# Use-inspired Science for Groundwater Governance: Science Production, Transfer and Use in Southern Arizona

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## Executive Summary


### *Problem statement*

Groundwater is a key component of sustainable water supplies for Arizona's residents and growing economy. In southern Arizona, groundwater is nearly the sole water source in the Santa Cruz Active Management Area (SCAMA). Here, groundwater is stored in shallow aquifers that are vulnerable to fluctuations in streamflow and precipitation. To ensure effective management of groundwater supplies in SCAMA, both adequate scientific information and science-based management are essential. *This project investigates how scientific information for groundwater is produced, transferred and used among stakeholders and considers how stakeholders' perceptions of groundwater, surface water and climate affect how they use scientific information to guide policy, management and practice.* By better understanding the science-policy interface for groundwater, the project contributes to advancing effective governance of this "hidden" but critical resource for our planet's future.

### *Key findings*

This scoping project produced findings regarding (1) the status of groundwater science and policy, (2) barriers in the science-policy process, and (3) persistent information needs in SCAMA. This project revealed that processes for collection, transfer and use of groundwater science in management are generally positive and successful in SCAMA. The key contributing factors to this success are:

- Groundwater data are centrally-compiled by Arizona Department of Water Resources (ADWR) and made publicly-available.
- There is a consistently high level of stakeholder engagement. Multiple organizations that host regional meetings, providing frequent and regular opportunities for networking, engagement and communication of scientific information.
- ADWR promotes stakeholder involvement and offers structured mechanisms for acquiring input, such as the Groundwater Users Advisory Committee.
- Tight social networks have developed over time, although this has been strained by agency downsizing and a reduced number of ADWR staff in local areas since 2010.
- In addition to ADWR, other organizations (e.g. Water Resources Research Center [WRRC], University of Arizona) provide convening, research and communication services, aiding the transfer and translation of scientific information among stakeholders and the public.
- The University of Arizona and WRRC are able to work beyond of the scope of state and local government agencies, complementing their efforts, for example, by engaging in cross-border collaboration with Mexico.
- Science and management both acknowledge the unique physical system and are responsive—they include site-specific research and management strategies.
- Legislative regulations govern groundwater use in SCAMA, requiring monitoring and reporting of pumping, which has provided a record of groundwater observations over time. Regulations also promote scientific research to support the achievement of defined management goals.

Barriers in the science-policy process in SCAMA are not technical, but instead are related to funding, resources, capacity and staffing. While there is interest shared among stakeholders, local officials do not necessarily have the staff and capacity to implement innovative and complex management regimes. Lack of capacity for implementation of new management schemes is compounded by the ongoing rulemaking moratorium (enacted by the Governor's Office in 2009) that restricts new regulations in the state in order to not interfere with growth of private industry.

Scientific data needs identified are primarily related to the need to better understand the dynamics of the connections among groundwater, surface water and climate variability. This includes improved measurement of stream-aquifer interactions, better monitoring of groundwater-dependent riparian ecosystems and a better understanding of aquifer recharge mechanisms. Specific groundwater data needs include vertical-interval samples and aquifer tests – both of which would provide additional information to better understanding groundwater flow in underground aquifers.

*Project design*

To ensure that this research was use-inspired, the research began with joint problem framing with stakeholders in SCAMA. By speaking with stakeholders and observing regional stakeholder meetings, the need to better understand the transfer of information and how perceptions affect the use of such information was revealed. This need is tied to the broader societal challenge of groundwater governance, a research field which remains nascent. Stakeholder analysis was conducted to hone a list of stakeholders most relevant to this research and identify their role, perspective and responsibilities to best answer the research question. Instead of working with only one stakeholder or user, this project engaged multiple stakeholders to address a common need. This project combined participant observation, semi-structured interviews and document review—I participated in five regional meetings and spoke with 12 individuals from multiple stakeholder-organizations.

*Next steps*

Based on stakeholders' suggestions for how to make results of this research usable for them, I will disseminate the results in a one-page summary handout and via presentations at a regional conference (either AZ Water or Santa Cruz Research Days) in 2019. Stakeholders emphasized the need for a succinct summary of research results written for a lay-audience.

Further research will include dissemination of an online survey regarding groundwater information collection, transfer and use on a state-wide basis to compare science-policy processes for groundwater across different U.S. states. Additionally, the elements of success identified for SCAMA could be used to develop a heuristic for science-policy processes for groundwater and used to evaluate the development of science and policy in other basins in Arizona. It would be interesting to apply such a framework to non-AMA areas experiencing groundwater declines. While non-AMA areas are not regulated by the Groundwater Code, using the elements identified in SCAMA could help guide the development of a new regulation approach for these areas. For example, in the Willcox basin in southeastern Arizona, many wells have gone dry in recent years due to long-term agricultural withdrawals. In 2015, local residents proposed establishing a new type of groundwater conservation area to address groundwater declines. The elements of success identified in SCAMA could help guide development of criteria and management structure for such a conservation area.

*In sum*

Groundwater comprises 97% of globally-available freshwater. As climate change and variability make surface water sources less reliable, groundwater supplies will become increasingly critical for human sustainability, especially in arid regions. The need for effective science-based management of these precious resources is imminent. This project contributes to better understanding science-policy processes for groundwater and can inform similar studies in other arid regions.

## Introduction

Groundwater governance is a complex challenge for the 21st century. In arid regions such as southern Arizona, surface water is limited so water users rely on groundwater. Effective groundwater governance requires legal and policy frameworks and sound science. However, integration of groundwater science in policy is challenging due to the difficulty of monitoring this "hidden" resource, the uncertainty in and highly technical nature of groundwater models, and the local nature of aquifers.

