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Opening the Black Box: Using a Hydrological Model to Link Stakeholder Engagement with Groundwater Management

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Abstract: Stakeholder participation is a foundation of good water governance. Good groundwater governance typically involves the co-production of knowledge about the groundwater system. Models provide a vehicle for producing this knowledge, as well as a "boundary object" around which scientists and stakeholders can convene the co-production process. Through co-production, stakeholders and scientific experts can engage in exchanges that create system knowledge not otherwise achievable. The process involves one-way transfer of information, active two-way conversations, and integration of multiple kinds of knowledge into shared understanding. In the Upper Santa Cruz River basin in Arizona, USA, the University of Arizona Water Resources Research Center (WRRC) convened a project aimed at providing scientific underpinnings for groundwater planning and management. This project, entitled Groundwater, Climate, and Stakeholder Engagement, serves as a case study employing the first two stages of knowledge co-production using a hydrological model. Through an iterative process that included two-way communication, stakeholders provided critical input to hydrologic modeling analyses. Acting as a bridging organization, the WRRC facilitated a co-production process, involving location-specific and transferability workshops, which resulted in new knowledge and capacity for applying the model to novel problems.

Keywords: groundwater modeling; groundwater management; stakeholder engagement; knowledge co-production; Santa Cruz River Basin

1. Introduction

Stakeholder participation is a foundational principle of good water governance [1]. Groundwater governance has varied definitions, but in general it refers to the overarching framework, usually spanning multiple jurisdictional levels, of laws, regulations, and customs for groundwater management [2]. It is distinguished from government in emphasizing processes of influence rather than control [3]. Principles of good water governance call for replacing hierarchy with networks of relationships in which stakeholders play a major role [4,5].

Groundwater management operates within the governance framework. Lautze *et al.* argued that good water governance and good water management are separate goals that should be evaluated on different criteria [6]. The goals of water management are outcome oriented, while the goals of good governance are process oriented. The definition of groundwater governance adopted by Groundwater

Governance, Global Framework for Action to achieve the vision on Groundwater Governance, includes good management outcomes: "control, protection and socially-sustainable utilization of groundwater resources and aquifer systems for the benefit of humankind and dependent ecosystems" [7]. There is still debate, however, on whether the processes of good governance are necessarily linked with positive management outcomes. The contrary examples of India, China, Jordan and Saudi Arabia provided by Lautze *et al.* make the claim difficult to support [6]. Individual good governance practices, such as stakeholder engagement, however, have been linked with improved implementation of groundwater management actions.

Stakeholders include any individual or group with a stake in the outcome of a project or action. In general, stakeholder engagement aims to include a wide range of interests influenced by or influencing a decision [8] for reasons of effectiveness [9], as well as legitimacy [10]; that is, engaged stakeholders are more likely to view policy outcomes as legitimate and less likely to impede their implementation. Many economic, environmental, and social benefits are gained from effectively engaging stakeholders in water resource decision making. Systematic and inclusive stakeholder engagement improves the chances that the time and resources invested will yield the desired return and stakeholder issues can be handled effectively [11]. Outcomes, such as support for reforms, are more likely. Less tangible benefits also can evolve from better co-operation, including knowledge development, conflict avoidance, and social cohesion [12].

It is recognized that stakeholders may engage for the purpose of controlling or disrupting collective efforts. Interest conflicts may dominate, especially where potential outcomes are likely to produce winners and losers. In these instances, developing a shared understanding of the issue context may be insufficient to resolve differences, and the benefits of stakeholder engagement will be more difficult to realize [13].

Despite this possibility, it is generally accepted that scientific information and system understanding are associated with better management. The many endeavors producing groundwater science in support of effective management are evidence of this association, and many have successfully translated scientific information into improved management outcomes [14,15]. However, good science is likely to be ineffective in producing better management when there are communication failures between scientific knowledge producers and users [16,17]. To overcome this disconnection, it is necessary to engage science users in jointly producing knowledge appropriate to the management context [16,18,19].

For effective groundwater management, many kinds of knowledge are essential. Knowledge of the physical groundwater system, its interactions with other physical systems, the social, political, and economic context, and other case-specific relevant factors are needed to manage the resource. Relevant knowledge does not reside in a single source but emerges through an interactive process. Scientists may take a leading role in this process, but they take part in a conversation in which people having other types of expertise, e.g., practical or local knowledge, are heard [20–23]. Co-production occurs when scientists and stakeholders interact to produce knowledge that can be used in the relevant water management context [19].

Co-production in the context of scientific research involves establishing linkages between researchers and research users [23]. A survey by Phillipson *et al.* of 21 research projects engaging stakeholders found "a complex and diverse range of knowledge exchange relations" [24]. In an assessment of conditions for successful joint knowledge production, Hegger *et al.* proposed in successful co-production, relevant resources are available to support the process. These may include so called "boundary objects", such as models, that lie at the cultural boundary between scientists and stakeholders and provide a focus for exchange [18].

Engaging stakeholders in modeling a natural system such as an aquifer is a recognized means of transferring knowledge about the modeled system [25]. Scientists engage in describing and explaining by presentations and responding to questions. Stakeholders contribute knowledge regarding the system only they can provide from experience with the system in their various roles. The model also provides a neutral platform on which system knowledge is built and agreed upon by stakeholders who may disagree about desired policies or practices.

