Linking knowledge with action in the pursuit of sustainable water-resources management

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Managing water for sustainable use and economic development is both a technical and a governance challenge in which knowledge production and sharing play a central role. This article evaluates and compares the role of participatory governance and scientific information in decision-making in four basins in Brazil, Mexico, Thailand, and the United States. Water management institutions in each of the basins have evolved during the last 10–20 years from a relatively centralized water-management structure at the state or national level to a decision structure that involves engaging water users within the basins and the development of participatory processes. This change is consistent with global trends in which states increasingly are expected to gain public acceptance for larger water projects and policy changes. In each case, expanded citizen engagement in identifying options and in decision-making processes has resulted in more complexity but also has expanded the culture of integrated learning. International funding for water infrastructure has been linked to requirements for participatory management processes, but, ironically, this study finds that participatory processes appear to work better in the context of decisions that are short-term and easily adjusted, such as water-allocation decisions, and do not work so well for longer-term, high-stakes decisions regarding infrastructure. A second important observation is that the costs of capacity building to allow meaningful stakeholder engagement in water-management decision processes are not widely recognized. Failure to appreciate the associated costs and complexities may contribute to the lack of successful engagement of citizens in decisions regarding infrastructure.

water management | water sustainability | public participation | stakeholder engagement

The management of water resources for sustainable use and economic development is a technically and politically difficult challenge for societies (1, 2). To be effective, knowledge systems that support decisions about water-resource management and development must link research- and experience-based knowledge to practices across a broad range of challenges (3). For example, many societies are faced with trying to meet or moderate increasing demands for water in the context of highly variable water supplies. Use of weather forecasts and analyses of climate conditions should be helpful to decision-making but often are resisted for institutional reasons, because they are not provided in a useful or timely way, or because there is little interest in using new sources of knowledge more generally (4–6).

Adding concerns about ecological sustainability and social justice to the management goals within watersheds greatly expands the kinds of knowledge that must be jointly considered (7, 8). For example, major water-infrastructure decisions, such as the construction of dams, the creation of irrigation delivery systems, and interbasin transfers, often have multiple, complex, and unanticipated longer-term impacts (9). Likewise, major water policies focused on demand management (rather than on supply augmentation) also may have impacts that unfold over decades, for example, by encouraging certain styles of development, housing, and landscaping or investments in certain types of agricultural technologies. Solving these sustainability issues can be challenging given political resistance to change and the requirement for long-term, integrated, and adaptive solutions (10). In some countries there has been a shift toward engaging citizen committees, river-basin organizations, expert panels, assessment procedures, and multistakeholder deliberation to help sort through the complexity of information and objectives and to incorporate local perspectives and values into the decision process (11, 12).

Institutional and organizational arrangements designed to build connections between knowledge and action for water-resources management are extremely diverse, and their performance is not yet well understood (13, 14). Some efforts are narrowly focused and short-lived, whereas others are expected to have longer time frames of engagement. Some maintain a strong separation of roles for experts, managers with authority, and the public, whereas others see all participants as stakeholders in a broader arena of shared responsibilities (3, 10). Relevant questions are whether useful lessons can be learned by evaluating how outcomes and decision processes are affected by the mode of participation and whether increasing participation results in predictable changes in the use of scientific information.

To help answer these questions, we report on a comparative study of four knowledge systems: in the Yaqui Valley, Mexico; the state of Ceará in northeast Brazil; the Ping River Basin, Thailand; and the Upper San Pedro River, Arizona. These basins were selected because the investigators already had developed significant relationships with decision-makers and stakeholders in these regions as a result of ongoing research and because these basins provided different perspectives on similar resource problems in arid and humid regions. Our approach included separate field investigations conducted in each area, followed by a workshop to compare the knowledge systems and perspectives

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of a small group of practitioners, researchers, and stakeholders from each basin.

