Serrat-Capdevila, A., A. Browning-Aiken, K. Lansey, T. Finan, and J. B. Valdés. 2009. Increasing social–ecological resilience by placing science at the decision table: the role of the San Pedro Basin (Arizona) decision-support system model. *Ecology and Society* **14**(1): 37. [online] URL: http://www.ecologyandsociety.org/vol14/iss1/art37/

Research

Increasing Social–Ecological Resilience by Placing Science at the Decision Table: the Role of the San Pedro Basin (Arizona) Decision-Support System Model

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ABSTRACT. We have analyzed how the collaborative development process of a decision-support system (DSS) model can effectively contribute to increasing the resilience of regional social–ecological systems. In particular, we have focused on the case study of the transboundary San Pedro Basin, in the Arizona-Sonora desert region. This is a semi-arid watershed where water is a scarce resource used to cover competing human and environmental needs. We have outlined the essential traits in the development of the decision-support process that contributed to an improvement of water-resources management capabilities while increasing the potential for consensual problem solving. Comments and feedback from the stakeholders benefiting from the DSS in the San Pedro Basin are presented and analyzed within the regional (United States–Mexico boundary), social, and institutional context. We have indicated how multidisciplinary collaboration between academia and stakeholders can be an effective step toward collaborative management. Such technology transfer and capacity building provides a common arena for testing water-management policies and evaluating future scenarios. Putting science at the service of a participatory decision-making process can provide adaptive capacity to accommodate future change (i.e., building resilience in the management system).

Key Words: *collaborative development; decision-support system model; participatory water management; resilience; social–ecological systems; stakeholder feedback; sustainability learning*

INTRODUCTION

Mankind has drastically redefined its relationship with the earth's environment in the last 150 years. These changes are at a scale that is perhaps only comparable with the discovery of agriculture 10 000 years ago. Industrialization and significant technological advances have caused fast and dramatic changes across human societies. The discovery and use of fossil fuels (albeit soon, perhaps on the decline) and related greenhouse-gas emissions mean that human development is affecting global climate dynamics and changing land–atmosphere interactions. Although these developments have prompted increases in production systems, economic growth, and population growth, all life on our planet is now confronted with the challenge of adapting to the resulting global environmental changes. The sustainable management of systems and resources is now taking central stage, and terms such as "resilience" (i.e., the capacity to adapt to change and uncertainty) are the focus of multidisciplinary research efforts.

Population growth, industrial development, and extensive agriculture have meant that societies in many parts of the world are running out of available water resources. Tensions are increasing internationally on this issue. Efforts to solve this "tragedy of the commons" have led to two main conclusions. First, at the basin level, cooperative integrated water management may produce improved benefits (Snellen and Schrevel 2004). Second, at a local scale, "bottom-up"organization may be an efficient mechanism for water allocation and conservation (Lansing 1991). The concept of bottom-up organization implies that public participation in

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water-resources management at a local scale will influence decisions and policy making at this level as well as at higher levels of administration.

We analyze how the collaborative development of a decision-support system (DSS) can effectively contribute to increasing the resilience of regional SESs. We focus on the transboundary San Pedro Basin in the Arizona–Sonora as a case study. This is a semi-arid watershed where water is a scarce resource that is used to meet competing human and environmental needs. We explore the traits essential to the development of a decision- support process that contributed to an improvement of water resources management capabilities here (and advancing regional sustainability goals), while increasing the potential of consensual problem solving. Stakeholders (working in a partnership) who benefited from the DSS in the San Pedro Basin have provided comments and feedback on the process of model construction and use. We analyze these within regional, social, and institutional contexts. We argue that putting science at the service of a participatory decision-making process provides the adaptive capacity to accommodate future change (i.e., building resilience in the management system).

After discussing the methods we used, we review the meaning of resilience and outline how it relates to concepts of sustainability, equity, and justice. We then focus on attempts to bridge theory and practice. We provide a brief description of the institutional landscape within which the DSS was developed, and describe how the DSS initiative emerged and developed. We describe how the DSS model development process was analyzed in terms of its potential contribution to a more resilient SES in the San Pedro Basin, and outline the capacity of the process to help the partnership address its sustainability challenges. We present a thematic analysis of the interviews conducted with partnership members, and outline the key contributions of the DSS development process, lessons learned, and influence of the process on policy making. We then elaborate on the contributions of the DSS development process to building better capacity for facing new challenges, and a resulting increase in social–ecological resilience in the Upper San Pedro Basin. Finally, we summarize the findings of our work.

METHODS

The objective of the current research was to gain insights into the essential traits of the San Pedro DSS development process. We have sought to uncover what contributed to an improvement in water-resources management capabilities with respect to regional sustainability goals, and to an increase in the potential of consensual problem solving. This is a post-intervention assessment of a concrete social process.

As our research was focused on a very concrete process that took place primarily within the technical committee of the Upper San Pedro Partnership (USPP), the sample of individuals involved is relatively small. These individuals represent different stakeholder agencies and interest groups from a range of backgrounds. The insights we obtain are generally qualitative rather than quantitative. For these reasons, we attempted to sample as many individuals involved in the process from as many stakeholder groups as possible, in order to capture the greatest variety of perspectives, opinions, and insights. Such an approach captures variability. Although the results may not be directly applicable to other settings, some key lessons may be generalized (with care and accounting for the broader context). Once we became familiar with the DSS model and gained an understanding of model components, dynamics, and sets of alternative management strategies, we carried out our field research.

We observed participants at the monthly technical committee meetings of the USSP. The goal in attending these meetings was to witness and gain familiarity with the process in terms of discussion, participation, stakeholder involvement, and the interactions between scientists and different stakeholders. This was essential to understanding the collaborative process, in order to contextualize the results of the personal interviews that constituted the next phase. We interviewed the 17 stakeholder members of the USSP who were involved (directly or indirectly) in the development of the DSS model. The interviews were carried out in person and through phone conversations. They were 1 h long on average. Although a list of explicit questions was prepared, they were formulated to provide a topic outline that would avoid constraining individuals in their roles and allow for a more open frame of engagement. This flexible format allowed the subjects to elaborate on related ideas, providing the opportunity to access new ideas and facilitate continuity in the conversations. The interviews were designed to gather opinions, criticism, and suggestions from the stakeholders regarding the process in which they had participated. We were seeking commentary on what was particularly positive about the process (i.e., what contributed to better management and problem solving), what could have been improved, and what should have been done completely differently. Patterns of opinions and their correlation with the individual stakeholders' affiliations were analyzed. Finally, we sought impressions on the contribution of the model development process to solving management challenges and providing resilience for the future.

