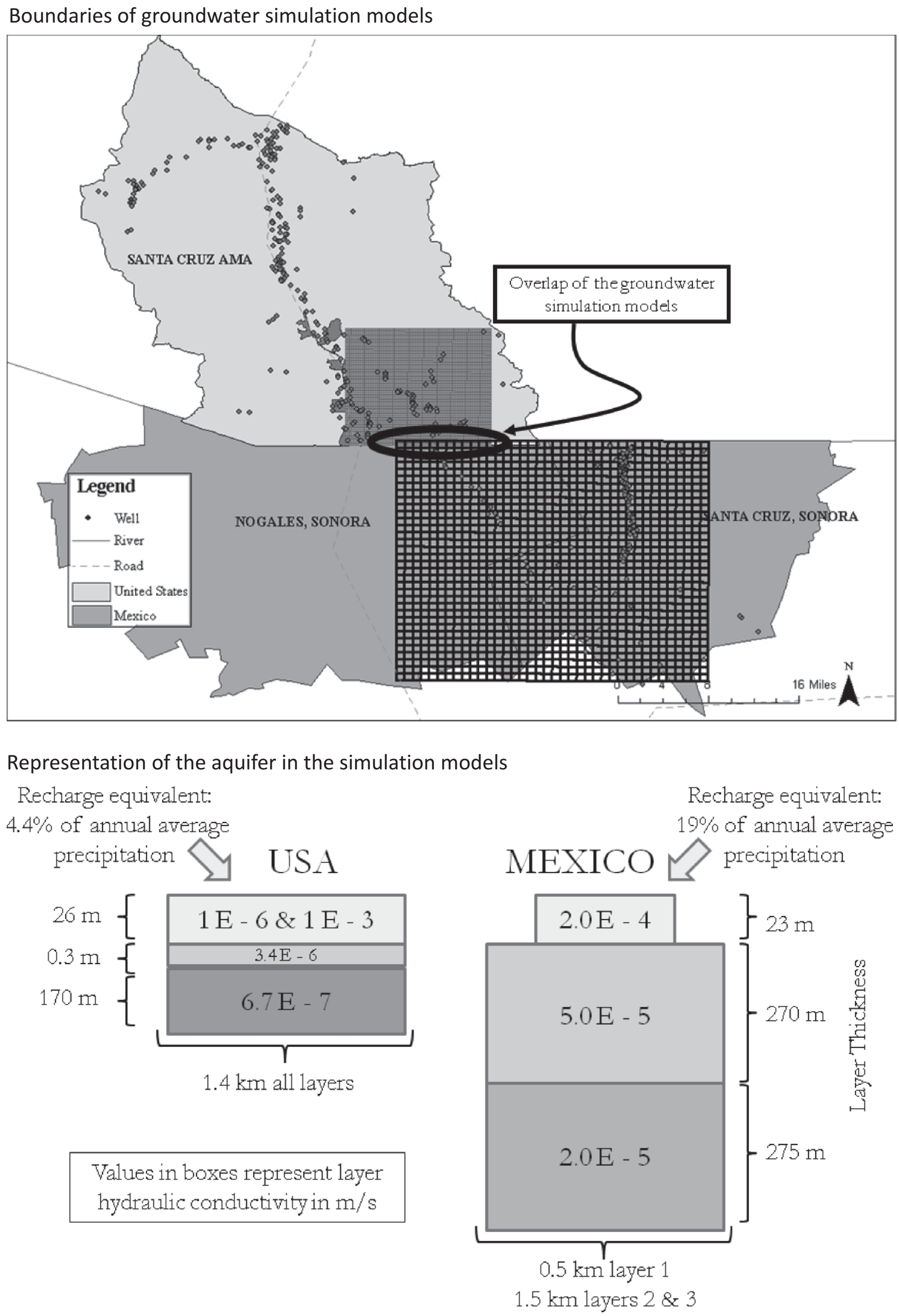

Figure 2. Extent and details of the groundwater simulation models developed for each side of the border.