The Four Study Basins

The watersheds of the four study areas are quite disparate, but drought or seasonal water scarcity is an issue in all four. The Yaqui Valley and San Pedro basins are geographically close: Both span the Arizona–Mexico border. The San Pedro River flows north to connect to a tributary of the Colorado River. The Yaqui River flows southwest to the Sea of Cortez. Both the San Pedro and the Yaqui basins have a bimodal climate system, with winter rains associated with El Niño-Southern Oscillation (ENSO) conditions as well as a summer monsoon. Drought is particularly acute in Ceará, Brazil, where it has significant impacts on the large rural population that depends on rainfed agriculture and precarious drinking water-supply systems. Ceará has only one rainy season, in the spring, and again ENSO is a strong regional climate driver. The arid landscapes of these three regions have a similar vegetation structure: desert scrub with lush but very limited riparian areas. The Upper Ping River, in a monsoon-dominated climate regime, passes through Chiang Mai, the biggest city in northern Thailand, and its sister city, Lamphoon. Extended periods of wet weather are followed by a long dry season; both flooding and water scarcity are issues in this river basin.

Institutional water-management arrangements also vary. In the Yaqui Valley an irrigation district and the National Water Commission each have roles in water management. In the Upper San Pedro a voluntary citizen partnership is the key decision-making body, although a more formal district is under consideration. In Ceará there are management roles at the state and federal level as well as local water committees, and in the Ping River Basin a hierarchy of river basin and subbasin committees is overseen by a National Water Resources Committee.

Basin 1: Yaqui Valley, Mexico. Water use in the Yaqui Valley is nearly exclusively agricultural: With its legacy as the birthplace of the irrigated-wheat Green Revolution, the Yaqui Valley has contributed up to 40% of Mexico's total wheat output in recent years (15). Irrigation water from the Yaqui River is the lifeblood of the regional economy; the main focus of water management is on supply-side solutions, especially infrastructure improvements and intensified groundwater-pumping schemes to augment surface-water supplies. In the future, growing urban centers both inside and outside the basin are likely to influence water allocation.

Two entities are primarily responsible for water management in the Yaqui Valley. The Yaqui Valley Irrigation District, a water-user group created in 1992, is directly owned and managed by the irrigators who employ trained engineers to operate the system. The democratically run district oversees the annual planning, allocation, and delivery of water to farmers and maintains and operates all irrigation infrastructure (e.g., canals, roads, and drains) transferred from the federal government at the district's inception. The federal National Water Commission, Comisión Nacional del Agua, administers all water rights and coordinates reservoir planning with the irrigation district via a special "hydraulic" committee. The past 10 years have been characterized by extreme drought, punctuated by near-disaster in the 2002–2003 cropping season, when reservoir storage was completely depleted (16). Since that time, both management entities have taken steps to avoid repeating the experience of that year. Important water-related knowledge in the Yaqui Valley is generated by both the management entities and research institutions in support of (*i*) infrastructure development and maintenance, (*ii*) integrated management of groundwater and surface water, (*iii*) annual allocation decisions, (*iv*) field-level investment and water conservation, and (*v*) improved institutional design.

Basin 2: Upper San Pedro Basin. The main water issue in the Upper San Pedro basin is conflict between preserving the San Pedro National Riparian Conservation Area, a critical habitat for millions of migratory birds, and serving the water needs of the growing human population. Like much of rural Arizona, rapid population growth is straining the water supplies in the region. Groundwater pumping is the only source of water for municipal, industrial, and agricultural uses in the basin, and groundwater use has been gradually depleting the base flow of the river, causing increasing concern about whether the river will continue to flow perennially (17). Although the population of the basin (120,000) is very small compared with the other basins in this study, the Upper San Pedro River has an extremely high profile because of the biodiversity it supports (18).