BACKGROUND

Resilience and Sustainability

Human and natural systems coevolve and are integrally linked together. The response of ecosystems to human use is rarely linear, predictable, or controllable. As noted by Scoones (1999), there are three main characteristics of the "new ecology" movement: the acknowledgement of uncertainty, dynamics, and complexity; the exploration of nonlinear interactions across different-scale systems (and a more global approach to recognizing spatial patterns); and a historical memory of systems and their temporal dynamics. The relevance of these concepts is well-illustrated by the challenges of water resources management in SESs and their associated dynamics. "Resilience" refers to the potential of a system to remain in a given configuration (maintaining its functionality), to reorganize itself after a disturbance, and to adapt to change (Holling 2001). The term "adaptive capacity" is also sometimes used to indicate resilience. Building resilient systems involves learning, the flexibility to experiment and adopt new solutions, and the ability to respond broadly to challenges.

Building resilience in a system requires enhancing social, economic, ecological, and other structures and processes that enable it to reorganize following disturbances and in the face of new challenges, in addition to reducing factors that undermine the system. Adger (2003a) claims that as resilience and vulnerability are both shaped by global and local economic forces, the ability to deal with these issues depends on how we frame sustainability questions within environmental policy, and how we weigh the benefits of sustainability against free trade, economic choices, and growth. Objectives that guide the quest for sustainability at different scales include building the capacity of societies to manage their resources appropriately, and fostering decision-making that promotes stability and adaptation to unforeseen circumstances. In natural-resource management, concepts of justice and equity can be directly related to flexibility, self-organization, diversification, freedom, and the ability to adapt. These properties, along with issues of sustainability, arise from the entitlement to, and access to, resources and security. Adger says that together justice and resilience promote sustainability. Justice in a sustainable system is measured by the outcomes of resource allocation and policy decisions. It describes how both the adverse and beneficial effects of human actions are distributed across society. Sustainable management must include a recognition of value differences, and representative participation from different sectors of society in the decision making process. Decision making processes are only just and equitable if there is fairness in terms of representation when building empowerment for self-governance. Fundamental questions of resource management and politics include who decides who gets what, when, and how, and how we decide such things (Blomquist and Schlager 2005). The way these issues are embedded in the management of a system is key to its sustainability and resilience.

From Theory to Practice: System-Specific Resilience

The evaluation of social–ecological resilience in real-world systems and adaptive capacity within water-resources management settings are relatively new concepts. The application of resilience knowledge can currently only be done at certain scales. At the largest scale, the earth is a global ecosystem, composed of many smaller SESs that are interlinked, have more or less permeable boundaries, and are divisible into a myriad of minor connected systems. Recent literature on natural-resources governance has focused on multistakeholder involvement and participatory management (Ridder et al. 2005). Arguments for collaborative resource management focus on a process that generates mutual understanding and trust that, in turn, create a sense of legitimacy (Bingham 1986, Born and Genskow 2001, O'Leary and Bingham 2003, Sabatier et al. 2005). The role of collaborative participation in "face-to-face information exchange and problem-solving among all the relevant stakeholders" (Weber 1998) is emphasized. Lemos and Morehouse (2005) argue that usable knowledge is coproduced in the context of interactions between scientists, stakeholders, and policy makers. Similarly, Scott et al. (1999) regard science–stakeholder collaboration as a form of interactive research where "researchers, funding agencies, and user groups interact throughout the entire research process, including the definition of the research agenda, proper selection, project execution, and the application of research insights." Acknowledging that a small group can no longer learn and manage on behalf of all other stakeholders (Pahl-Wostl et al. 2007), the concept of "social learning" sheds new light on an understanding of the management process (Pahl-Wostl 2002, Craps 2003, Bouwen and Taillieu 2004, Pahl-Wostl 2007).

Attempts to assess system-specific resilience have examined a series of characteristics: stakeholder development of conceptual models, the importance of a multidisciplinary approach, the selection of sustainability indicators, the significance of the site-specific context, and the development of social networks and institutional knowledge. Walker et al. (2002) present an approach to analyze and manage resilience with the close involvement of stakeholders. This approach has four phases: stakeholder-led development of a conceptual model of the system, stakeholder visions for the future, an exploration of the SES for resilience in an iterative way, and stakeholder evaluation of the process and outcomes in terms of management implications. Walker et al. (2002) argue that multidisciplinary discussions will contribute significantly to building a common understanding of resilient pathways, and of what is sustainable in the long run. Their conceptual approach is similar to the process that has taken place within the USPP as it developed the DSS model in response to water-management challenges in the San Pedro Basin. Similarly, Lynam et al. (2002) present two case studies where models were developed and used with stakeholder participation to tackle common resource-management problems. Discussions were facilitated with the use of different participatory tools (spidergrams, spatial mapping, belief models, and multi-agent system models) so that stakeholders would find a common understanding, define goals and priorities, and propose potential alternative solutions to address problems. They found that (1) models played a key role providing a common and changeable representation of the problem, (2) models are imperfect but important for recording the evolution of understanding a system, and (3) local people tend to take ownership of an initiative in such a context.

Carpenter et al. (2001) emphasize the need to contextualize resilience as a site-specific measure, as well as the variables that control it. In a similar way, Adger (2003a) states that the characteristics of adaptive capacity in a given location are culture specific and place specific. He argues that the social dynamics of adaptive capacity are defined by the ability to act collectively. Many aspects of adaptive capacity reside in the networks and social capital of the groups that are likely to be affected, both in developed or developing country settings. Their ability to make a sustainable transition will be determined in part by their networks and social capital. Social and institutional diversity itself promotes resilience (Adger 2003b, Folke et al. 2005). This observation is becoming clear in coevolving social–ecological systems in general. The relevance of social networks is also highlighted by Crona and Bodin (2006). They examine the communications networks related to natural resource extraction by villagers in a coastal community in Kenya. The authors discovered that communication was very limited between groups using different resource- extraction techniques, inhibiting an exchange of ecological knowledge and the successful regulation of resource-extraction. Thus, a lack of collective action being taken to address an unsustainable situation is likely to be conditioned by the structure of local social networks. Related studies in settings in developed countries also underline the importance of social networks for solving collective resource-management problems (Shannon 1998, Olson and Folke 2001, Olson et al. 2004).