Models present special challenges to engagement of stakeholders. The model structure must be scientifically defensible. It must also be explained well and as transparent as possible. This means communicating model assumptions and data, its reliability limits and uncertainty. Otherwise, trust in the model and trust between the scientists and stakeholders are undermined. Such communication achieves its goals more effectively when done through engagement and interaction [9,26]. Stakeholders who participate in posing questions and evaluating results of simulations are in a position to assess potential future states of the system under different scenarios [27]. Revealing the workings of the model builds confidence in the model as a platform for objectively answering stakeholder relevant questions.

Another element with a positive effect on knowledge co-production is the intervention of an individual or organization that carries out the functions of facilitating communication among the various parties. Universities commonly provide these functions in stakeholder engagement [28]. Academic examples include the Regional Integrated Science Assessment Centers, National Institutes for Water Resources, and Southwest Ecological Restoration Institutes [29]. Perhaps the most longstanding example is cooperative extension, which began as an institution to link scientists and farmers for information exchange, mutual learning, and decision support [30]. There are multiple designs for achieving this functional goal, including bridging organizations. Bridging organizations have a broad scope and engage in multiple functions [31]. A bridging organization serves as an entity that links people from multiple interests in order to help them solve problems that they would not have been able to solve if acting alone [32]. It is "a conduit of ideas and innovations, a source of information, a broker of resources, a negotiator of deals, a conceptualizer of strategies, [and] a mediator of conflicts" [33]. Bridging organizations might assist collaborative initiatives by gathering and interpreting technical information or providing legal, financial, or simply moral support. These organizations also can help balance power asymmetries in discussions [29], which is particularly important in water management engagement [34]. Bridging organizations also are important because they provide an arena where groups that assemble knowledge in very different ways can form productive relationships with one another [35,36]. Finally, bridging organizations have been widely cited as promoting learning [37].

2. Approach

This paper examines stakeholder engagement with an innovative modeling framework for the purpose of co-producing knowledge relevant to groundwater management. In so doing the paper seeks to fill the need for case studies that illustrate challenges and outcomes of knowledge co-production [38]. The project, Groundwater, Climate, and Stakeholder Engagement (GCASE) was defined initially with three goals: (1) Incorporating projected future climate change patterns into the modeling framework; (2) Engaging stakeholders to develop an understanding of the relevance of the model to water management problems; and (3) Establishing the transferability of the modeling framework and stakeholder approach to other areas. The technical accomplishment of the first goal is described elsewhere [14].

The hydrologic modeling framework was constructed over a period of years prior to GCASE by the Hydrologic Research Center in collaboration the Arizona Department of Water Resources. This modeling framework was specifically constructed to represent the dominant meteorological-hydrological-hydrogeological processes in the study region with an emphasis on climate variability and projected climatic changes. The hydrologic modeling framework has been used as a tool to assess the benefit and impact of various water resources strategies. The model selection, construction verification and case studies are available in following references [14,15,39–41], and a concise description of the modeling framework is in Section 3.3. The GCASE project sought to demonstrate the usefulness to stakeholders of the existing model with its climate enhancements. Use of an existing model also facilitated a focused approach made necessary by limitations of time and resources.

Engagement of stakeholders and scientists in developing management-relevant information places the project in the realm of knowledge co-production. Meadow *et al.* (2015) listed three principles of knowledge co-production: (1) building ongoing relationships between scientists and stakeholders; (2) ensuring two-way communication between scientists and stakeholders; and (3) maintaining a focus on usable science [38]. In this context 'usable science' refers to science produced in a form that can be used by stakeholders in their management and decision making roles. The project team employed an approach that emphasized these three principles.

The literature of co-production emphasizes principles, approaches, modes, and factors that foster successful joint knowledge production, but does not identify process steps [18,21,24,38,42,43]. Although Voinov and Gaddis provide twelve lessons learned regarding the participatory modeling process [9] and Michaels describe six strategies for knowledge brokering [19], steps are left to the project designer. This lack of prescribed steps is partially explained by the iterative nature of the co-production process. As a process involving stakeholder engagement, knowledge coproduction can be visualized as a wheel, in which actions are revisited, reevaluated, revised and repeated [44]. Knowledge co-production requires an adaptive approach in which actions are adopted and adjusted based on the nature of the project as it may change over time [17,27].

The GCASE project sought to demonstrate the potential of a specific combination of stakeholder engagement approach and hydrological model. The approach used was similar to the participatory integrated assessment as described by Meadow *et al.* who mined the current literature to provide typologies of modes of engagement and approaches to collaboration [38]. The principal participation mechanism used within this approach was the workshop because of it provides venue in which to work in a collaborative mode.

In keeping with guidance from the literature, the project's design aims included advice of key stakeholders, on-going and expanding stakeholder consultation, diverse knowledge, negotiated communication, effective dialogue on the model and its use, model analyses responsive to stakeholder queries, and transferability assessments. These aims were addressed in the construction of the stakeholder process as described in this case study.