The Upper San Pedro Partnership (USPP), formed in 1998, is a voluntary group of 21 federal, state, and local agencies and several nongovernmental organizations. In an unprecedented move in 2003, the US federal government established a mandatory goal of "sustainable yield" by 2011 for the USPP in the reauthorization act for Fort Huachuca. The sustainable yield goal has been interpreted to mean that water use in the basin will need to be reduced by about 10,000 acre-feet per year from 2003 levels to support the river's flow or new water supplies will need to be identified to offset this deficit (19). Possible solutions include a variety of augmentation and conservation schemes (20).

The USPP is unique in the United States because, even though it is a citizen's group, it has a federal mandate to manage water supplies with a specific, quantified goal; it also is unusual in the level of federal funding, having received more than $40 million to support research, model development, and project implementation in the last 8 years (20). Knowledge-based decisions are required to (*i*) establish the water budget for supporting sustainable yield; (*ii*) understand the spatial relationships between groundwater pumping and surface water flows; (*iii*) understand ecosystem dynamics, especially relative to supporting the riparian area; (*iv*) evaluate and select alternatives for managing demand; and (*v*) analyze and select augmentation alternatives. Although the Arizona Department of Water Resources is the primary water-management agency for the state, it does not have direct oversight authority over the USPP's activities. Through collaborative learning processes with university researchers, USPP members have evolved a series of unique land- and water-management tools that incorporate new scientific information in an "adaptive management" context (20). The USPP itself is also evolving with the authorization of a new management district.

Basin 3: Ceará, Brazil. In response to the past record of debilitating drought, the federal (and state) governments have engaged in a major program of water storage in the hundreds of reservoirs that now dot the state of Ceará. Ninety percent of Ceará's water supplies are moved from sources both inside and outside the state through a federal system of canals and reservoirs to serve a population of nearly 8 million. Reservoir releases allow three major rivers, once only seasonal, to run year round. This water is used for agriculture as well as human consumption; very little groundwater is available in most basins of the state. The water-management system has been in transition for several decades, and there are multiple levels of federal and state involvement in water management. Significantly, in 1993 a state water-resources management company, Companhia de Gestão dos Recursos Hídricos (COGERH), was established to manage water resources in the state. COGERH supports a system of participatory water-basin management councils and reservoir-user committees in 8 of the 11 principal watersheds. These councils and committees are responsible for annual decisions regarding reservoir allocations, which are based on volumes in storage and expectations regarding climate conditions for the following year. The basin-management councils, which include water users, civil

society, and representatives of key institutions, decide the operating rules for major supply reservoirs. The reservoir-user committees include stakeholders who are affected directly by water-use decisions in the smaller local reservoirs.

The knowledge base for water management in Ceará resides in multiple agencies, with Fundação Cearense de Meteorologia e Recursos Hídricos (FUNCEME, the state Foundation of Meteorology and Water Resources) being the key source of climate information. Hydrologic information comes from the National Water Agency (Agência Nacional de Águas), the National Department of Works to Overcome Drought (Departamento Nacional de Obras Contra as Secas), and the urban water-distribution company (Companhia de Água e Esgoto do Ceará), as well as from COGERH and FUNCEME, all of which generate and use information. Infrastructure decisions continue to be made at the federal level. Large new canals, such as the "Integration Canal" connecting two river systems, and a major diversion of the San Francisco River are under construction. Types of knowledge generated for water management include physical climate information, engineering data, and social and economic information.

Basin 4: Upper Ping River, Thailand. The Ping River is one of the main tributaries of the Chao Phraya river system and drains much of the northern region of Thailand. The intermontane valley around Chiang Mai has a history of more than 700 years of communal and state irrigation (21, 22). Approximately 2.5 million people now live in this basin, with expanding water needs for industry and municipal uses (23). Floods and erosion are important issues during the wet season, and inadequate water supply and water quality are key issues during the dry season.