Other published work presents conceptual models for sustainable participatory resource management, giving recommendations as to how integrated water-resources management should be carried out and what the role of each involved entity should be. We do not intend to present another new conceptual framework or speculate as to how problems should be solved. Instead, we analyze a real-world process. We present the collaborative development of a DSS that identifies high-quality solutions to human-induced environmental problems. We summarize the feedback given by the involved stakeholders, including their perceptions and what they feel has been learned. We distill the relevant key points for resilience and sustainability. Although we contextualize the resilience analysis in the San Pedro watershed and its social–ecological setting, our findings are exportable and may be useful elsewhere.

The San Pedro Basin: Regional and Institutional Context

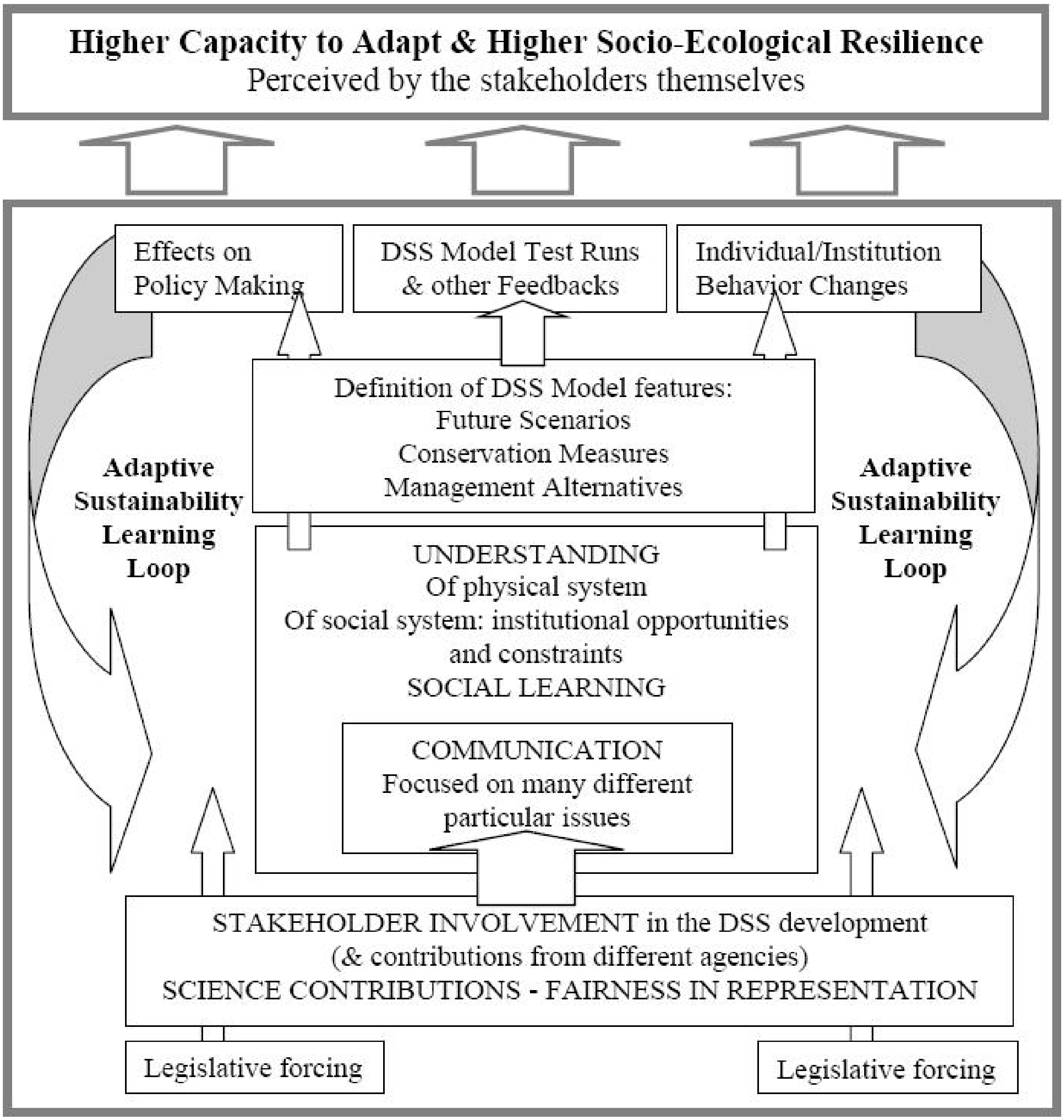
The San Pedro River originates in northern Sonora, Mexico, and flows north into Arizona, USA, eventually joining the Gila River that flows into the Colorado River (Fig. 1). The Upper San Pedro River Basin (USPRB) covers approximately 10 660 km^2. Arizona encompasses 74% of the study area and Sonora encompasses the remaining 26% (Steinitz et al. 2003). The USPB is home to approximately 177 755 people in Arizona (Steinitz 2003) and 32 000 in Sonora (INEGI Census 2000) who live and work in seven incorporated towns and several unincorporated communities. The USPRB is one of the most ecologically diverse areas in the western hemisphere. It contains perhaps 20 different biotic communities and supports a number of plant and animal species of special concern to both the United States and Mexico. Issues of water allocation for human and environmental uses are of critical concern and have led to divisiveness among water users and water-management entities. Agriculture, cattle grazing, mining, and recreation remain the predominant land uses, although they are being supplanted by increasing urbanization.