Water management activities are significantly value-driven

Compounding the effects of divergent conceptual models, uncertainty also stems from ambiguity in definitions of "safe" yield. One common conception of safe yield is as a quantity determined by natural recharge; this definition is premised on the depletion of storage from any pumping greater than recharge. A second common perspective is that the amount of groundwater available depends not on natural recharge, but rather on capture (Bredehoeft 2002). This definition accounts for the fact that an aquifer contains multiple equilibrium states because changes in groundwater gradients induce water to flow into the aquifer. It also considers that stream depletion may be considered an acceptable way to increase water availability, as, in some environments, storage of stream water in the aquifer will reduce evaporative losses. Yet even pumping at rates less than (natural and induced) recharge can lead to declining water levels, depletion of stream flow and ecosystem deterioration (Zhou 2009). Consequently, the definition of "sustainable" (rather than "safe") yield considers the response of the aquifer to pumping and the effects of this response on the environment and society (Kalf and Woolley 2005, Zhou 2009).

In the Santa Cruz Aquifer, the water values held by each country influence the definition of "safe" yield it has adopted and consequently, the management activities it undertakes. Arizona's culture of water management centres on the use of mathematical models for decision making to protect growth and the environment, as well as existing water users. Priorities include protecting the vibrant riparian corridor, protecting the habitat of several endangered species,[13] preserving the character of the community, and requiring assured water supplies before further development is permitted. Thus in Arizona, safe yield includes the requirement that water tables cannot fall below a specified level, so that pumping costs are contained and (in theory, at least) the ecosystem is protected. As a result, the SCAMA determines water availability by considering both water balances and localized declines in water-table levels, defined as drawdown that exceeds one standard deviation of historically measured levels (ADWR 1995b, Corkhill 2006, ADWR 2007).

In Mexico, the emphasis of water management is on addressing unmet human needs (as the majority of the population does not have 24-hour water service) and prioritizing future growth and development. This prioritization was expressed by one official who 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" (meeting for the Transboundary Aquifer Assessment Program, 28 January 2008). In addition, the Mexican Constitution declares water to be the "patrimony of the Mexican people" (Farias 1993, Instituto Mexicano de Technología del Agva (IMTA), pers. comm. 14 June 2006), a sentiment regularly echoed by interviewees. The water located in Mexico, they argued, should be used to best benefit the Mexican population, and should not be relinquished to the United States. These values are reflected in the Mexican calculation of water availability, which is based on an average annual water-balance analysis and does not consider annual variation in water-table levels (CONAGUA, n.d.), as well as by the recommendation to capture for human use the water currently being "wasted" as evapotranspiration by riparian vegetation (SeismoControl 1996).

Both these operational definitions for yield base the amount of water available for withdrawal on an estimate of renewable supplies and neither is designed to lead to groundwater mining. Yet they result in divergent perspectives on availability. Moreover, they inform the management activities each country undertakes. In line with its values, ADWR is using groundwater simulation models it developed in 2007 to conduct stochastic simulations to improve their ability to regulate water level drawdown (ADWR, pers. comm., 30 October 2007). It is also coordinating with researchers from other institutions to investigate stream-aquifer interactions,[14] causes of tree die-off in the region[15] and the feasibility of conducting aquifer recharge and storage.[16] In addition, preliminary discussions are under way on comprehensive water-management planning, including formation of an entity with the legal authority to lease store or sell water across the border, to secure supplies and protect the environment (water lawyers, pers. comm. 17 and 18 October 2007, ADWR, pers. comm. October 2007).

Water-management activities in Mexico stem from its values that unmet human needs take priority. Efforts to improve water-supply services include the construction of phase two of the "Acuaferico" project,[17] which aims to upgrade and extend water-system services via the drilling of new wells, and construction of new pumping stations, water tanks and distribution lines. Smaller projects are also in progress, which will connect several neighbourhoods to the citywide piped-water network. Increases in water abstraction are being monitored and CONAGUA has been active in registering and regulating concessions of water, especially those providing water for delivery by tanker trucks. On the Mexican side of the border, the agencies are also working to install water meters, repair leaks, rehabilitate wells and educate the public regarding water conservation.