GCASE engaged a diverse group of stakeholders in a series of workshops that acquainted stakeholders with the modeling framework and elicited questions and comments to guide scenario development and analysis. Through an iterative process that emphasized two-way communication, stakeholders provided critical input on hydrologic modeling analyses that incorporated climate uncertainty and simulations of alternative pumping scenarios. In addition, stakeholders provided suggestions on model modifications that could make the GCASE methodology transferable to other locations with different ground and surface water management issues. Scientists and stakeholders shared knowledge through workshop interactions, email correspondence, and a dedicated web site. The University of Arizona Water Resources Research Center (WRRC) acted as the stakeholder convener or bridging organization to ensure that requirements for effective stakeholder engagement, such as open, consistent communication, inclusiveness, and interactivity, were met. In order to avoid the pitfalls of black-box science, workshops were designed to lay open the model and its assumptions. The WRRC monitored stakeholders' understanding of the information presented and adapted communications based on their input.

3. Case Study

3.1. Setting

The Santa Cruz Active Management Area (SCAMA) covers 1850 square kilometers of river basin along the Upper Santa Cruz River, a desert stream characterized as ephemeral, except from an effluent fed river section downstream from the Nogales International Wastewater Treatment Plant (NIWTP) (see Figure 1). The Santa Cruz River flows southward from its headwater in Arizona into Mexico, where it continues southward for a short distance before turning northward to reenter Arizona five miles east of the City of Nogales, Arizona. From there it enters the SCAMA and flows north and west into the Tucson Active Management Area.

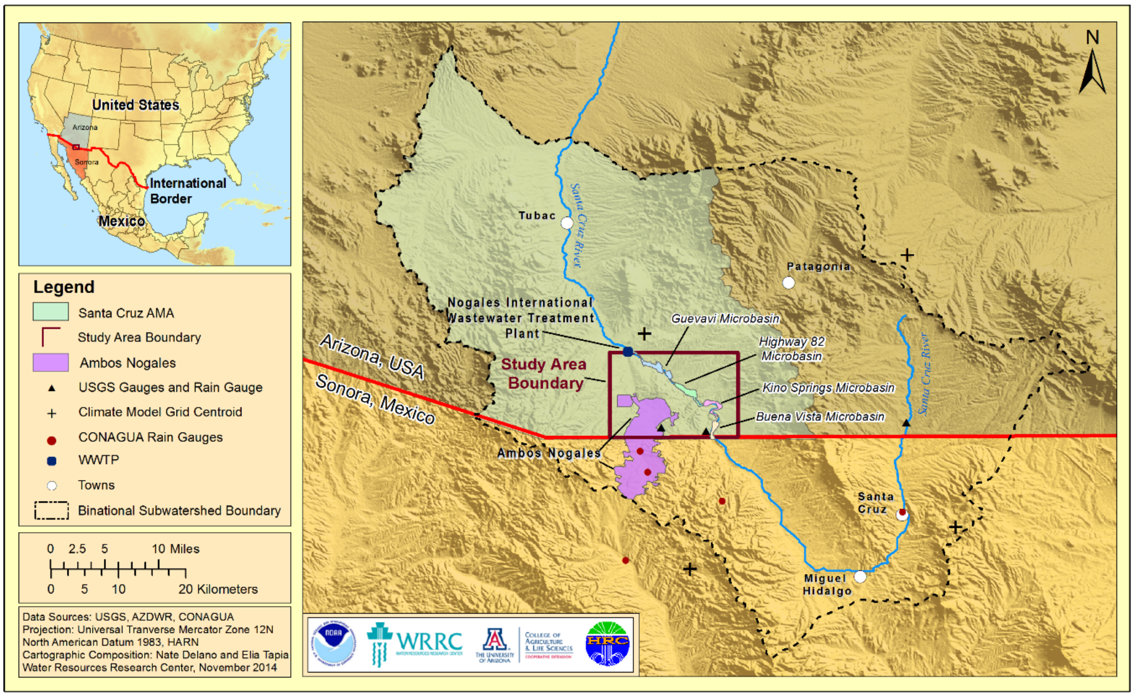

Figure 1. Map of case study area. Nogales, Arizona and Nogales, Sonora are collectively refered to as "Ambos Nogales".

The SCAMA aquifer can be roughly categorized as two systems. The first is the "Microbasin" region along the river from the International Boundary to the NIWTP. This region consists of a series of relatively shallow alluvial aquifers that are tightly dependent on the Santa Cruz River's intermittent rain driven streamflow events. The second system, which is located north of the NIWTP and extends to the northern SCAMA boundary, is a wider and much deeper aquifer. This aquifer also relies on recharge from the Santa Cruz River and it receives treated wastewater effluent from the NIWTP.

Nogales, Arizona is the largest city in the SCAMA, with a population of little more than 20,000 people. In contrast, Nogales, Sonora has a population of approximately 200,000 people. The two cities are jointly referred to as Ambos Nogales. Industrial growth south of the border has spurred population growth since the passage of the North American Free Trade Agreement in 1993, while the population of Nogales, Arizona grew much more slowly in the same period. Water supplies for Nogales, Sonora come from local aquifers in the Santa Cruz River and the Los Alisos River. Future increases in water use from the Santa Cruz watershed in Sonora could reduce flows into Arizona. Although the Nogales, Arizona water demand is expected to remain stable [45], the Arizona Department of Water Resources (ADWR) projected increase in urban water demand for the entire SCAMA by 2025.