The San Pedro Riparian National Conservation Area (SPRNCA), an approximately 18 200-ha area in the Arizona portion of the San Pedro Basin, is managed by the United States Bureau of Land Management (BLM). The United States Congress established the SPRNCA as a major North American migratory bird corridor in 1988. However, this did not automatically ensure its survival. The goal of the SPRNCA is to protect the 60-km riparian corridor north of the United States–Mexico border. Population projections for the U.S. portion of the basin parallel those elsewhere in the southwest, with a roughly 50% increase projected from 2000–2030. This will result in a major increase in water use to support municipal and domestic needs. In the face of such projected population growth, great concern remains regarding the long-term viability of the San Pedro riparian system. Groundwater is essential for sustaining the baseflow within the river during dry seasons.

Most of the demand for water in the basin has been for mining, municipal use, domestic use, and irrigated agriculture. Recent research suggests that riparian vegetation also requires a large portion of the water budget. The basin is currently considered to be in a water deficit, with annual water withdrawals exceeding recharge by approximately 6–12 million m^3. Water use is increasing and is expected to continue to do so. A predicted decline in the availability of water in northern Mexico not only threatens the viability of the San Pedro River, but exacerbates the increasing competition for water resources among the agricultural sector, the industrial sector, and domestic consumption (Magaña and Conde 2001). The groundwater deficit in the basin threatens the baseflow in the San Pedro River. This in turn threatens the existence of the largest local economic engine, the Fort Huachuca military base. The existence of this base is tied in part to the health of the river because of legal implications of the Endangered Species Act.

In the past century, adaptation processes such as investments in infrastructure and technology (dams, canals, wells, electricity, and groundwater pumps) and institutional arrangements such as insurance policies, have greatly reduced perceptions of climate vulnerability. However, even if technological investments represent an adaptation to climate variability, they may not be sustainable over the long term, because their effects have yet to be seen (Finan et al. 2002) and may include stimulating demographic growth in the basin. If pumping extractions exceed natural recharge, then the water resource is being mined, and the dynamics of aquifer-related ecosystems will be negatively affected. That is precisely what is happening in the San Pedro Basin, where the river and its riparian area are closely linked to the aquifer, naturally allowing perennial flows in the desert during seasons without rainfall. When groundwater pumping is excessive, the water table is lowered and it gets disconnected from the riparian area. At this point, the river goes dry and phreatophyte vegetation (i.e., trees that need to access groundwater with their roots) dies. These links, their spatial nature, and the implications for sustainability, are not easily understood by the general public, making it difficult to collectively address the situation.

Figure 1. The authors' conceptual representation of the DSS development process in the San Pedro Basin, illustrating the key mechanisms contributing to resilience in the basin's social–ecological system.



In response to the region's water issues, stakeholder entities in the Arizona portion of the Upper San Pedro created the USPP under an interagency memorandum of understanding in 1998 to facilitate and implement sound water management and conservation strategies in the Sierra Vista subwatershed of the basin. The USPP is a consortium of 21 members including federal, state, and municipal agencies, such as the Fort Huachuca Military Base, BLM, Cochise County, City of Sierra Vista, and non-governmental organizations such as The Nature Conservancy and the Audubon Society. The full list of member agencies (either land or water stakeholders in the basin or agencies providing resources to help the partnership accomplish its purpose) and their profiles can be found at http://www.usppartnership.com/about_memberagency.htm . The USPP is structured into three committees: (1) the partnership advisory committee (PAC) (the decision making body analogous to a board of directors) representing all member entities, (2) the executive committee (the administrative and implementing arm) representing all member entities that make financial contributions to operations and projects (i.e., that have "project responsibility"), and (3) the technical committee, providing technical and scientific advice and oversight by participating and by coordinating and synthesizing research findings and information for partnership members and others. The technical committee is composed of members with professional and scientific credentials, representing member entities. It reports to the advisory committee, so that decision making has the best available scientific basis.

This partnership has made considerable progress toward achieving its goals, but the remaining challenge of reducing groundwater use a further 40% during times of drought is daunting. The DSS model was developed in order to help decision makers understand the impacts and cost-effectiveness of alternative water-conservation measures and management policies (Richter 2006).

The DSS Model Development: A Collaborative Process

Since its inception in 1999, the USPP's mission has been to find sustainable solutions for the management of water resources in the San Pedro Basin. In its commitment to science-based decision making, the partnership involved scientists from the beginning. The idea of a DSS model for the Upper San Pedro Basin was first discussed in 2000–2001. The chair of the USPP technical committee requested that different experts come and talk about their experiences with DSS models to see whether the idea might be of benefit to the partnership. In particular, a hydrologist who was developing a dynamic DSS model for the Middle Rio Grande Basin in a similar collaborative way, presented the potential capabilities of such tools for decision making (Tidwell et al. 2004). Connections to the University of Arizona led to the involvement of faculty with the right expertise who were interested in conducting stakeholder relevant research in the area. After several demonstrations of the capabilities of system-dynamics modeling in support of decision making, the USPP decided to proceed with this.

A report had already been commissioned for a semiquantitative analysis of potential alternatives, considering interbasin transfers and conservation measures. The USPP was in need of a user-friendly way to handle large amounts of information, and evaluate different management alternatives and the impact of decisions. The different options and strategies outlined in the report constituted the starting point for the conservation measures packages that would be built into the DSS model. The DSS initiative evolved from a reconnaissance-level project to a two phase modeling project. The first phase of the model accounted for an overall water budget with a set of conservation measures and management alternatives. The second phase of the project included linking the DSS with a detailed groundwater model developed in parallel by the U. S. Geological Service.

Funding for the model development came from different sources during the process. Initially, it was funded exclusively by a science and technology center at the University of Arizona supported by the National Science Foundation (Sustainability of semi-Arid Hydrology and Riparian Areas (SAHRA)), with a strong mandate to support stakeholder-relevant research. After the first year, the partnership provided a 50% match for these funds. The project also benefited from other funding opportunities.

Discussions regarding model development were held at monthly meetings of the USPP technical committee, generally in Sierra Vista (located in the basin). The development of the model was a collaborative and open process in which any of the partnership stakeholders could participate. Members found common ground on alternatives and conservation measures to be built in the model, assumptions to be made, the design of a user-friendly interface, and other relevant issues. In each meeting, the main modeler presented advances made on the model based on previous discussions, and sought approval from members. If necessary, items would be re-discussed and could be changed. As the model developed, the technical committee reported back to the PAC and the general public attending the meetings, in order to elicit feedback. Although stakeholders from the Mexican part of the basin did not participate in the model-development process, a history of collaborative efforts exists, and workshops regarding DSS modeling capabilities took place with Mexican water-management authorities. The Mexican National Water Commission's (CONAGUA) recent creation of a multistakeholder basin council for the Mexican portion of the basin may well be a result of the efforts mentioned above. This sets the stage for future collaborations.