While sufficient scientific information is key to effective groundwater management, it is not the presence of information alone that improves policy (Rice et al. 2009). It is equally important to understand how science is transferred, interpreted and used. Yet, differences in management goals, problem framing, institutional structures and cultural norms complicate the transparent communication and transfer of science (Weichselgartner and Kasperson 2010; Reed et al. 2014).

This project examines the role of science in groundwater aquifer management. More specifically, this project seeks to understand: (1) how groundwater information is produced, transferred and used by stakeholders; (2) how stakeholders' perceptions and problem framings influence their use of information; and, (3) what barriers exist for the use of scientific information in groundwater management. The research questions, developed in coordination with regional stakeholders, address the broad societal need for enhanced water security in arid regions, and more specifically, address stakeholders' need for improved coordination and better alignment among science, practice and policy. Because groundwater aquifers are typically limited in geographic extent, this study uses the case study of the Upper Santa Cruz aquifer in southern Arizona and then projects how findings could be applied to other aquifer systems in Arizona and beyond.

## Background

### *Groundwater policy and management*

Groundwater is difficult and costly to observe and monitor. Compared to surface water, groundwater resources are more local and dispersed, and each aquifer can have different physical properties affecting the quality and accessibility of the resource (Puri and Aureli, 2005). While groundwater is commonly privately developed (Milman and Scott, 2010), yet is subject to the management challenges of a common-pool resource. It is difficult to exclude new users and overuse of the resource can ultimately reduce the amount available for others (Ostrom et al., 1999). Groundwater systems are often subject to delayed impacts or irreversible effects (Dietz et al, 2003)—for example, the cumulative effect of on-going overuse or pollution may be difficult to detect. The availability of adequate information about the physical nature of groundwater resource systems is key to successful common-pool resource management (Ostrom et al., 1999).

Researchers agree that groundwater policy and management must be informed by a sound scientific understanding of groundwater systems, even more so in transboundary contexts (Eckstein and Eckstein 2005; Nanni and Foster 2005). To be ensure sustainable and resilient resource availability, hydrogeologists argue that groundwater management approaches must address groundwater storage, yield, recharge and pollution prevention (Foster and MacDonald 2014: 1490).

### *Use-inspired science*

Use-inspired science produces results that both improve scientific understanding and that are of direct use to society (Stokes, 1997). This suggests that use-inspired research should be developed with societal needs in mind and that stakeholders should easily be able to utilize the information produced and disseminated to them. Thus, both the nature of the science produced and the way in which the information is delivered to stakeholders are important features of the research design.

“Usable science” is characterized by being easy to understand, delivered in a timely fashion, being accessible to users based on their capacities and directly addresses user needs (Dilling and Lemos, 2011). Cash and colleagues (2002) emphasize the need for science to be salient, or relevant the user, legitimate, or produced fairly, and credible, or from reputable sources. Lemos and colleagues (2012) describe that how new knowledge relates to existing information already used by decision-makers is also key in determining its functional use.

Information is transferred among stakeholders via both “push” and “pull” modalities (Dilling and Lemos, 2011)—in other words, information is disseminated to users by producers and, conversely, requested by users from producers. Information flow can be enhanced by having publicly-accessible information, and supportive institutional structures and social networks through which information can be transferred. For instance, information flow can occur differently at various agencies and governance levels (Timmerman and Langaass, 2005). However, the exchange of information, and more broadly, of knowledge, also involves how information is translated across disciplines and institutions and transformed through the filter of social context (Reed et al., 2014). To effectively exchange knowledge, scientists need to build trust through on-going stakeholder engagement and be attentive to the needs and priorities of stakeholders.

However, science is only one of many inputs in a decision-making process (e.g., Armitage et al., 2015). Other factors affecting the decision-process include politics, institutional norms, culture and stakeholder mindframes (Timmerman and Langaass, 2005). Timmerman and Langaass (p. 179) define a mindframe as “the window through which people view the world…an assembly of our cultural background, professional training, character, experience, expertise, roles and responsibilities”. They go on to describe that decisions are made using a combination of rational, value-based and socio-cultural frames (ibid.)

*Site description*

In 1994, the Santa Cruz Active Management Area (AMA) was designated as a separate management area, having previously been part of the Tucson AMA (Figure 1). The legislative distinction was made based on the unique physical characteristics of aquifers in this area and the site-specific challenges of its cross-border nature (ADWR, 1999). The aquifer system consists primarily of shallow alluvial units that underlie the Santa Cruz River, which in this area flows north from Sonora, Mexico across the international border into Arizona and eventually to Tucson (Figure 1). These aquifer units are directly connected with surface water and are recharged by episodic streamflow events driven by monsoon patterns. The region is part of the Sonoran Desert – a semi-arid region receiving between 14 and 36 inches of rainfall annually (ADWR, 2010). Other, deeper units of basin-fill sediments exist in portions of the basin, e.g., the Potrero well field, and are not hydrologically-connected with surface water.

Where shallow aquifers underlie the Santa Cruz River, they provide critical water supplies for cottonwoods and other riparian vegetation of groundwater-dependent ecosystems. Downstream of the Nogales International Wastewater Treatment Plant, located approximately 10 miles north of the international border, the riparian ecosystem relies on the treated wastewater released which also contributes to shallow aquifer recharge.