The City of Nogales, Arizona, provides water for its population from two groundwater sources: the Santa Cruz River microbasins and the Potrero aquifer on the west side of the city. The microbasins aquifer is recharged by flows in the Santa Cruz River triggered by precipitation events. The Potrero aquifer, which is deeper, is replenished through slower recharge processes. The city's water managers prefer to use the relatively shallow microbasins aquifer because they determined it provides better quality water at lower pumping costs. Some wells in the Potrero aquifer produce water with arsenic concentrations higher than allowed by United States federal drinking water standards. Reliability of the microbasins as a water supply depends largely on climate and understanding the regional climate variability and uncertainty could improve water supply practices for the city.

The Santa Cruz River aquifer is a binationally shared resource and developments upstream in Mexico have the potential to affect supplies in Arizona. Water quality is a chief concern, but potential quantity implications exist. Of special interest is the ongoing development of the El Pilar mine concessions in the Santa Cruz River basin southeast of Nogales, Sonora. In addition, flow in the Santa Cruz River downstream from the NIWTP is dependent on discharges from the plant, which treats wastewater from both Nogales, Arizona, and Nogales, Sonora. Mexico's portion of the discharge is approximately 55 percent and could be diverted away from the NIWTP and the river if Mexico decides such action would be in its best interest. This action would likely reduce flow in the river, with a negative impact on the downstream riparian ecosystem in Arizona [46].

3.2. Management Framework

The Arizona the Groundwater Management Act of 1980 established ADWR as the agency with regulatory responsibility for water resources management. The Act created Active Management Areas (AMAs) in those groundwater basins where groundwater pumping was leading to severe water level declines. Approximately 80 percent of Arizona's population resides in an AMA. Within these AMAs, groundwater withdrawals are limited based on historic use, and conservation requirements restrict growth in groundwater use. Four AMAs were created in 1980 and a fifth, the SCAMA, separated from the Tucson AMA in 1994. For each AMA, a groundwater management goal was specified, and for three of the five AMAs that goal includes reaching "safe-yield" by 2025. Safe-yield, as defined in statute, is an attempt "to achieve and thereafter maintain 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" [47]. The Act mandated that periodic management plans be written that prescribe actions toward achieving the management goal for each AMA by 2025.

The SCAMA separated from the Tucson AMA in part because the SCAMA region was already in safe-yield. The SCAMA has a two-part management goal. In addition to the safe-yield goal, the SCAMA aims to prevent local water tables from experiencing long-term declines. The management goal did not specify the protection of riparian natural resources. Although many people maintain that such protection was the intent of the goal, others reject that interpretation. Developing SCAMA rules to achieve the management goal depends on definition of the term "long-term decline", which is undefined in the statute. One interpretation would prevent declines of sufficient duration to endanger riparian vegetation such as cottonwood trees. Understanding the likely effects of pumping in the microbasins could inform this discussion.

The Act also mandated rulemaking to ensure that growth within AMAs is supported by an assured supply of water for 100 years. These Assured Water Supply rules deny a developer permission to subdivide land for sale or lease without showing water availability. Unless a subdivision developer has obtained a written commitment from a designated water service provider, he/she must obtain a certificate of assured water supply from ADWR before the subdivision can be approved. Criteria for granting a certificate of assured water supply include proof of physically, legally, and continuously available supply for 100 years. In addition, the developer must show consistency with the AMA management goal and management plan. Water service providers must obtain a designation of assured water supply from ADWR in order to support growth within their service areas. The same criteria apply.

Prior to a moratorium on rulemaking in Arizona issued in 2009, and still in effect after this project's completion, there was a major effort to establish assured water supply criteria consistent with the SCAMA goal. Recommended rules were developed based on a historical analysis of the aquifer [48], but review and adoption were halted before any action could be taken. Deliberations focused in part on interpretation of that section of the management goal that would prevent long-term water level declines.

Regulating groundwater use for growing population centers remains a major water management concern for stakeholders in the SCAMA. Other concerns focus on vulnerability to climate variations and the need for water storage. In addition, the City of Nogales desires to optimize use of the microbasins.

As a statement of policy, the SCAMA endorsed consideration of "community and stakeholder input to the highest degree possible" [49]. Stakeholder involvement in the development of AMA management plans involves public consultation and opportunities for comment. Meetings at which the plans are discussed are open to the public and notifications of meetings are sent to interested stakeholders. Draft plans receive review and comment from a range of stakeholders. However, outreach to stakeholders is limited by departmental resources and engagement does not reach the level of knowledge co-production.

Groundwater Users Advisory Councils (GUACs) to the ADWR Director are groups consisting of five members, appointed by the governor on the basis of their knowledge of, interest in, and experience with the local water resource issues. A vehicle to solicit stakeholder input, the GUACs have no authority to implement recommendations, but they are kept abreast of relevant agency activities and provide input to plans and regulatory proposals developed by ADWR.

3.3. Modeling Framework

In order to have sufficient information on water supply and demand for planning and regulation of groundwater management, ADWR undertook the development of physically-based groundwater models in the AMAs. Beginning in 1997, ADWR initiated a field monitoring program in the SCAMA to provide data for conceptual model design and model calibration. In the mid-2000's ADWR developed a MODFLOW groundwater model simulating conditions south of the NIWTP to the Mexican border [50] and north of the NIWTP to the AMA northern boundary [51]. The capabilities of this physically-based model were enhanced to accept stochastic input from ensemble simulations of likely-to-occur rainfall and streamflow scenarios, developed by the Hydrologic Research Center (HRC) (Hydrologic Research Center is a public benefit nonprofit organization with 501(c) (3) status in the United States) with ADWR funding and cooperation [40,41]. The rainfall-streamflow scenarios in conjunction with the groundwater model enabled a risk-based assessment of various water withdrawal scenarios and their effect on the aquifer [15,39].