Although the main objective of developing the DSS model was to provide a decision-making tool and a common ground for communication, the development process itself provided an open door for the direct involvement of stakeholders and decision makers. The scientists' role was that of the technical facilitator.

RESULTS AND DISCUSSION: STAKEHOLDER FEEDBACK

The results of this research have been structured around operational constructs or themes that capture the range of contributions of the DSS development process to resilience. These include communication, understanding, the development of institutional networks and knowledge, the role of multidisciplinary scientists in the DSS development, fairness in representation, the influence of the DSS process on policy making, and an improved ability to adapt to future challenges. The stakeholders' views on what should have been done differently constitute the lessons learned. Figure 1 is our graphical representation of the DSS development process and illustrates the key mechanisms that we believe have contributed to resilience in the basin's SES.

Communication, Understanding, and the Development of Institutional Networks and Knowledge

According to the individuals we interviewed, the communications associated with the DSS development process (alllowing stakeholders to interact verbally during meetings and express their opinions regarding what went into the DSS model, and how it was fed in) served multiple purposes. The development of the model forced the involved individuals to focus their communications on particular issues, ranging from processes and features represented in the model, to assumptions, conservation measures, and alternative scenarios. The main sets of options containing each group of conservation measures and policies, and their links and overlaps, had to be well defined and agreed upon. As the model was developed collaboratively, every single decision embedded in it was a product of extensive discussions between scientists and stakeholders during the periodical meetings of the technical committee. This required bringing a range of stakeholders with different backgrounds and scientific knowledge onto the same page. Preliminary findings presented as the model was being built also stimulated further discussions about improvements and updates. The model development process provided an excellent setting for ongoing simultaneous discussions about different issues. In the words of one participant, it provided an ongoing "opportunity to ask questions, focused questions, the good questions." Focused and itemized communication was the key to a better understanding of the overall behavior of the system, the nature of the problem, and alternative solutions.

The DSS development contributed to an enhanced understanding for participants at many levels (along with other scientific processes within the USPP). First, it helped stakeholders (such as city managers) understand the physical system, and in particular the spatial distributions of pumping and land-use management effects on the riparian corridor. The location and intensity of pumping or artificial recharge processes would have different effects on the water table adjacent to the San Pedro River. Visual tools developed by scientists (in particular, the "capture map" developed by the U.S. Geological Survey) were especially useful. This tool is a contour map that demonstrates, in particular locations, the percentage of water that would be removed by the drilling of a well (water that would otherwise contribute to flows in the river). It clearly depicts the areas where pumping would have a more immediate impact on the riparian area (Appendix 1). Referring to the DSS as well as other scientific processes, one participant noted that "the DSS has allowed people to understand groundwater pumping impacts in the river; it allows stakeholders to realize there is this connection, that we are actually altering the hydrological system." Further a high-level member of the USPP stated that "it showed the need for preventing development along the Babocomari River and the San Pedro, that we needed to restrict well density, especially in certain areas, and also showed the benefits of closing down alfalfa fields. The science process has been very good for land-use planning and zoning." Although changes in behavior are hard to assess, it is nonetheless clear that a better common understanding of the physical riparian system (including the impacts of pumping) led to a generalized acknowledgment of what actions were more or less sustainable in the riparian area.

In addition to providing a better understanding of the natural system, the DSS process allowed for a better understanding of the drivers and constraints of each stakeholder and the agencies being represented. The complexities of the negotiation process can only be understood by determining what drives each agency's decision making, and which measures are politically feasible, legally possible, and economically viable. One stakeholder reported "I understand now the challenges of legislation that has to balance the needs of their constituency and the needs of the environment. It is a complex suite of decisions to be made." The process, therefore, provided insights about what limits existed on each stakeholder's range of action. The "nontechnical" people indicated that they learned about the overall functioning of the models and how the groundwater model and the DSS were linked, as well as the limitations of the models. Parallel to this, the stakeholders reported learning each other's "language and jargon, and what we really mean when we speak."

The perceptions of different stakeholders about each other's concerns seemed to depend on the direction of understanding. Participants tended to report that they understood other people's concerns better, but were not necessarily satisfied with other people's level of understanding of their own concerns. This process of building an understanding of individual values and perceptions at the same time as an understanding of the complexity of the SES can be regarded as a form of social capital. Putnam (1993) views social capital as "features of social organization such as networks, norms, and trust that facilitate coordination and cooperation for mutual benefit." Social capital is created as an organization's members establish understanding and trust, and it is part of the knowledge and understanding, norms, rules, and expectations shared by individuals participating in a collaboration (Coleman 1988, Ostrom 2004). The Resilience Alliance (2006) argues that not only must policies seek to transfer knowledge and understanding to local individuals, but they must also develop institutional flexibility by encouraging the formation of networks of individuals that bridge institutional boundaries. These groups of individuals can act as agents of reform within their institutions, and the nucleus around which new institutions can crystallize. These individuals would represent the catalyzers of an adaptive complex system and benefit from institutionalized capacity building regarding environmental knowledge about the SES. Indeed, multistakeholder representatives in public-participation processes need these kinds of individuals to function effectively.

Several partnership members (actively involved since the partnership's inception) noted that it would be hard to attribute an improvement in understanding to the DSS development process exclusively, separate from the ensemble of previous and current working processes ongoing in the partnership. Although the technical committee assumed the role of "the science feeder" into the broader partnership, it is acknowledged that other processes may have also contributed to an increase in understanding, social capital, and institutional knowledge.