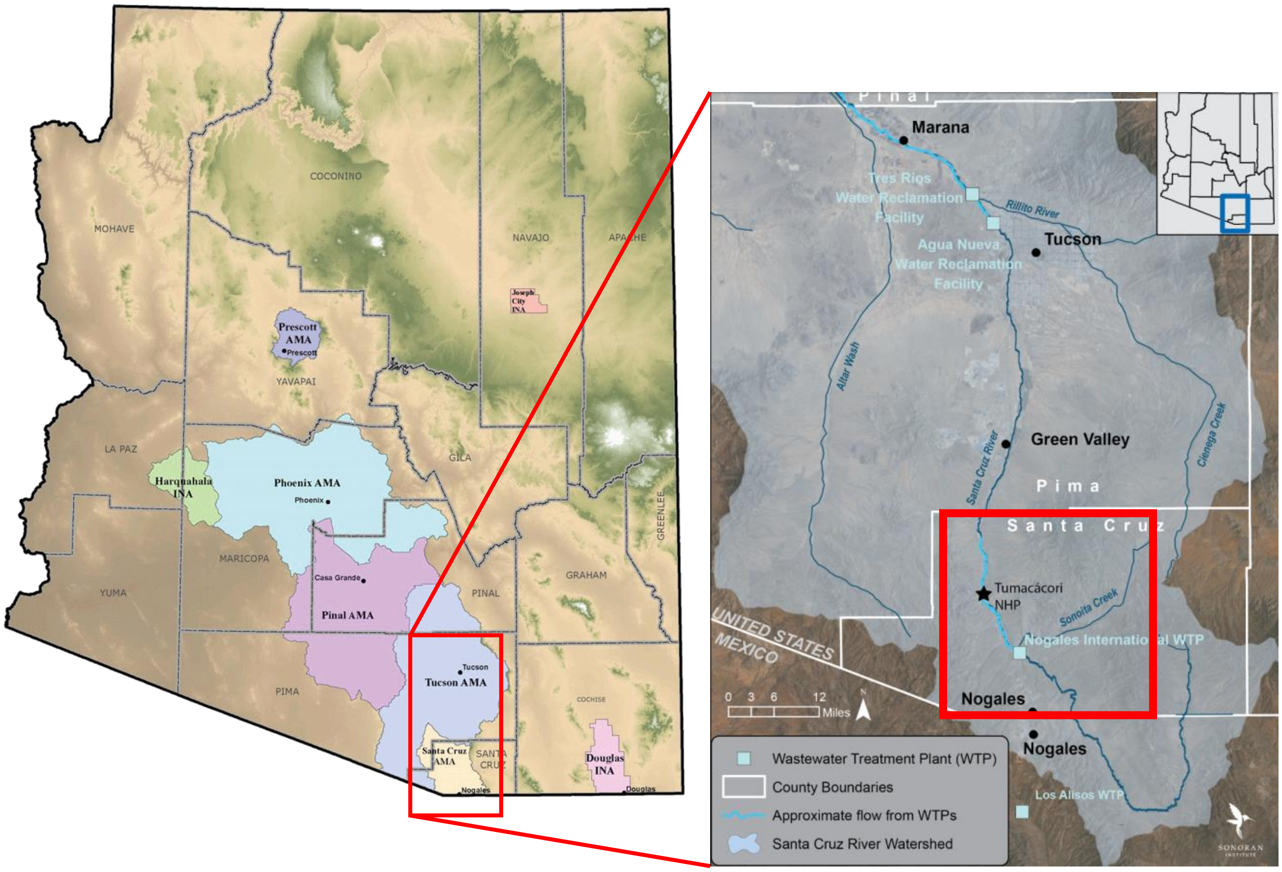


**Figure 1: Location of the Arizona's Active Management Areas on left (image from ADWR). The Santa Cruz River on right with study area highlighted in red box (image from Sonoran Institute).**

*Science-based management*

The management goals for SCAMA are two-fold: (1) to maintain safe yield and (2) to prevent long-term groundwater level declines throughout the aquifer (A.R.S. §45-561). These goals are rooted in a scientific understanding. The goal of "safe yield" is defined as maintaining "a long-term balance between the annual amount of groundwater withdrawn in an active management area and the annual amount of natural and artificial recharge in the active management area" (A.R.S. §45-561). Thus, it is based on an understanding that groundwater is not an unlimited resource and depends on recharge in order to maintain sufficient volumes. "Safe yield" is also a useful management goal because it is easy to understand and quantifiable. Both goals rely on groundwater observation and monitoring for their implementation (Table 1). According, the production, transfer and use of scientific information is a key component of groundwater management in Arizona's Active Management Areas.

**Table 1: Management goals for the SCAMA and the scientific components that contribute to achieving and maintaining them.**

| *Management goal:* | Safe yield | Prevent long-term water level declines |
|---|---|---|
| *Necessary scientific elements:* | Natural recharge<br>Incidental and artificial recharge<br>Outflows<br>Variability<br>Aquifer storage<br>Water withdrawals | Historic water levels<br>Aquifer response to stress<br>Aquifer storage |

For AMAs, the Groundwater Code restricts new agricultural uses, limits groundwater withdrawals, implements conservation requirements, requires new developments to ensure dependable supplies (e.g., Assured Water Supply program) and requires monitoring and reporting of withdrawals (ADWR, 1999:1-2). Due to the shallow nature of groundwater in SCAMA, the legislature specifies an appropriate approach for "coordinated management of surface water rights and groundwater rights" (ADWR, 1999: 1-2)—this approach is unique to the Santa Cruz AMA. Management plans also rely on many science-based management tools, such as water budgeting, recharge estimation, minimum well spacings and the Assured Water Supply requirement.