The different definitions of sustainable yield and the culture of water held by each country are reflected in their transboundary plans and practices. On the Mexican side of the border, the plan is to increase aquifer pumping. In contrast with Arizona's fears, no detrimental cross-border effects are expected. This difference arises in part because Mexico prioritizes addressing unmet needs, and in part because the conceptual model of the aquifer held by the Mexican water managers suggests a greater availability of water than the model used on the Arizona side. The difference is not unrecognized, as during an interview, an Arizona government official quoted a Mexican official as having said: "You [Arizona] want water for your fish, but here in Mexico we have people without water to drink. God will punish you" (2 June 2006). Whatever the accuracy of this recounting, the interpretation of it by the Arizona official suggests that the different culture of water held by each country is understood across the border. From the perspective of Mexico, an agreement that allows Arizona to improve water availability for fish, but that does not improve water availability for the Mexican population, would be unthinkable.[18]

The US Congress-funded Transboundary Aquifer Assessment Program (TAAP) has sparked some movement towards collaboration in the form of data collection and sharing. The Santa Cruz Aquifer is one of four priority aquifers listed in the TAAP (United States Senate 2006). The programme does not represent a formal agreement on transboundary groundwater management; rather it is a mechanism for funding joint investigations and has led the US and Mexico to reach an agreement on joint data collection. The hope is that the programme may be instrumental both in reducing framing uncertainties and in the formation of cross-border networks and social capital, hypothesized to be key components of cooperation (Young 1989, Blatter and Ingram 2001). The effectiveness of the TAAP has yet to be determined, as even three years after its approval it has progressed little due to funding constraints.[19]

Conclusions and implications

We have argued that the sparseness of data on the Santa Cruz Aquifer combines with the subjectivity of hydrologic interpretation to allow each side of the border to develop divergent models of the aquifer. Differences in the analytic models and analytic frames held by each country allow for each country's water-management values to come to the fore: in the absence of a consensus on hydrologic processes and definitions of safe yield, prioritization of water use and sovereignty concerns drive and legitimize unilateral decisions. At present the water-management activities in both countries are a continuation of the status quo; within each country activities are proceeding in line with that country's management paradigms.

In demonstrating how uncertainty bolsters the influence of within-country political factors, our findings problematize the concepts of "equitable and reasonable", "no harm" and "benefit sharing". Each of those concepts is a routine recommendation in the transboundary literature. Each relies upon a common conception across the border that then forms the basis on which the impacts of water-management activities are evaluated. Yet uncertainty in the physical processes allows for multiple models of the system, and thus supports multiple frames or perspectives. Brugnach *et al.* (2008) suggest that recognition of all three different types of uncertainty – imperfect knowledge of the system, inherent variability and multiple frames – are necessary for problem resolution. However, the hydrological literature focuses on better data and better models without explicit recognition of framing differences, while the management literature acknowledges the uncertainties but usually excludes them from their formal analyses.

There is reason to believe that our findings are representative of transboundary groundwater management beyond the Santa Cruz Aquifer. Due to the large quantity of data required to determine flow processes and the subjectivity of interpretation of the available information, groundwater availability and the impacts of groundwater use are frequently uncertain (Kalf and Woolley 2005). In many countries, small amounts of data are available, as water levels and water-abstraction rates have not systematically been measured, nor has hydrogeologic testing been undertaken. Moreover, as Waterbury (1997, p. 281) explains, "riparian claims typically combine incommensurables – human survival, economic growth, national security" and often "countries do not share common measures of what constitutes legitimate demand". Such incommensurable ideas of needs, demands and legitimacy would readily lead to divergent frames within which "the" groundwater situation is to be understood and represented.

There are many reasons besides uncertainty for the prevalence of the status quo and the resistance to collaboration over transboundary waters. Jarvis (2010), citing several authors on groundwater management, concludes that politics will often overcome rational management principles. Hamman (2005) suggests that interests vested in the status quo will work to prevent changes to it unless ongoing disputes reach crisis proportions. Drawing on the protracted history of negotiations on the CALFED Bay-Delta Program, Innes and Booher (2010) find that, even when a degree of water collaboration is achieved, collaborative planning always remains in tension with self-interest. Indeed they argue that collaboration can at once challenge parts of the status quo while protecting other aspects of it (Innes and Booher 2010, p. 114). We do not argue, therefore, that less analytic uncertainty alone will lead to common values for water and compatible analytic frames. We do argue that greater uncertainty, by reducing the perceived value of collaboration, will prolong status-quo driven management regimes. Rather than seeking cooperative solutions that maximize joint benefits or commit allocations or flows of water, groundwater collaboration might best begin through efforts designed to reduce the multiple uncertainties that exist. Where uncertainty cannot be minimized, low-regret steps that allow for adaptation as water-management objectives are re-defined, and as knowledge of hydrologic processes, costs and benefits increases, may serve to open up a pathway for cooperation when (and if) its need becomes clear.