The Roles of Scientists in the DSS Development Process

Science was brought to the negotiation table by several of the organizations involved in this process, including the U.S. Department of Agriculture's Agricultural Research Service and Southwest Watershed Research Center, the U.S. Geological Survey, the Udall Center for Studies in Public Policy (University of Arizona), and SAHRA (University of Arizona), which is responsible for developing most of the DSS model. The individuals with scientific backgrounds representing these organizations contributed hydrologic and land-use data, modeling expertise, environmental conflict mediation procedures, and knowledge of the political and policy process. The process benefited from a broad range of disciplines. Those on the technical committee believe this will continue. As one of the participants stated, “in this process, I learned a lot from other disciplines, things I would otherwise hardly have ever learned.” All but one individual indicated that the scientists from the participating organizations were “instrumental,” “with very high abilities,” “crucial,” “essential,” “doing a very good job,” “highly thought of,” and “able to communicate very technical things in layman’s terms.”

The scientific process and the scientists involved were well described by one individual, who commented “...really good job...they are highly thought of within the broader USPP. The need for science is recognized by everybody, although some people may not want that, since it legitimates the outcomes of the model and its findings and there is less room for wiggling. It legitimates results all the more by the fact that there is input from various scientists. It really helped, especially for the understanding of laypeople.” Thus, the contributions of science, multisector involvement, and multistakeholder participation were very visible factors in terms of developing networks that enhanced local knowledge systems.

The overall ability of the DSS model to replicate the hydrological system was derived from, and tested against, a detailed groundwater model developed by the U.S. Geological Survey. The DSS was able to replicate the overall hydrological system with enough accuracy to perform its decision–support function. It is state-of-the-art science. However, where there were simply no data available to provide estimates about certain processes or phenomena, assumptions had to be made. These were relatively small components of the overall water budget, and they do not represent a significant component of the overall functioning of the hydrological system. Initial uncertainty with such issues was dealt with through extensive discussions among the stakeholders. In such cases, the most likely value range was narrowed down with further research, information from existing studies, and other collected data. As one participant said, “as decisions are driven by consensus, there is always some science or data somewhere that can be used to obtain a best guess.” Although all the interviewees expressed satisfaction with the process, the final assumptions made, and the estimates used in the model, there was an impression that individuals tended to defend numbers that supported their case. As an example, the issue of recharge through artificial detention ponds came up many times. Some stakeholders claimed that recharge volumes were much higher than they actually turned out to be. Through subsequent data gathering and discussion, this was corrected. As one participant noted, “with time, estimates get very reasonable.” One individual observed that even though assumptions might initially seem reasonable, the challenge was to keep an “audit trail” to explain or justify them to the principal stakeholders at a later date. The suggestion was that the process and the basis for decisions should be documented. One participant provided a good summary. “It takes longer to agree when there is less science, and we usually end up in the middle since we have a broad group of stakeholders. Coming up with budget numbers, leakage estimates, ...the process of having to develop the DSS has been very good in helping to define additional research needs, helping realize what you don’t know, in terms of both research and monitoring.”

Fairness of Representation in the Process

All participants agreed that the DSS model development process was inclusive, open, and fair. Several stakeholder groups did not have “project responsibility” (the entitlement to implement water- and land-management projects) and chose not to participate in the DSS development process, although they showed interest in its outcomes. The participating entities were in complete agreement that representation was fair and objective. The meetings were led by a very skilled individual with a background in ecological science, and abilities as a moderator that were well recognized within the stakeholder group.

This characteristic fairness and willingness to accommodate all points of view did, however, make this a time-consuming process. One participant commented on the ongoing debate between economic growth and ecosystem sustainability (referring to the wider partnership at its early stages rather than the technical committee). “Early on... there was heavy political representation. They had this growth mantra. But these politics had little impact on the technical committee itself.” The nontechnical people, and particularly those often referred to as “policy people” who were outside the

USPP technical committee were described as "overanxious" for the DSS to be completed on a short timeline. These individuals were not directly involved in the model development process and appeared not to appreciate to the same degree the benefits of such a collaborative process.

Lessons Learned: What Would You Change?

Those interviewed were asked what they would change in the DSS development process if they had to start from scratch. The main criticism (from all parties, including the modelers themselves) is that the process was very slow. Nonetheless, some of those involved in the model development felt that the benefits from it accrued before its completion. In other words, the model development process contributed greatly to addressing problems in the basin, long before the product was completed. Those interviewed were pleased with the final product, and acknowledged that it should be continually updated to evolve alongside the real-world situation, including the implementation of new projects and conservation alternatives. The comments about changes in the process are summarized below.

- Try to do it faster.

  The slow pace of developing the model took its toll on efforts to maintain momentum, interest, and the belief that the initiative would be useful. Because of the extended timeline, there was concern that some of the ideas and alternatives in the DSS might be outmoded or obsolete by the time the model became operational. Yet some individuals also acknowledged that it takes time to build trust and operate by consensus.

  One participant in particular (with a managerial background) was very critical of the long timeframe involved with the scientific discussion. He stated that discussions about "...how to phrase documents or present results for the greater public can go on for months." He argued that "the public is not going to learn hydrology and doesn't need to know words like evapotranspiration or ephemeral." "The smartest person wasn't there when something was decided and a month later he/she comes to the meeting and re-starts a discussion and changes things that were already decided. And then we have to go back and have to go through stuff again and change things. We need to go from an academic exercise to something in the engineering world. We have to go from the planning tools to the shovel!"

  Another participant with limited involvement in the process suggested that perhaps the modelers "didn't state strongly enough the model's limitations, that it provides a relative scale of results," and "perhaps they should talk more in probabilistic terms."

- Better management of expectations.

  A more realistic acknowledgement of the time needed to complete the construction of the model would have reduced the feeling of frustration caused by the slow process. One participatant stated that "[the main modeler] always talked as if the model completion was around the corner."

- A clearer chain of responsibility and a business contract.

  The main modeler reported back to the technical committee at monthly meetings. It was percieved that sometimes members were not present when a decision was made and, therefore, the issue would be put back on the table in a following meeting. It was also felt that the technical committee often checked back with the broader USPP to seek approval for decisions. One participant suggested that political representatives should have been on the committee with insights and the "power to say what to put in the model." Another individual also suggested that the main modeler should report back to a single individual (a project manager) rather than directly to the technical committee. The same individual stated, "if we were bound to a financial budget within a financial year, we would be forced to work on a timeline and within a budget." Another policy-level participant stated that the complete absence of a business contract, where results are promised in a certain time for a certain amount of money, was a problem. When asked if he would rather have contracted the work to a consulting firm, he answered, "no, no, I would do it the same way but would wish that academia [took] more into account the time deadlines that we have." On the other hand, a technical person (not from academia) stated that the feedback loops and communications between the main modeler and the USPP were necessary and that most of the work on the model should have been done by a small group of "worker bees." "If all the people (including policy people) had been involved, progress would have been almost impossible. [If there is] no consensus, [then there is] no advancement."