As part of the GCASE project, HRC, and the University of Arizona, Department of Atmospheric Sciences, examined regional dynamically downscaled climate models to project future climatic changes in the SCAMA. These projections were used to modify the rainfall-generating component of the modeling framework. The key factor affecting changes in rainfall patterns was projected changes in inter-annual trends in both the summer and winter seasons, when most of the rain falls in typical years [14].

The modeling framework employed in GCASE included simulation of the hydrologic system from rainfall, through streamflow to groundwater response for the microbasins portion of the SCAMA. The hydrologic model components reproduce well the working of the ADWR MODFLOW model and allowed for multiple queries to be analyzed with relatively short turn-around times. This modeling framework provided a tool to examine various groundwater management strategies under historic and projected rainfall regimes.

With knowledge of how climate and groundwater management strategies interact, decision makers can optimize their pumping to achieve groundwater management goals. They are also able to make tradeoffs with respect to factors such as system reliability, storage needs, and groundwater recharge optimization.

3.4. Stakeholder Engagement

The study team began identifying stakeholders to participate in project workshops by exploiting established connections in the study region. Relationships built over time formed the core of the outreach. The WRRC has undertaken engagement activities throughout the state of Arizona that created relationships of trust and respect with a numerous community of actors in the water arena. These relationships are cultivated consistently through personal contacts, meetings, and various forms of outreach. Extending these relationships is a strategic goal of the WRRC.

3.4.1. Stakeholder Identification and Recruitment

Known stakeholders were polled to identify additional individuals and organizations to be invited to participate in workshops. Because the goal of engagement was to develop an understanding of the relevance of the model to water management problems, the focus of the engagement was on expert stakeholders. Expert stakeholders are people who are professionally or institutionally involved with the issue and have "gained domain specific expertise through their profession" [52]. This focus eliminated the option of advertising workshops broadly. Invitations were sent to individuals and organizational representatives with a known or apparent interest in the water resources of the study region.

Efforts in stakeholder identification and recruitment aimed at broad participation among expert stakeholder interests. The goal of stakeholder recruitment was to provide a large pool of ideas and perspectives for input into the modeling process. The number of invitations sent ranged from 39 for the first workshop to 81 for the third workshop. Table 1 shows the range of stakeholder interests at the case study workshops. An average of 21 stakeholders participated in each of the three case study workshops. Approximately half of all participants attended two or more workshops.

Table 1. Categories of stakeholders present at case study workshops.

Attorney	Binational Commission	City Government
Council of governments	County government	GUAC member
Mexican water utility	Non-Governmental organization	Private consulting firm
State government	United States federal government	United States water utility
University		

Individual communications were used to activate stakeholder networks and generate interest in the study research. Invitations emphasized the interactive nature of the research and the importance of stakeholder input. Follow-up messages and telephone calls encouraged participation. To provide incentives for key stakeholders to attend and to make sure their knowledge was included, they were asked to be workshop speakers. For example, the Kickoff Meeting agenda included representatives from ADWR, the City of Nogales, a National Park, an NGO focused on protection of the Santa Cruz River, and representatives of regional and federal agencies, in addition to project scientists.

Formation of an advisory committee was a key to developing a project that encouraged co-production of relevant knowledge. Members were identified as essential links between the science and management contexts. The committee was kept small—four external members—to minimize cumbersome logistical arrangements for meetings and reviews. The Deputy Director of ADWR and the Director of Public Works for the City of Nogales were joined by representatives from the United States Geological Survey and the Salt River Project, a major water supplier in central Arizona. In addition to influencing the direction of the project and design of workshop, they provided advice on transferability of the project to other regions in Arizona. They also were consulted on development of communications with other stakeholders.

3.4.2. Stakeholder Communication

Throughout the project, stakeholders were kept informed about the project and its progress through intermittent email communication. In addition, a website was created for posting of project-relevant information, including workshop presentations and summaries. An effort was made to engage stakeholder in an on-line conversation about the project through an access-limited dialogue page.

One key project innovation was the preview of technical workshop presentations to evaluate their ability to communicate to stakeholders. Stakeholder or non-technical surrogates (staff and students) previewed workshop presentations and provided feedback on understandability and effectiveness in communicating key messages. Use of scientific jargon presented an initial challenge and engendered conversations on how to translate terms or define them in everyday language. It was also necessary to explore the purpose information—to answer the question "Why are you telling me this?" Slides were critiqued to promote simple, self-explanatory graphics and discourage complex charts and graphs that were difficult to explain. These exercises were appreciated by all the presenters whose presentations were previewed, who reported that their presentations were improved without sacrificing scientific credibility.

3.4.3. Case Study Workshops

Workshops were designed to maximize stakeholder participation. The first section of the workshops emphasized information sharing; researchers and key stakeholders presented background needed for discussing research goals and strategies. Ample time was allotted for question and answer, which delved into the workings of the modeling framework and the climate projections. At this stage the emphasis was on learning through interactive listening, with a goal of one-way information transfer. The model must be explained and understood before it can be usefully queried.