## Methods

This project combined multiple methods including participant observation, semi-structured interviews and document review. Participant observation took place at regional workshops and stakeholder meetings, including the Southeast Arizona Citizen's Forum hosted by the International Boundary and Water Commission (n=2), the Santa Cruz Research Days workshop hosted by the Sonoran Institute (n=2), and the Santa Cruz AMA Groundwater Users Advisory Committee meeting (n=1). Between 30 and 60 people attended each meeting of the Southeast Arizona Citizen's Forum. Minutes and presentations were accessed for other quarterly meetings not attended (n=3). The 2018 Santa Cruz Research Days workshop involved 15 presentations, 3 panels and more than 100 attendees.

Document review combined with participant observation informed the stakeholder identification. At least one stakeholder in each agency/category was contacted to participate in a semi-structured interview. A total of 12 individuals were interviewed representing seven organizations including: state government, county government, NGOs, university, and private companies. Unfortunately, I was unable to gain access to speak with  a representative from local water utilities at this time.

Data collection was primarily conducted between January 2018 – January 2019, with the exception of background research and attendance at two meetings in Fall 2017.

## Results

### *Stakeholders analysis*

Based on data collected via the above methods, stakeholder analysis was conducted to (1) identify key actors and their roles, and (2) map information flows (Reed et al., 2009; Pohl et al., 2017). Following the method described in Pohl et al. (2017), stakeholders were identified, and then categorized based on their position in the policy cycle and the type of knowledge with which they primarily engage (Table 2). A heuristic of a policy cycle would include four stages: (1) problem framing (identifying and defining the issue), (2) policy development (developing an approach to address the issue), (3) policy implementation (implementing the new approach in practice) and (4) policy evaluation (assessing how well the policies address the issue) (Wuelser et al., 2012 cited in Pohl et al., 2017). Pohl et al. (2017) suggest that stakeholders from government, civil society, the private sector and academia are interacting in all stages of the policy cycle.

Stakeholders were also categorized as either data *producers*, *users* or both. For this study, data *producers* are defined as engaging in producing or compiling basic data (e.g., taking water level measurements) or producing secondary data analysis products (e.g., groundwater flow models). Data *users* are primarily engaged in utilization of existing information, whether for translation into management goals, implementation in management plans or to inform the development of new policies or regulations. Some stakeholders are both producers and users of groundwater information (Table 2).

However, in practice, the roles of actors are overlapping and messy. Many organizations are involved in both science production and use, but in different ways. For example, the U.S. Geological Survey (USGS) is primarily concerned with collection of basic scientific information, such as measuring streamflow or mapping geologic units. The Arizona Department of Water Resources (ADWR) produces basic data (e.g., groundwater level measurements), secondary data (e.g. results of groundwater modeling), compiles data (e.g., annual reports from water users), implements the Groundwater Code's management requirements (e.g., reporting) and makes decisions regarding how the law should be implemented. Utilities collect basic data through water use monitoring; academics and private consultants often utilize existing data to produce secondary analyses, and so forth (Table 2).

**Table 2: Stakeholders in the Upper Santa Cruz aquifer (Arizona) and their roles in science, policy and decision-making.**

| *Relevant Actors* | *Producer/User* | *Data type* | *Primary Position in Policy Cycle* | *Decision-making* |
|---|---|---|---|---|
| City of Nogales | Producer | Basic data | Implementation | Operations |
| Liberty Utilities (formerly Rio Rico) | Producer | Basic data | Implementation | Operations |
| Arizona Department of Water Resources | Both | Basic data, secondary data, compilation, implementation | Implementation, Evaluation | Director makes decisions within the scope of the Groundwater Code |
| Santa Cruz Groundwater Users Advisory Committee | User | | Framing, Development, Evaluation | Recommendations to ADWR Director |
| Santa Cruz County Public Works | User | Basic data | Implementation | Operations |
| University of Arizona | Producer | Basic data, secondary data | Framing, Evaluation | - |
| Water Resources Research Center | Producer | Secondary data, compilation | Framing, Development, Evaluation | - |
| U.S. Geological Survey | Producer | Basic data | Framing | - |
| Sonoran Institute | Both | Basic data, secondary data | Framing, Evaluation | Minor advocacy |
| Friends of the Santa Cruz | Both | Basic data | Framing | Minor advocacy |
| Private consultants | Producer | Basic data, secondary data | Framing | - |

*Information flow*

Data were used to produce maps of information transfer among stakeholders (Figures 2 and 3). The data reveal that the Arizona Department of Water Resources (ADWR) serves as a central compiler of information. Not only does the department receive annual water use reports, which are required by law, from water users and well completion logs from wells drilled within AMAs throughout the state, the department hosts an online database of groundwater well locations and measurements. The Groundwater Site Inventory (GWSI) database includes water level measurements from index wells, automated measurement stations and manual measurement taken during "well sweeps" (e.g., comprehensive sweeps measuring as many groundwater levels as possible in a single AMA, conducted every few years). Much of this data is collected by ADWR staff. It also includes water levels measured by USGS and researchers at the University of Arizona. A separate online database includes water rights and pumping data. The Water Resources Research Center (WRRC) also compiles data from various sources in SCAMA. In collaboration with a private consulting firm, WRRC produced a separate web-based database tool specific to the SCAMA, the Water Resources and Climate Assessment tool (WARCAT), that compiles in real-time water and weather data, including forecasts. Data are compiled from: the U.S. Geological Survey (USGS), the National Oceanic and Atmospheric Administration (NOAA), SCAMA ALERT System, ADWR, the Arizona Department of Environmental Quality (ADEQ), the National Centers of Environmental Prediction (NCEP-NOAA) and the National Weather Service (NWS). This tool makes it possible to evaluate historical climate data and future climate forecasts together with water level data in streams and groundwater within SCAMA.