- More outreach and public input.

  One participant stated that a more aggressive approach to getting everyone to understand the model was necessary, so that they would trust the model upon completion. He commented on the need to keep the stakeholders and the public updated on the inner workings of the model.

- Involve policy people from the beginning.

  A number of individuals stated that policy people ought to have been more involved in the process, as the DSS was meant to be a tool for decision makers. Many individuals stated that there was a gap between the technical people and the policy people. Although the DSS was in the hands of the technical committee, it was as if the policy and management people walked away saying, "call me when you are finished." The consequence of this was the perception that there was a gap between the political realm (where things are constantly evolving) and the DSS model that, as previously stated, took a great deal of time to be developed by consensus. Because certain policy people were not involved in the development of the DSS, it was felt that some of the options built into the DSS may not be politically feasible. The few sessions organized with the intention of training policy makers to use the model turned into further model-modification sessions.

- Show examples beforehand and ensure documentation.

  Many individuals had no clear idea of where the DSS model effort would lead the partnership. They stated that it would have been helpful to see other similar models and examples at the beginning of the process, in order to have a clearer idea of what the model would ultimately do for them, how would it look, etc. They expressed a desire to more explicitly define the purpose and goals of the DSS (as well as its limitations), to have more information upfront on how the product would be used, and to keep these things in mind as the product was developed. One participant stated, "the partnership didn't know what they wanted until they saw what he [the DSS engineer] had."

- Feeding current, accurate, and updated data into the model.

  There was general consensus that the expertise of the technical people involved in the model development ensured that the model remained up to date, but that this would be an issue to to keep in mind for the future. (This issue concerned groundwater data, spatial dimensions, smaller grid cells, the accuracy of data from different agencies, water-use estimates, data projections per capita, data projections per home, etc.)

- Capacity building.

  It was felt that capacity building might be needed within the partnership itself in order to modify the model in the future when academic modelers were no longer be involved with the project. The point was raised that somebody within the USPP should be able to modify and update the model and the data that feed it, as well as implement any new conservation strategies that might appear feasible. "Otherwise, if [the main modeler] leaves the state and stops working on it, nobody will be able to take care of things and move on from here."

  In the words of one participant, "the model will help us a lot in our planning and zoning, our municipalities and county entities, water districts, water planning, etc. We don't know how to use it yet, and my concern is how to keep it up to date with future science, options, and alternatives. If federal funding fails to help the BLM, the State, Fort Huachuca and the Agricultural Research Service [and others] ...if no more money comes, all will be lost."

- Change nothing.

  "The DSS was like creating something that had never been done. A really good process."

Influence of the DSS Process on Policy Making

It was widely recognized that the greatest influence on decision making and policy making would come with the use of the DSS model by managers and policy makers. The Upper San Pedro Partnership as an entity does not yet have any power to impose policies or regulations. However, it can issue recommendations and push for policies. In the words of one participant, "it can't impose anything but as a group [of entities] we can influence each other." Indeed, as some of those interviewed stated, the DSS development process has already influenced policy. In Cochise County (the Sierra Vista subwatershed), limits have been established for development density within 3.2 km (two miles) of the San Pedro River. Futher, regional planning in the county government includes the possibility of transferring development rights in areas far from the riparian corridor, where pumping effects on the river are known to be more distant and spread over time.

In addition, the Arizona State Legislature recently passed Bill A.R.S. §38–431.02 , creating an Upper San Pedro Water District with taxing and other regulatory powers, to be approved by voter referendum. Awareness, understanding, and institutional knowledge raised by collaborative processes such as the DSS development have certainly contributed to such policies being implemented. Policies and regulations with sustainability goals in the San Pedro Basin can be seen as a reflection of behavior changes brought about by an increased understanding about the system. Although Bill 321 (Defense Authorization Act 2004, Public Law 108–136) helped focus sustainability questions in the basin, and established a clear goal for the USPP, building the DSS laid out the potential strategic alternatives for achieving that goal. Bill 321 recognized a clear difference between the concepts of safe yield and sustainable yield. Whereas safe yield considers a water budget that could be maintained (while still having substantial adverse effects on the river), sustainable yield explicitly requires the protection of the riparian area and its ecosystems while introducing spatial and temporal concepts of impacts to the aquifer. Although the bill mandates the attainment of sustainable yield by 1 October 2011, it does not provide any associated funding to accomplish this task. Bill A.R.S. § 38-431.02 gives decision makers the opportunity to raise funding locally. Putting density limits on development within 3.2 km (two miles) from the river and transferring development rights to areas far from the river are two policies that challenge rural America's traditional approach of guaranteeing private-property rights. The implementation of these measures is a strong indicator of a commitment to address the environmental impacts of growth in the basin. As Saliba and Jacobs (2007) noted, a shift associated with the DSS process from a water budget approach to one with a spatial management approach has caused land-use planning to be directly influenced by water-supply availability.

Despite the partnership's lack of legislative or enforcing powers, the different agencies that are part of it do have influence within their particular jurisdictions. Individuals involved in the partnership's science processes can bring new perspectives and ideas to influence their respective institutions. As noted by Folke et al. (2005), such networks of individuals emerging from collaborative processes can bridge institutional boundaries and be catalyzers of change within the system. The need to involve policy people to a greater degree from the beginning of a process (as expressed by those interviewed and documented above) is very indicative of their understanding of such processes and their influence on bringing about change.

The Road to Resilience?

Most of those interviewed thought that processes related to the collaborative development of the DSS contributed to an improved ability to face future challenges. The process is seen as having set a structure in place, along with a set of commonly learned constructs and learned procedures. In one individual's words, "the process set up a foundation for having future discussions to address future problems." In addition to allowing for a better understanding of how different components of the system interact, the process provided a way that new hypotheses and the impacts of new scenarios and alternatives could be modeled and tested within the broader system. The DSS process allowed "what-if gaming" and a look forward into the future, yet at the same time understanding and appreciating differing points of view. One participant remarked that "the DSS process itself has been an adaptive effort. The nature of the DSS process has allowed the people involved to apply this approach to other aspects of their work."