The second workshop session consisted of facilitated discussion in which stakeholders were presented with a series of open-ended questions about their groundwater management concerns, their expectations of the modeling framework, and what questions they would like the model to answer. Here the emphasis is on two-way communication in which knowledge pertinent the model's potential role in groundwater management is co-produced. GCASE analyses depended on this knowledge to structure relevant scenarios.

The workshop participants examined key aspects of the modeling framework, such as the use of the observed rainfall records and the nature of the uncertainty in projections. They were instrumental in developing a list of questions to explore in simulations based on assumptions regarding future conditions. These questions were used in the development of case study scenarios that provided a range of possible futures for groundwater use and recharge under current and future climate.

At the three location-specific (SCAMA) workshops, stakeholders raised questions that sought to explore the physical limits of the groundwater system, the range of climate impacts, and model capabilities. They were more reticent about suggesting potential water demands and allowable drawdown of the aquifers. There was little overt conflict over management goals, although opinions were divided on the interpretation of those goals as referring to maintenance of riparian vegetation. Comments and questions focused on potential uses of the model and the kinds of information it could provide. The possibility of significant change in water management in the Santa Cruz watershed in Mexico was raised, and it was admitted that this was a major uncertainty that could not be addressed in the GCASE project.

3.5. Transferability

An additional series of five workshops engaged stakeholders in discussions designed to investigate the transferability of the GCASE methodology to other locations and groundwater management contexts. The transferability workshops necessarily involved a broader set of stakeholders from outside the SCAMA. Some SCAMA workshop stakeholders attended a transferability workshop, while the majority of stakeholders at each of those workshops were new to the project. The new stakeholders possessed knowledge about the water management issues particular to each workshop region and were interested in the potential of the project methodology to be applied locally. The project team engaged organizations in each location to co-host the transferability workshops. The workshop co-hosted by the International Boundary and Water Commission was bilingual and involved stakeholders from Mexico. Agreeing to cohost demonstrated the interest of these organizations and provided a mechanism to reach more local stakeholders. Table 2 shows the location and co-host for each of the five transferability workshops.

Table 2. Locations and co-hosts, transferability workshops.

Location	Co-Host
Prescott, Arizona	Yavapai County Cooperative Extension
Phoenix, Arizona	Arizona Department of Water Resources
Tucson, Arizona	Pima Association of Governments
Sierra Vista, Arizona	Upper San Pedro Partnership
Rio Rico, Arizona	International Boundary and Water Commission

The five workshops employed formats similar to the SCAMA workshops. The first part of the workshop was devoted to presenting a description of the case study and its results. The case study presentation was revised following each workshop based on the participants' questions and comments. Stakeholder input was thereby used to increase the effectiveness of communicating the impacts of climate change on water resource planning, the capabilities of the modeling framework, and its potential for informing planning and management efforts. Questions of clarification were answered during the presentations, often leading to discussion of the modeling framework and climate projections.

Stakeholders were interested in the capability of the modeling framework to link climate projections with hydrological system responses. It was acknowledged that hydrologic projections based on historical data were not likely to reflect future conditions. The capability of the framework to capture the range of uncertainty was considered useful to water resource planning.

A short presentation on transferability criteria was followed by a discussion on the potential for transferability to the region. Participants engaged in assessing the potential according to the following five criteria: (1) local climate is a major factor in the state of the local water resources; (2) rainfall and streamflow are highly variable and difficult to predict; (3) future climate projections indicate increased variability and uncertainty; (4) informative datasets are available for the region; and (5) local agencies and stakeholders are engaged.

Stakeholder transferability concerns centered on whether the transferability criteria were met. In the greater Phoenix area, dependence on large regional aquifers means local climate plays a relatively minor role in the state of local groundwater resources. The lack of compatible data sets was raised by Mexican stakeholders, and a range of solutions were discussed involving additional data manipulation within the modeling framework. It was concluded that an increased level of stakeholder engagement may be needed where data are scarce.

A discussion of potential uses of the project methodology followed. Stakeholder demonstrated a grasp of the modeling framework's capabilities by suggesting feasible location-relevant applications. Many of these applications challenge the model to produce analyses different in kind from the SCAMA case study. For example, one suggestion was to use the model to investigate the impact of development on baseflow in a protected creek fed by shallow groundwater. Another suggestion identified the need to determine the impact of a new well field in an aquifer at the headwaters one of the few perennially flowing rivers in Arizona. These applications would necessitate modifications to the modeling framework, but they are well within its capabilities, assuming transferability criteria are met. It was acknowledged that transferring the methodology would require stakeholder engagement to drive integration of new questions into modifications of the modeling framework.

3.6. Outcomes

For the SCAMA, model outputs clarified groundwater management issues relating to aquifer resilience, potential for maximizing recharge, and increasing supply reliability. Results clearly showed greater uncertainty under future climate conditions that challenge reliability, increase groundwater deficits, and decrease recharge. Results also indicated, however, that a management strategy that included high pumping rates and deep pumping cessation thresholds could be employed to minimize these effects. The implications of this strategy, however, must be carefully considered in the context of SCAMA management goals.

Stakeholders demonstrated in their discussions an understanding of the results and their implications. Maximizing water supply from the microbasins would have impacts on infrastructure needs and the environment. Climate uncertainty, which exacerbates planning uncertainties, fueled the desire for better data and forecasts.