The Upper Ping River Basin Organization (UP-RBO), established in 2002, was one of the first two such organizations established in Thailand. (A total of 25 are planned.) It is within the Department of Water Resources structure, with oversight from the National Water Resources Committee. It has been given an ambitious mandate for integrated water-resources management but relatively modest human resources and budget. Most of the expertise and key decisions for both small and larger projects and programs remain within the well-established line agencies, such as those concerned with irrigation, forestry, or local administration (23). Several pilot river subbasin organizations (RSBOs) also have been formally started and eventually may have clearer mandates and functions than the UP-RBO (24). Both the UP-RBO and RSBOs have potential to become arenas in which knowledge is shared and deliberated across government planning and implementation agencies and, to a lesser but still important extent, among other stakeholders. The research capacity to evaluate water-management issues lies primarily within academic institutions and, in a few areas, small groups in the bureaucracy. External consultants and staff of multilateral banks and overseas development agencies still are fairly prominent in assessment, feasibility, and policy studies. Decisions about larger infrastructure projects, however, still appear to be based largely on reports by a handful of private consulting companies with close ties to government and are not yet on the public agendas of the river-basin organizations (23).

Expanded Stakeholder Participation

Water-management institutions in each of the basins have evolved over the last 10–20 years from a relatively centralized water-management structure at the state or national level to a decision-making structure that involves engaging water users within the basins and the development of participatory processes. This evolution is consistent with global trends in which states increasingly are expected to document public acceptance for larger water-infrastructure projects and policy changes before implementation (25). In each case, expanded citizen engagement in identifying options and in decision-making processes has changed the manner in which water-related knowledge is produced and communicated, but with some variability in details across the basins.

We found three primary implications of increased participation for knowledge systems in all four of the cases. First, there is significant focus on the transparency and fairness of processes of assessment and deliberation, with expanding perceptions that the process of decision-making itself is as important as whether the decisions are technically well supported or produce equitable outcomes. This focus is a substantial deviation from the expert-dominated decision processes of the past, which were judged almost exclusively on the basis of engineering criteria with little evaluation of social or environmental issues.

Second, the involvement of larger numbers of people and more diverse interests creates demand for building the capacity, on the one hand, of technical agencies skilled in conducting participatory and deliberative exercises, and on the other, of the wider public in gaining a broader view of water resources and the challenges in their management. However, when one group with superior power and knowledge dominates a stakeholder group (as was observed in all cases), the stakeholder group is not necessarily an effective advocacy tool for less-powerful stakeholders. In the Yaqui Valley, short-term water-management decisions are controlled largely by agricultural water-user groups. Agricultural water-user groups and government entities both rely primarily on internal, experiential knowledge for routine management. A government-sanctioned "Watershed Council" has been created but as yet has not proved to be a meaningful forum for nonagricultural water users because of political and knowledge imbalances among the players.

Building a common understanding of the facts, as well as of differences in interests, values, and preferences that might become the basis for negotiation, requires significant time and resources: Building this understanding requires learning about and integrating different kinds of knowledge, including some sources and interests that may never have been considered in previous decision-making. Tellingly, the San Pedro Basin experience suggests that even when a knowledge system is very strongly integrated with the decision-making process, such integration does not make difficult political decisions any easier to make (20).

Third, multistakeholder processes are more likely than more narrowly defined groups to bring in the diversity of interests and kinds of knowledge needed to negotiate sustainable water-management objectives (12). But participatory processes can easily turn into cosmetic exercises designed to gain public acceptance for, and to strengthen the legitimacy of, decisions manipulated by the state. (This circumstance is not as evident in the San Pedro case as it is in the other arenas). Participation exercises also may be a tool for confining public debate to a narrow set of decision points while over-arching goals and key infrastructure decisions are not scrutinized. In each of the cases evaluated in this study, the mechanisms for stakeholder participation focused on the management-related components of the knowledge system, as opposed to the knowledge used for developing infrastructure. In all cases, determination of the supply of water is derived primarily by experts outside the participatory process, but the public/stakeholders play more significant roles in allocation and management. An example is the planning process in the UP-RBO, which generally is confined to microprojects, whereas the knowledge informing decisions about large-scale infrastructure that demands truly integrated approaches to water-resource management remain largely consultant driven and nontransparent.