Although most those interviewed were positive about the contribution of the DSS process to adaptive capacity, many of them also stated the need for policy makers and people in the political arena to appropriate and translate adaptive capacity into better management practices. Political boundaries and constraints are outside of the technical committee. These are not seen to be science driven. It was felt that nontechnical USPP members and the general public might need some guidance as to how to properly use the DSS model. Since 2006, there have been three training sessions for policy people within the broader USPP on how to navigate the user interface and understand the model.

All interviewed individuals expressed high expectations for the DSS model to be used by all members of the partnership (i.e., the more policy-oriented members and decision makers. This was expressed with a sense of accomplishment and the wish to see a work recognized and used to its full potential. A factor that is very relevant in terms of adaptive capacity is that the process itself contributed significantly to the high level of trust that participating individuals and agencies had in the quality of the DSS and its results. "It's not seen as a black box; everybody's concerns went into it." "It gives confidence, the results are respected, and there is a sense of ownership of the model. The DSS project has been like a microcosmos for consensus building. It has not been done to smooth controversies but to make a practical tool to be used and to address problems."

Such a sense of ownership and trust is an outcome of the collaborative process derived from some of the essential traits of the DSS, contributing to a higher adaptive capacity in terms of managing the system. These key factors can be summarized as follows:

- Multistakeholder involvement in an open process with well-facilitated, periodic meetings that represent a constant opportunity to express one's concerns and opinions.

- Focused and itemized communication on different issues at a detailed level. This type of communication allows for a better understanding of the physical system but also the socio-political landscape, agents, constraints, and opportunities.

- Strong multidisciplinary science inputs into the collaborative process guarantee science-based decision-making and confidence in the results by all parties.

- The model's progressive development represents a commonly understood and agreed-upon representation of the system and a recorded history of collaborative accomplishments to date.

- The perceived influence of the process on policies and regulations passed at different institutional levels provides a sense of confidence in the process itself. The expressed need by most of the individuals to involve policy people to a greater degree, and sooner, in the process demonstrates their perception of the process as leading to sustainable learning.

Population growth and climate change are the main challenges that the USPP technical committee will address next. Serrat-Capdevila et al. (2007) quantify the impacts of climate change on the water resources of the San Pedro basin and predict a decrease in its water budget. It is hoped that the lessons learned from the DSS will contribute to helping to meet the significant challenges that lie ahead.

CONCLUSION

As a result of bottom-up initiatives (now recognized legally) to solve the water problems in the San Pedro Basin, a network of varied multisector entities has emerged, the main hub being the Upper San Pedro Partnership. This local, but far-reaching, institutional network benefits from active research programs and from reliable knowledge-transfer mechanisms, making it a well-established knowledge system. The ability to act collectively has enabled the partnership to tap into varied resources such as information, funding, power, and knowledge. Its social and institutional diversity promotes resilience (Adger 2003b), or at least, it paves the way to it.

We have analyzed a multistakeholder collaborative development of a DSS in the San Pedro Basin, with the goal of achieving sustainable management of water resources in a watershed where social and ecological needs compete. Detailed opinions and views on the process were collected from stakeholders and analyzed within the unique institutional setting of this partnership. Overall, stakeholders perceived the DSS development process as positive and believed that it contributed to an improved capacity for facing water-management challenges in the basin.

It was found that broad stakeholder involvement, fairness in representation, the openness of the process, and a significant scientific input were features that enabled what Tabara and Pahl-Wostl (2007) termed "sustainability learning." The participatory model development process allowed simultaneous and focused discussions on particular issues, such as the identification of problems, alternative solutions, and potential future scenarios. Consequently, the process produced an increased understanding (both social and ecological) among stakeholders. As pointed out in Lynam et al. (2002), models can provide a commonly agreed representation of a problem. They are an image of the common understanding that, although imperfect, can be changed and improved with time. The participatory analysis during model development, and its contribution to decision making, brings with it the necessary social learning that can alter and inform perceptions of local problems and their cause–effect relationships.

The collaborative development of the DSS in the Upper San Pedro Basin forced a negotiation environment where potential long-term sustainable solutions were democratically agreed on. The outcome of this inclusive approach to decision making is a product (the DSS model) that benefits from a sense of ownership and trust. The social capital forged during the process and the broad range of personal and institutional views that fed the development of the model are the foundations of its legitimacy. The sense of trust, ownership, and legitimacy that comes with such consensus-building processes is likely to guarantee the support and sustainability of any of its chosen adaptation strategies.

Indeed, these efforts have significantly influenced policy making in the basin and are likely to continue to do so. The ability of this process to influence policies and be a promoter of change and novelty ("revolt" in Holling's (1973) terms) has proven to be a token of adaptation. We think that such a collaborative model development is an exportable and universal mechanism for promoting novelty, learning capacity, and adaptation, thus promoting resilience, as culture and context specific as it has proven to be.

The most significant output of an environmental conflict mediation process in this context is concerned and educated water users who make thoughtful and reasonable decisions in terms of the use of the resource. This type of knowledgeable stakeholder will understand that reinvesting in ecosystem health is profitable for the community in the long term. Unused strategies and options will be available for accommodating future change.

Responses to this article can be read online at:
http://www.ecologyandsociety.org/vol14/iss1/art37/responses/

Acknowledgments:

This research has been funded by the Udall Center for Studies in Public Policy and SAHRA (Sustainability of semi-Arid Hydrology and Riparian Areas) at the University of Arizona. Holly Richter and Dave Goodrich provided valuable help and insights during the field work. Christopher Scott, Kathy Jacobs and Robert Merideth provided valuable comments. The interviewed stakeholder members kindly provided their time and attention for this study. All contributions are gratefully acknowledged.

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APPENDIX 1. Capture map developed by the U.S. Geological Survey demonstrating, in particular locations, the percentage of water that would be removed by the drilling of a well (water that would otherwise contribute to flows in the river). This is a visual aid showing the areas in which pumping would have a more immediate impact on the riparian area.