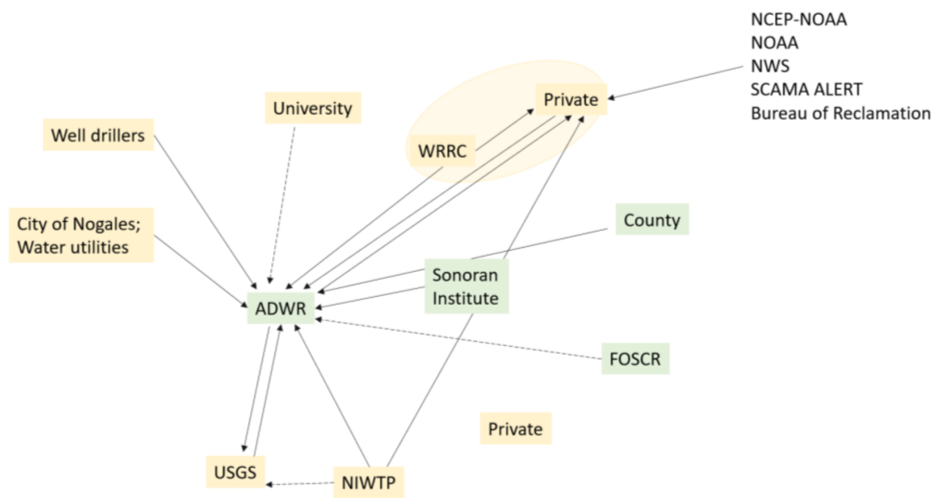


**Figure 2: Diagram of information transfer focusing on to whom organizations actively provide information to (e.g., reporting). ADWR=Arizona Department of Water Resources; USGS=U.S. Geological Survey; NIWTP=Nogales International Wastewater Treatment Plant; WRRC=Water Resources Research Center; FOSCR=Friends of the Santa Cruz River; NCEP= National Centers of Environmental Prediction; NOAA=National Oceanic and Atmospheric Administration; NWS=National Weather Service. Yellow shading denotes organization is both a producer and user of data; green shading denotes a producer (see Table 2).**

The next diagram focuses on where stakeholders access information. This diagram shows how stakeholders in SCAMA access information from a variety of sources—this means they are aware of the many organizations involved in collecting and producing information and that they have a means to access that information, either through web-based databases or by requesting the data directly. Interview data showed that the network of stakeholders in SCAMA is small and most stakeholders know each other and would make direct contact when information was needed from another organization (e.g., they would call or email an individual that they know professionally).

Private companies (e.g., environmental or water consulting firms) access data from state, federal and university-based sources, including the WRRC (based on University of Arizona's campus), but also rely on the data that their clients supply (privately) for individual projects. University of Arizona researchers tend to work closely with collaborators on a project-specific basis. NGOs, such as the Sonoran Institute, are aware of state databases and utilize them, however also, to a lesser extent, produce their own data as needed to answer specific questions. For example, the Sonoran Institute recently worked with a private consultant to collect groundwater levels near the Santa Cruz River to better understand riparian-zone shallow groundwater availability and how this changes seasonally. While they are aware of state and federal data sources, they determined that additional data were needed for this effort. Water utilities, such as the City of Nogales, are aware of state and federal data sources, and also are aware of the WARCAT tool as they were involved in workshops for the development of this tool.[1]

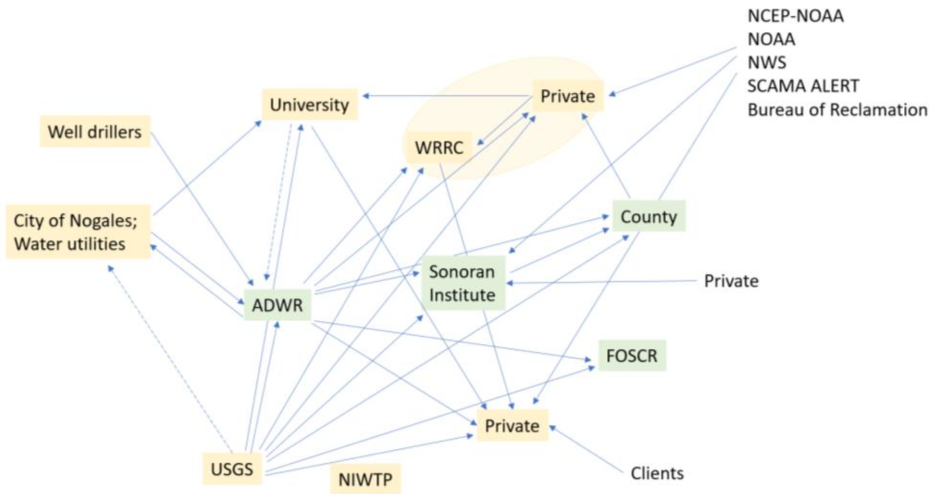


**Figure 3: Diagram of information transfer focusing on how organizations access information (e.g., web-based databases) or request information from other stakeholders. ADWR=Arizona Department of Water Resources; USGS=U.S. Geological Survey; NIWTP=Nogales International Wastewater Treatment Plant; WRRC=Water Resources Research Center; FOSCR=Friends of the Santa Cruz River; NCEP= National Centers of Environmental Prediction; NOAA=National Oceanic and Atmospheric Administration; NWS=National Weather Service. Yellow shading denotes organization is both a producer and user of data; green shading denotes a producer (see Table 2).**