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Notes

1. For example, Drieschova *et al.* (2011) categorize ex-post uncertainties in international surface-water treaties as either exogenous (related to [1] variability in water quality and quantity, [2] resource vulnerability, [3] internal politics, [4] external politics, and [5] market fluctuations) or endogenous (related to the treaty itself including [1] how the treaty will be implemented, [2] how valid data collected is, and [3] how the treaty will be financed). These uncertainties relate to treaty effectiveness. The impact of ex-ante uncertainty has been more frequently analyzed for non-water related environmental agreements (for example, Young [1994], Helm [1998], Kolstad [2005]).
2. In the Municipality of Nogales, Sonora, 5% of residents have water service 24 hours per day, 60% of residents receive water service 12 hours per day, 30% of residents receive water service four to five hours per day, and the remaining 5% of residents receive water every other day (OOMAPAS, pers. comm. 4 October 2007).
3. See Milman (2009, chapter 2) for more detail.
4. All interviews for this research were conducted by the lead author in Spanish or English.
5. The conceptual model of an aquifer is the schematic representation used to describe the key features – hydrogeologic, hydrologic and human-ecosystem interactions – of the groundwater system.
6. Water shortages are experienced through intermittent water service; see footnote above.
7. The Organismo Operador Municipal de Agua Potable Acantarillado y Saneamiento (OOMAPAS) is the municipally run water utility of Nogales Sonora, and the primary abstractor of water from the Santa Cruz Aquifer on the Mexican Side of the border.
8. The University of Sonora also measured water levels in 11 wells quarterly between 2000 and 2003, however much of the time all but a few of those wells were dry (Padilla 2005).
9. Seismocontrol (1996) reports a total pumping of 28.4 Mm^3/year for 1997 and the CONAGUA well census reports a total of 9.77 Mm^3/yr. The CONAGUA "Disponibilidad" document reports 19.6 Mm^3/yr for 1996. (See Milman [2009, table 6.4]).
10. Since this research was completed, additional cross-sections have been developed (CONAGUA 2009).
11. Transmissivity is a measure of the rate at which water moves through an aquifer and is equal to conductivity multiplied by depth.
12. Beven (1993) uses the term equifinality to describe how, given the large number of parameters and the complexity of flow within groundwater simulation modelling, the same output, that is, the same model results, can be obtained from different combinations of model parameters and even from different model structures.
13. These include the gila top minnow, the southwest fly catcher and the yellow cuckoo (United States Fish and Wildlife Service, pers. comm., 12 October 2007).
14. See http://www.uawater.arizona.edu/grants/grants07.html.
15. See http://www.uawater.arizona.edu/documents/Fellowship200607/McCoy.pdf.
16. See http://www.usbr.gov/lc/phoenix/programs/progdescon.html.
17. See http://www.nadbank.org/pdfs/state_projects/FS%20Nogales%20SON%20W.pdf. for information on Phase I.
18. An anonymous reviewer for this journal suggested that these diverging priorities might create a suitable opportunity for side payments. Side payments are commonly considered mechanisms for resolving disagreements, especially in game-theoretic solutions. However, in order for side-payments to be effected, both parties must view the proposed trade-off as acceptable. Where ambiguities mean there are no common perceptions of the system under consideration, and where values are incommensurate, side payments may not be practical. Within Arizona there has been discussion of a payment to Mexico that would allow for artificial recharge of the aquifer; however, as this would entail Mexico rescinding sovereignty over a portion of its water

resources, such a solution has not been able to move forward. See Milman (2009, chapter 3) for details.

19. Although Senate Bill 214 authorized US$50 million for the TAAP during the years 2007 to 2010, only US$500,000 was allocated.

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