In follow-up discussions, local stakeholders agreed that access to the types of data used in the modeling framework would improve the capacity of local operators to manage groundwater withdrawals. Meetings with the SCAMA GUAC and other stakeholders were instrumental in conceptualizing a new project. Specifically designed to meet the needs of groundwater users in the SCAMA, the project will provide a web-based data service based on data analyses and visualization tools of pertinent local hydro-meteorological datasets that are updated in real time. An additional component of the web site will include analysis of the Climate Forecast System from the National Centers for Environmental Prediction to provide a seasonal forecast of rainfall. Stakeholders will take part in workshops to provide input on project development and products.

Transferability discussions produced a set of options for future work demonstrating the effectiveness of stakeholder engagement with the GCASE modeling framework. Stakeholder connections developed in the context of these discussions form a base for partnerships in linking scientific models with groundwater governance.

4. Discussion

The centrality of stakeholder engagement to the GCASE project was explicit from the beginning. Meadow *et al.* (2015) listed three principles of knowledge co-production: (1) building ongoing relationships between scientists and stakeholders; (2) ensuring two-way communication between scientists and stakeholders; and (3) maintaining a focus on usable science [38]. In this context 'usable science' refers to science produced in a form that can be used by stakeholders in their management and decision making roles. The project team employed an approach that emphasized these three principles.

Identifying stakeholders who are willing and able to contribute input requires knowledge of the context and will benefit from access to existing networks that can extend the limits of prior knowledge [53]. Stakeholder identification depends strongly on the context of the engagement process and should be sensitive to its specific topic and goals [54]. Stakeholders who are likely to participate in co-production processes, which may require repeated engagement, typically are recruited from the ranks of paid representatives of agencies and organizations with a stake in decisions and unpaid citizens with a deep interest in sustainable water management and related issues [55]. They tend to be connected through networks of interest that can be tapped through involvement of key known individuals.

It was a challenge to capture the attention of busy stakeholders for engagement in the GCASE project. It helped that the WRRC was known to many of the potential participant as a source for even handed facilitation and respectful interactions. More persistent personal communication was used to assemble the participants of the first workshop, which probably accounts for the high percentage of invitation acceptances—more than half. As we expanded the invitation list of potential participants, the acceptance rate dropped. A core group of stakeholders remained interested and engaged throughout the process. This core group consisted mainly of people whose professional positions involved management of water or related resources. An attempt was made to keep the project in the forefront of participants' minds by frequent communications about project progress and requests for input, but the development of high quality communications necessitated some time gaps. It was also important to consider the possibility of stakeholder fatigue.

A small group of key stakeholders can be useful as advisors when projects are linking stakeholders with research efforts. Their feedback can shape the design of stakeholder participation events and products meant to communicate results to the wider stakeholder group [44]. The choice of these key stakeholders may be based on existing relationships and may be made to ensure participation of key organizations and/or representatives with important content knowledge [56].

The choice of Advisory Committee members was based both on existing relationships and on their possession of key expertise. The extent of their engagement was directly related to their involvement in water management in the case study region and previous experience with the modeling framework. Their guidance remained important throughout the project, although emails tended to replace face-to-face and telephone meetings as the project progressed. Their assistance was also critical in framing discussions of transferability.

Organizations and agencies that are represented in a co-production process are committing resources and therefore they should see in the process a connection to their missions. Institutional support through the creation and communication of information and through participation in co-production dialogues can be instrumental in the success of these efforts. Without such support, the process may be jeopardized. The engagement of both ADWR and the City of Nogales was instrumental in linking GCASE to practical groundwater management considerations. They contributed staff time and expertise to the advisory committee, workshops, and other stakeholder communications. Their involvement could be considered intrinsic to the project, as both were already vested in development and application of the modeling framework at the inception of the GCASE project.

Communication between scientists and research users can be challenging when the parties are not accustomed to dialogue. Plain language should be used to communicate complex information [53]. In the GCASE project, communication issues were specifically addressed in workshop discussions. The meaning of key terms and their translations were agreed on through a consensus process. Trained facilitators led group discussions with a goal of promoting general understanding. At one point an online dialogue capability was suggested, so that the conversation could continue between workshops. Such a capability was developed, and all the participants were invited to join. However, it remained unused, perhaps because it required registration, but more likely because stakeholders were too busy. The capability was passive and not designed to push information to the stakeholders and no one was generating content regularly to spur responses. Workshops provided time to focus on GCASE related issues, engendering discussion.

People who are skilled and trusted as translators between experts and non-experts can be needed to close the gaps in understanding [43,53]. Translation proved an important skill for making sure the presentations of project scientists communicated effectively to other stakeholders. GCASE explained and promoted understanding among participants of climate uncertainty, likely future climate conditions, and the operation of the microbasin system as simulated by the modeling framework. It was important that everyone understand how model analyses were produced and what they meant. By pre-screening presentations, it was possible to improve their ability to communicate. Perhaps surprisingly, there was no resistance among the presenters to critiques that focused on communication to stakeholders. There was, however, in-depth discussion on how to translate the technical content without losing scientific integrity. An informal evaluation indicated that participants were satisfied with results.