Although the socioeconomic conditions in the four basins vary dramatically, it was striking how similar the observations of participants were when they were given an opportunity to share perspectives in an international workshop. In all cases, there

were discussions of the tension between the knowledge needed for making better decisions and available resources to put that information to use, issues related to the difficulties of decision-making under conditions of uncertainty, and frustration about the nature and effectiveness of participatory processes.

Alternative Arenas for Engagement

In all four basins there is an increasing need for, expectation of, and effort to achieve better integration of planning and implementation at multiple levels with respect to water. There is a hope that this process may help facilitate progress toward sustainability. The expansion of interests and organizational mandates beyond single uses and narrowly defined objectives arose from different starting points in each of the basins but ultimately reached a similar set of knowledge-system challenges associated with integration and scale. Our comparative study suggests that fostering and maintaining effective links between knowledge and action in the development and management of water resources at multiple levels requires institutional arrangements that support both focused short-term interaction and broader, longer-term engagement.

Consistent with the findings of others (10, 26, 27), arriving at a joint understanding of the nature of the problem and an understanding of hydrological reality appears to be fundamental to building a base for collaboration. All the cases examined involved formation of a technical assessment group that engaged in joint fact-finding. Establishment of a common base for decision-making through such processes is commonly cited as an important first step in collaborative processes. The USPP Technical Committee, for example, has actively and deliberately conducted joint research efforts to answer critical questions, expanding the knowledge base over time, and this activity is strongly supported both financially and politically.

Shorter-term engagement processes often take the form of task forces, working groups, and committees, whereas longer-term issues usually require more permanent organizations. Typically such structures include a strategic body or council that meets a few times a year, and an operational unit with significant knowledge-brokering capacities. Such efforts need more secure funding to operate. The World Bank has had an important historical role in funding the establishment of such organizations in multiple locations, including three of the four in our study areas. In Ceará, linkages between stakeholders and those who generate water-related knowledge are generally well supported by state government institutions, such as FUNCEME and COGERH, but the initial engagement was affected by World Bank policy, which, in a reversal of previous approaches, recently focused heavily on including stakeholders in water-related decisions. In the Yaqui Valley, the World Bank supported decentralization of water management to district-level organizations, which it had a hand in designing. In Thailand both the Asian Development Bank and World Bank provided funding for initial establishment of river-basin and river-subbasin organizations (24).

Although the USPP has received tens of millions of dollars from the US government for projects and studies, it is not clear that this level of funding will continue. Ongoing funding is critical, because major infrastructure investments are contemplated. In the Yaqui Valley, in contrast, private funds from agricultural water-user groups are becoming a major new source of funds for financing knowledge-producing activities (in support of infrastructure planning). Federal funds are limited, leading to increased reliance on partnerships with other state/local agencies or the private sector for water-management research and projects.

In all four basins, however, we noted that the longer-term knowledge systems being established nevertheless may continue to support and strengthen skills making in short-term decisions rather than the more strategic, long-term considerations that are significant for sustainability. This situation may relate to the nature of knowledge systems themselves, because it is much easier (and less politically charged) to process short-term incremental decision-focused knowledge than the bigger-picture assessments required for investment policy decisions (26).

Individuals can play an important role in helping create and expand the influence of citizens in decision processes, but conventional skills in leadership do not seem to be most important. In the Yaqui Valley case, key individuals were influential in the evolution of the knowledge system because they were able to bring different forms of knowledge into engagement processes and mobilize its sharing across the actors. In several of the cases, participants noted that experts who live in the community they serve are more trusted and more in tune with local concerns than experts who live at a distance.