Participant observation at regional meetings and workshops confirmed that the network of stakeholders involved in water, or groundwater, in SCAMA is small and close-knit. Key individuals attended multiple events, and it was clear that these individuals had ongoing professional relationships with other individuals from other organizations and other stakeholder groups. For instance, some had worked together at other agencies in the past or had known one another during graduate school studies. Others had built relationships through regular attendance at stakeholder meetings and workshop. A great benefit for the SCAMA is that there are multiple organizations that host regional meetings, providing frequent and regular opportunities for networking, engagement and communication of scientific information. ADWR hosts regular meetings of the SCAMA Groundwater Users Advisory Committee (GUAC); the International Boundary and Water Commission hosts quarterly meetings of the Southeast Arizona Citizen Forum; the Sonoran Institute hosts a broadly-attended annual research workshop; the WRRC hosts workshops for individual projects. ADWR seems to have a strong commitment to stakeholder engagement, scientific collaboration and public engagement—the Groundwater Users Advisory Committee is a Governor-appointed committee of stakeholders including ranchers and local utility workers who provide recommendations directly to the ADWR Director regarding various decisions such as what rates should be charged for water withdrawals and appropriate conservation measures.

[1] I was unable to connect with City of Nogales representatives for this scoping study, however the relevance of such information is noted.

## Science-Policy Processes

### *Science and policy cycles*

As described above, the goals specified in Arizona's Groundwater Management Act are science-based. The need for groundwater regulation came about after continued observations revealed groundwater level declines in many parts of the state. Following observations of changes in the environmental system, typically additional investigative studies are carried out to better characterize the system and the challenges faced. The cycle of science production for groundwater in Arizona generally includes the following:

1. Identification of a change via groundwater level observation or observation of land-surface changes (e.g., land subsidence).
2. Assess the status of the groundwater resource via a water balance study (e.g. input versus output).
3. Investigative research to further understand the physical system, including geologic studies and hydrogeologic studies to characterize the aquifer extent and intrinsic properties (e.g. hydraulic conductivity).
4. Monitor the resource and its use over a period of time (e.g. establish a period of record with data).
5. Develop a groundwater model to understand how the resource (e.g. available volume) has changed over time and understand mechanisms of recharge that replenish the source.
6. Devise science-based management goals and science-based strategies for implementation.
7. Continued monitoring to support implementation.
8. Produce analytical scenarios of possible future conditions.
9. Incorporate new datasets as available.
10. Conduct site-specific studies to address specific questions (e.g., in SCAMA, the connection between groundwater and streamflow).

These science activities provide critical information relevant at multiple steps in the policy process. For example, steps 1, 2 and 3 contribute to problem framing; steps 4, 5, and 6 contribute to policy implementation; steps 6 and 7 contribution to policy implementation; and, steps 8-10 contribute to policy evaluation. However, both cycles are iterative and often do not progress at the same pace. Policy development, and in particular the adoption of new policies or regulations by legislative process, is not a linear process and may progress in larger increments when opportunities arise to pass legislation. The process of science production also may not occur at a consistent speed, as it is subject to funding for specific studies, and on-going support of state and federal agencies who produce a bulk of the information.

### *Mechanisms for stakeholder engagement*

ADWR has formal and informal mechanisms for public comment and stakeholder input in groundwater management in the AMAs. Formal mechanisms are specified in the Groundwater Code (A.R.S. 45.420 & 45-421) and AMA management plans. ADWR holds hearings to obtain comments from the public on draft management plans, which also undergo technical review by an independent consulting firm. ADWR feels that "public involvement is instrumental to the success of Arizona's water management efforts" (ADWR, 1999: vi). The Groundwater Code mandates that a Groundwater Users Advisory Committee (GUAC) is formed for each AMA, comprised of 5 members appointed by the Governor (A.R.S. 45.420). The role of the GUAC is to provide recommendations to the ADWR Director regarding groundwater withdrawal fees, conservation requirements, water augmentation projects, and conservation assistance proposals. In addition, ADWR works with water users to ensure that groundwater management regimes are efficient and promote mutual benefits. Other stakeholders, such as scientists and consultants, may also file comment on proposed legislation—for example, if the proposal is hydrologically-infeasible or otherwise scientifically flawed.

Stakeholders find that regional meetings are helpful for networking and sharing research results. In the SCAMA, the interactions among groundwater, surface water and climate are complex, so how scientific results are communicated is key. Many agencies give scientific presentations at these workshops and meetings. The WRRC ensures that results are presented in a way that helps stakeholders and the public understand the information and have in the past had outreach personnel trained in effective communication techniques lead the presentations. While effective communication can help audiences understand the scientific material, this does not necessarily lead to any influence on decision-making or practice.

*Science, policy and practice*

In an effort to promote economic growth, specifically private industry, in Arizona, Governor Brewer issued a moratorium on new rulemaking in 2009, which has persisted since that time. This limits the passage of new regulations throughout the state, including environmental regulations. For groundwater in SCAMA, the moratorium has affected the development of site-specific criteria to implement some management tools specified in the SCAMA Third Management Plan. For example, prior to 2009, scientific studies were conducted to determine the appropriate criteria to use for implementing the Assured Water Supply (AWS)[2] requirement in SCAMA, but implementation of these criteria was halted due to the moratorium (Eden et al., 2016). Since 2009, additional scientific research has improved our understanding of the impact of long-term and short-term climate fluctuations on water supplies in SCAMA (Eden et al., 2016; Shamir et al., 2015; Shamir, 2017), yet it is still not possible to formalize AWS criteria for SCAMA. AWS criteria will greatly influence how new development can occur. Both due to the rulemaking moratorium, and due to severe staffing limitations experienced at ADWR since downsizing occurred in 2010, the agency is nearly 10 years behind in the process of completing scheduled updates to the legislatively-mandated SCAMA management plan—the most recent Third Management Plan was intended to cover the period from 2000-2010. Due to these holdups, the agency is expected to carry over the bulk of the third management plan into the current term with few substantive updates.