Organizations that facilitate translation of science to use typically provide expertise that neither the research user nor the research provider possesses [57]. Thus, convening and nurturing stakeholder engagement is often best carried out by such an organization, which can tailor the processes and tools to specifics of the issue context [43]. Tailoring engagement processes and tools 3has been demonstrated to improve participation and outcomes [54]. The University of Arizona Water Resources Research Center provided these functions as a bridging organization. The WRRC brought together expertise in the modeling framework and climate science with expertise in the groundwater management context and the knowledge of concerned stakeholders for open exchange. Efforts to engage stakeholders and to keep them engaged involved frequent individual communication. Stakeholder comments and suggestions, not just from the advisory committee guided design of communications and workshop agendas. Facilitation during workshops afforded balance and direction to discussions.

In the co-production process, certain types of exchanges between scientists and other actors have been associated with successful stakeholder engagement. For example, Phillipson *et al.* found research was more likely to have an impact on stakeholders who participated in events, such as workshops, where they provided feedback on research findings [24].

Workshops were designed with the intension of providing in-depth background information first, in order for stakeholders to be able to discuss use of the model on the basis of shared knowledge. The focus of the background presentations necessarily shaped the following discussions. In addition, facilitators were prepared with questions to prompt discussion that also focused attention on project goals. These factors may have limited the range of topics discussed, but helped elicit information about stakeholder concerns specifically relevant to model scenario development and analysis. Facilitation also encouraged participation.

5. Conclusions

The GCASE case study provides one example of how knowledge co-production can be achieved through use of a hydrological model when two-way interactions are focused on development of usable science. Best practices in stakeholder engagement were employed in the GCASE project, which sought to enable decisions relating to the unique SCAMA groundwater management goals. The modeling framework, which was the focus of stakeholder engagement, provided the capability to integrate climate-related uncertainty in groundwater management decision processes. Stakeholders possessed context specific knowledge necessary for model analyses, and scientists acknowledged the need to educate stakeholders and to learn from them. A bridging organization ensured that stakeholders and scientists engaged in two-way communication regarding the use of the modeling framework.

The hydrologic modeling framework was developed in previous work for the SCAMA involving collaboration with ADWR, which has its own public participation policies, but without a well-defined process for stakeholder engagement. Its selection, enhancement, and use with stakeholders were based on the previously perceived need to account for climate uncertainty in simulations of groundwater behavior. The use of an existing modeling framework specifically developed for the study region focused stakeholder involvement on defining issues for analysis and scenarios for model simulation.

A statewide moratorium on rulemaking created a disconnection between the GCASE results and groundwater management decision making. Thus, stakeholders focused their attention of developing an understanding of model capabilities, climate change implications, and groundwater management. Although workshops in which scientists and stakeholders co-produced system knowledge advanced common understanding of these issues, rulemaking was not directly affected. Intimate involvement of ADWR personnel, however, aided communication among scientists, stakeholders and decision makers that focused interest on the potential of the project approach. The web-based data service being developed through a follow-on project resulted directly from knowledge co-production with influential stakeholders, specifically members of the SCAMA GUAC and ADWR modelers.

Workshops presented positive evidence that stakeholders and scientists who engage in facilitated two-way conversations can co-produce useful knowledge if they adhere to principles of respectful relations, dialogue, and focus. It was evident from discussions that stakeholder grasped the implications for groundwater managements of model outputs and the scientists grasped the implications for their research of stakeholder input. Transferability discussions produced suggestions for modifications of the modeling framework to fit new conditions and management issues.

The GCASE case study demonstrated the usefulness of best practices as offered by the literature on stakeholder engagement. Pre-existing knowledge of the stakeholders and their context can help tailor general guidance to a specific case. Personal contacts are useful in engaging key stakeholders and should be cultivated over time. Bridging organizations with a history of cultivating stakeholder contacts can supply the context knowledge and personal contact. Such organizations also can monitor and improve communications that are relevant to a co-production project.

The case study also illustrated that construction of stakeholder engagement around published strategies for successful co-production of knowledge can produce joint learning. Seeking the advice of key stakeholders, attention to stakeholder networks, and ensuring that diverse knowledge are represented all contributed positively to GCASE outputs. Important activities that expanded the toolbox of stakeholder communication included negotiating meaning and previewing workshop presentations. The productivity of workshop dialogue on the model and its use was enhanced by skilled facilitation, which ensured that model analyses were responsive to stakeholder queries. Finally, transferability assessments established the potential for future GCASE style projects.

Over the long term, however, efforts at knowledge co-production may be limited by resources and time constraints. Bridging organizations with established connections to the stakeholder community can maintain relationships and trust built up over the course of successful co-production processes as a basis for other projects. Results of individual projects ideally have a long-lasting impact on the resolution of groundwater management issues; however, widespread understanding and acceptance still depends on maintaining communication with a cast of interested parties likely to change over time. Maintaining communication may depend on structural support for long-term engagement mechanisms.

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Abbreviations

The following abbreviations are used in this article:

ADWR	Arizona Department of Water Resources
AMA	Active Management Areas
GCASE	Groundwater, Climate, and Stakeholder Engagement
GUAC	Groundwater Users Advisory Councils
HRC	Hydrologic Research Center
NIWTP	Nogales International Wastewater Treatment Plant
SCAMA	Santa Cruz Active Management Area
WRRC	University of Arizona Water Resources Research Center

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