Finally, we found that in several of the basins key forums for bringing together knowledge and action sometimes may lie, literally, beyond the reach of the basin's inhabitants. The World Bank continues to have a significant impact on the knowledge systems of the basins in Mexico, Brazil, and Thailand. As the World Bank's goals have changed over time, study participants observed that there have been changes in the pressures on the institutions in their countries. In Brazil, establishing water markets was critical to the Bank in its first loan agreement; in the second loan agreement, that focus on water rights and price signals to encourage efficiency was de-emphasized, and the third had an entirely new focus on participatory decision-making. This new focus, along with other influences such as the rise of environmental activism in the United States, probably is correlated with the trend toward participatory decision-making generally.

The World Bank goals continue to influence water-management institutions and the broader social structure of countries long after the completion of infrastructure that resulted from the loan. In Thailand, the Asian Development Bank also has been influential, attaching conditions to an agricultural loan that led to the creation of a new Department of Water Resources, a National Water Resources Committee, and the introduction of river-basin organizations, including the UP-RBO (23). An interesting parallel in Arizona is that in the 1970s the US federal government insisted that the state change its water-management system and manage groundwater more actively in return for the federal investment in the major new surface-water delivery infrastructure for the state, the Central Arizona Project.

Decision-Making, Participation, and Uncertainty

Actual or perceived uncertainties in the knowledge base profoundly affect how people act on information about water resources and development options. Hydrologic uncertainties affect the willingness to make difficult decisions, but in many cases the sources of uncertainty within the knowledge base were not well understood by the stakeholders. Whether the uncertainties derived from a lack of understanding of the connections between surface water and groundwater or from inadequate knowledge of climate drivers, for example, we found evidence in all four basins that key organizations and actors often struggled to understand and communicate uncertainties and to know how much information was adequate to make a decision.

In all four cases we observed tension between those who believed that decisions could be based purely on scientific information and those who acknowledged that values are inseparable from decision processes and even from science itself. Because politics benefits from a degree of ambiguity that is not always compatible with the degree of precision suggested by scientists, acknowledging that shared knowledge is negotiated among parties rather than devoid of social values could have been a useful part of these conversations; to our knowledge, this issue was not explicitly addressed.

Although it evolved primarily in the context of managing ecological resources, adaptive management, sometimes characterized

as "learning by doing," has been suggested as an approach to decision-making under uncertainty (10). The reality is that some kinds of decisions, for example major infrastructure decisions, do not leave much scope for fine-tuning or reversing once the facilities are completed (28). This consideration, along with the major financial investments required, may be part of the explanation for not involving stakeholders in such high-stakes decisions. This principle is illustrated in Ceará, where the introduction of basin committees has led to broader acceptance of an adaptive management framework but primarily for decisions on shorter timescales. Ceará formally incorporates climate forecasts for the next year in the allocation decisions but allows for changes in these decisions throughout the year. The need to learn-by-doing also is well accepted in the activities of the Thai river and subbasin organizations. Adaptation in the Yaqui basin has been driven by a prolonged drought crisis that prompted significant changes in management objectives and strategies, and hence research needs, aimed at lowering the risk of prolonged or repeated crises involving the reliability of the water supply. The San Pedro case has involved adaptive reactions to new sources of information, although so far all the commitments made are relatively low-cost and low-impact projects in comparison with the large augmentation schemes that also are being considered.

Effectiveness

Based on a comparison of cases and the comments of the participants, we identified criteria by which to assess the effectiveness of these knowledge systems in supporting sustainable water-resources management (Table S1). These criteria include a "culture of learning," or the capacity to integrate both science and stakeholder knowledge into adaptive decision processes; the presence of a monitoring system to evaluate the success of past decision processes; secure funding; the degree to which the process is "trusted" by the participants, which we represent in Table S1 as transparency; the degree to which the process can support both long- and short-term decisions; and whether participants believe that nongovernmental participants have a meaningful role in decisions. Several of the criteria selected for this comparison are derived from the findings of the Effective Knowledge-Action Systems for Seasonal to Interannual Climate Forecasting workshop developed within the broader Knowledge Systems for Sustainable Development Project (29).