In addition to barriers in the legislative process, there are also limitations to the uptake of science-based recommendations in local practice. Studies completed by researchers in collaboration with the WRRC suggest that water management systems in the City of Nogales, Arizona are overdesigned—with excess redundancy incorporated in an effort to reduce climate-related risks. The studies propose ways to streamline water management and avoid excess by planning based on short-term climate forecasts, e.g., based on the expected precipitation for the next three months (Shamir, 2017). However, these suggestions have not been implemented in practice. While City managers have shown interest in the research and are apprised of the findings, implementation would require additional manpower and the City is not equipped to take on complex management schemes at this point in time.

*Perceptions*

Stakeholders shared a perception that the unique physical characteristics of groundwater in SCAMA—its shallow, low-storage aquifers that are tightly-connected with surface flows—dictate the need for local, site-specific management. Streamflow in the region relies on flashy, episodic precipitation events. Because of this, stakeholders were, collectively, very aware of the importance of understanding (1) surface water-groundwater interactions, (2) the effects of climatic fluctuations, (3) resilience of groundwater-dependent riparian zones, and (4) the role of treated effluent discharge in the river and groundwater system. The SCAMA was split off from the Tucson AMA in 1994 in part due to this unique

[2] The Assured Water Supply programs requires that "new development within an AMA must demonstrate that sufficient water supplies of adequate quantity and quality are available to meet proposed uses for 100 years. The AWS Rules require the utilization of these supplies to be consistent with the AMA goal(s)." (ADWR, 1999: 1-8). Because the AWS criteria state-wide were updated in 1995, at the same time that the SCAMA was formed, consistency with SCAMA management goals was not included.

physical nature. Different from other AMAs, reporting requirements are for total "water withdrawal" for agricultural, industrial and municipal uses versus only *groundwater* withdrawals, noting the likelihood that withdrawing groundwater will likely affect streamflow as well. Distinguishing between surface water and groundwater, and identifying the critical interactions, will be a key challenge for future management plans.

There is a shared sense among stakeholders that sufficient groundwater data and scientific analysis have been collected for the SCAMA. This is owed to its designation by the State as an Active Management Area. All stakeholders felt that the agencies and organizations involved in groundwater monitoring and analysis were competent and credible. Stakeholders offered split feedback on whether enough wells exist for monitoring and data collection. On the one hand, some felt that "wells are everywhere". On the other hand, the Sonoran Institute found they needed to collect additional groundwater data in the riparian area at wells not regularly monitored by ADWR to address their questions. Agencies and researchers rely on the cooperation of land owners to access groundwater wells and measure water levels. ADWR has not had issues with this. NGOs bank on relationships built with community members and land owners. This was not identified as an issue in SCAMA, however in some areas of Arizona, particularly outside AMAs, access is likely more difficult.

While many stakeholders were aware of and use ADWR's central database of groundwater information, a few did not use this resource, or felt that they did not find the data they needed for their specific project there. Fewer stakeholders were aware of the WARCAT web-based tool. All stakeholders noted the separation between groundwater quantity and water quality data collection and management in the state of Arizona. Surprisingly few stakeholders consistently access and use water quality data. Water quality information is collected and compiled by the Arizona Department of Environmental Quality (ADEQ). While this information is also available via a web-based database, groundwater samples are not easy to separate from other water samples making its utilization for groundwater studies more laborious. While few stakeholders consistently use water quality information for groundwater studies, hydrogeologists at ADWR noted that they are looking at using water chemistry information to understand aquifer characteristics and groundwater flow. Most stakeholders mentioned contacts at federal and state agencies, as well as local government, by name with whom they have collaborated or would contact if they had a question.

Limitations to the science-policy process are general not technical, but are related to funding, resources, capacity and staffing. While there is interest shared among stakeholders, local officials do not necessarily have the staff and capacity to implement new and complex management regimes. Staffing limitations are apparent at ADWR as well. Having undergone a significant downsizing in 2010, administration of all AMAs was moved to the central office in Phoenix whereas in the past each AMA had its own field office with its own staff. The reduction of staff has also led to a delay in producing the fourth and fifth management plans for SCAMA, both of which are behind schedule. In addition to being delayed, the fifth management plan is expected to wholesale strategies from the third management plan with minimum updates and revisions. Capacity limitations, combined with the ongoing moratorium on new rule-making, have led to advances in scientific research without concurrent advances in policy or management. Some stakeholders perceive that changing the existing policy would be arduous and protracted; while other perceive that policy change is possible.