Discussion

Efforts to link knowledge effectively to water-resource decisions are underway in the four basins in this study. In all cases there is an expectation that increased stakeholder engagement, integration of stakeholders in planning and implementation activities, greater attention to resolving uncertainties, and focusing on adaptive management will lead to more sustainable use. The stakeholders we engaged universally saw benefit in being involved in decision processes. This observation is generally consistent with observations of others (30). However, stakeholder engagement in support of production and sharing of knowledge where there is conflict over water uses is not an easy task. A clear observation from all four cases is that government officials have been surprised by how much time and energy are required truly to engage stakeholders, a finding that researchers often did not identify previously. The transaction costs for public processes are high because significant capacity building is required to develop a common knowledge base. Unlike the more hierarchical system that is common in bureaucracies filled with experts and appointed officials, there is a lot of contested knowledge (31, 32) and a significant number of surprises—new perspectives, unexpected participants, and new sources of information. In stakeholder engagement, time is a necessary ingredient that cannot be replaced by other resources: Building trust and effective communication systems is time- and resource-intensive.

Despite the high resource requirements and the extra effort required to engage stakeholders, there are numerous benefits of multiparty participation, not the least of which is the much richer view of "facts" and the implications of joint learning before making decisions that impact water users. It appears that multistakeholder bodies or deliberative processes are more likely to engage the diversity of interests and kinds of knowledge needed to negotiate water-management objectives regarding sustainability than processes oriented around a single-use, although the latter type of process can be very efficient at getting the knowledge system to work toward purely economic goals. As observed by Priemus and colleagues (26) and noted by others (10, 25), actors are more likely to accept information if they are involved in defining problems and solutions, leading to "negotiated knowledge."

In all four cases, the processes of engagement themselves have become part of the outcome and have led to new methods and approaches to consensus-building, capacity-building, and conflict resolution. All the cases noted the importance of the role of vision and credible, inclusive leadership in the context of engagement, because without vision and leadership it is difficult to get beyond the issues regarding contested knowledge and to move to a collaborative joint fact-finding and problem-solving approach. Ability to encourage and continually integrate new knowledge sources while maintaining a clear sense of direction and commitment among the parties requires strong leadership, especially in the light of an ever-changing local, national, and global context.

Successful engagement can require deliberate design of new arenas for relationship-building and development of consensus-based knowledge, such as the forum created by the San Pedro USPP. This multistakeholder group has worked together on a voluntary basis during the last 10 years, overcoming significant obstacles in the process. Integration of research efforts with policy development in the context of a changing understanding of the facts is also difficult (33) and is one of the reasons that building bridges between knowledge and action continues to be challenging (3).

Uncertainties regarding facts in water-related situations mean that decisions must keep as many future options open as possible. Robust decision-making involves avoiding choices that foreclose the options available in the future (34). Technologies and understanding relevant to water- management evolve over time, and sustainable systems need to be flexible enough to encompass new sources of knowledge. Our comparative study suggests that in water-related decisions, the joint learning that now is being fostered through expanded opportunities for stakeholder participation and deliberation is not yet matched by comparable institutional capacities to learn through and about issues involving longer time frames. This distinction has not been widely recognized previously (but see ref. 35).

Expanded engagement with stakeholders, experiments with different forums in which stakeholders and government interests can collaborate, and attention to short- and long-term uncertainties are all crucial to the pursuit of sustainable water-resources management. The institutional ingredients for success in bringing the best available knowledge to bear on collaborative planning efforts, implementation procedures, and systems of monitoring and evaluation are invariably context-specific. Nevertheless, there is little doubt that actions pursued based on knowledge claims that can be challenged are, in the long run, preferable to those that are acted upon without an opportunity for review.

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