*Data needs*

While stakeholders share the sense that sufficient data on groundwater is available for SCAMA, there are always data gaps and additional information that would help better understand the physical system and guide informed management (Table 3). In general, better spatial and temporal resolution of water level and climate observations would be beneficial. Overall, the most important need was a better understanding of groundwater-surface water connections. Specific groundwater data was identified that would contribute to what is already known. For example, vertical sampling in wells is uncommon but would help quantify vertical water flows and connections between different vertical zones on an aquifer. Many old wells were screened throughout the entire water-bearing zone of the aquifer instead of isolating multiple zones, which would provide vertical samples. Other useful information includes (1) more aquifer tests (where an aquifer is stressed by pumping for a period of time to see how it reacts), (2) isotope data (used to estimate the age of groundwater, or how long it has been stored underground) and (3) tracer tests (where substances that don't break down in water are released and recaptured later to determine where was is flowing and how quickly).

**Table 3: Data needs identified for SCAMA.**

| | |
|---|---|
| Groundwater<br>• Isotope data<br>• Aquifer test data<br>• Tracer studies<br>• Vertical sampling<br>• Pumping data in non-AMA areas (if possible)<br>• Consistent time, date and location<br>• Improved temporal frequency<br>• Finer spatial resolution<br>• Historical water levels (if available)<br>• Statewide aquifer assessment | Surface water-groundwater interactions<br>• Improved measurement of stream-aquifer connection<br>• Relationship between riparian habitat, channel stability and groundwater<br>• Recharge estimates (effluent, stream, incidental and mountain)<br>• Better match of time scale between groundwater models and flash flood events<br>Weather/Climate<br>• Radar system improvements<br>• Better spatial resolution<br>• Better temporal frequency to alert for flash floods<br>• Tailor forecasts for site-specific needs |

Discussion

*Success in SCAMA*

The Santa Cruz Active Management Area is an example of many successful science-policy elements. Many of these elements result from the implementation of AMA groundwater regulations, however by reflecting on what is working in this basin, we can learn what elements contribute to success and explore ways to promote these strategies and tools in other groundwater systems.

Aspects contributing to successful collection, transfer and use of groundwater science in management of the SCAMA include:

- Groundwater data are centrally-compiled by ADWR and made publicly-available.
- There is a very engaged stakeholder group.
- The ADWR promoted stakeholder involvement and offers structured methods for acquiring input, such as the Groundwater Users Advisory Committee.
- Close interpersonal networks have developed over time, although this has been strained by agency downsizing and a reduced number of ADWR staff in local areas. This is a downside of centralizing information with a single agency.
- In addition to ADWR, other organizations (e.g. WRRC, UA) provide convening, research and communication tasks, essentially acting as boundary organizations aiding the transfer and translation of scientific information among stakeholders and the public.
- The University and WRRC are able to work outside of the scope of state and local government agencies, for example, international collaboration with Mexico.

- Science and management both acknowledge the unique physical system and are responding by providing site-specific information and management strategies.
- Legislative regulations apply to SCAMA requiring monitoring and reporting of pumping, providing a record of groundwater observations over time. Regulations also promote scientific research to support the achievement of defined management goals.

*Reflection on use-inspired science process*

To ensure that this research was use-inspired, the research began with joint problem framing together with stakeholders in SCAMA. By speaking with stakeholders and observing regional stakeholder meetings, the need to better understand the transfer of information and how perceptions affect the use of such information was revealed. This need also ties in to broader societal challenges related to the need for improved groundwater governance, a field which remains nascent. Stakeholder analysis was conducted to hone a list of stakeholders most relevant to this research and identify their role, perspective and responsibilities to best target their needs (Pohl et al., 2017). Instead of working with only one stakeholder or user, this project engaged multiple stakeholders to address a common need.

**Figure 4: Southeast Arizona Citizens Forum meeting in Tubac, Arizona.**

Some challenges were encountered. Being a basin where much prior research have been conducted regarding environmental, water and wastewater issues, stakeholder fatigue was experienced with some SCAMA stakeholders. Some contacts who initially replied positively to invitations to participate in this study were unable to be reached to arrange a meeting time. Others who were invited did not respond initially. Contact information for water users and private citizens is not publicly-available online. Because the pool of relevant stakeholders in SCAMA is very small, each missed connection creates a non-trivial gap in the story.

Finally, because this was a multiple-stakeholder project, it is challenging to gain high levels of participation from stakeholders because they all have slightly divergent priorities and their own workloads. It would be easier to design research to align with a single stakeholder. However, multiple stakeholders are key to this research question.

*Plans for dissemination and further research*

Based on suggestions of stakeholders for how to make the results of this research usable to them, I will disseminate the results in a one-page summary handout and I will present the results at a regional conference (either AZ Water or Santa Cruz Research Days). Stakeholders emphasized the need for a succinct summary of research results written for a lay-audience.

There are many directions for further research. The elements of success in SCAMA could be used to develop a heuristic for science-policy processes for groundwater and used to evaluate the development of science and policy in other basins in Arizona. It would be interesting to apply such a framework to non-AMA areas experiencing groundwater declines. While they are not regulated by the Groundwater Code, using the elements identified in SCAMA could help guide the development of a new regulation approach for these areas. For example, in the Willcox basin in southeastern Arizona, many wells have gone dry in recent years due to long-term agricultural withdrawals. In 2015, local residents proposed establishing a new type of groundwater conservation area to address groundwater declines. The elements of success identified in SCAMA could help guide development of criteria and management structure for such a conservation area.

Secondly, this research could be expanded to include the entire southern Arizona border region as well as the border region in Mexico. Expanding the research in this way would address questions about transboundary access to information, cross-border social networks and additional translation challenges—which are increasingly complex in transboundary groundwater systems.

Thirdly, the results of this research have been used to develop a preliminary survey. After completing this project, it seems most relevant to administer this survey on a statewide basis and use the results to compare the compilation, collection, access to and use of groundwater information in different U.S. states.

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