Science-Policy Dialogues for Water Security:

Addressing Vulnerability and Adaptation to Global Change in the Arid Americas

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Deputy Director of Mexican National Meteorological Service speaking at North American dialogue on the role of institutions in climate variability and change, Jiutepec, Mexico (2009).

Climate change and water-supply uncertainty coupled with mounting human demands for water are straining the availability and quality of freshwater in much of the world. These twin forces cause a palpable rise in societal vulnerability, here considered as susceptibility to adverse effects of global environmental change.[1] The vulnerability of water supplies (or, water vulnerability) places human communities at risk for exposure,[2] or change,[3] and thereby creates huge adaptation challenges. The actions being taken to reduce risks and capitalize on opportunities are considered *adaptation* or *adaptive strategies*.[4] The most sensitive and vulnerable communities are those that face the greatest exposure and are most limited in their capacity to adapt.

Rapidly growing and ever wealthier urban populations, expanding agribusinesses, diverse industries, extensive mining, power generation, and tourism often deprive water from or degrade its quality for use by marginalized populations of smallholder farmers and the urban poor, as well as for ecosystems along streams, lakes, and coasts recognized as biodiversity hotspots in the arid landscape.

The arid[5] Americas—as characterized by the southwestern United States, northwestern Mexico, north-central Chile and Argentina, and northeastern Brazil—manifest the just-described challenges especially well.[6] This article focuses on two areas where our research team has been developing science-policy adaptation strategies: (1) the Sonora-Arizona drylands shared by Mexico and the United States (See map at right), and (2) the drylands east and west of the Central Andes in Chile and Argentina (see map, page 32). In these areas water remains acutely limited even as drought and flood extremes increase, ecosystems are under growing pressure, and economic globalization drives water demand. These global-change conditions threaten the security of access to water. Yet the foregoing conditions prevail—with little regard for constraints to supply, insufficient understanding of vulnerability, and inadequate attention to adaptive measures.[7]

To the extent that such problems are attributable to human agency,[8] there is evidence that effective policies and actions can alleviate some of the harm.[9] Our article describes two interactive

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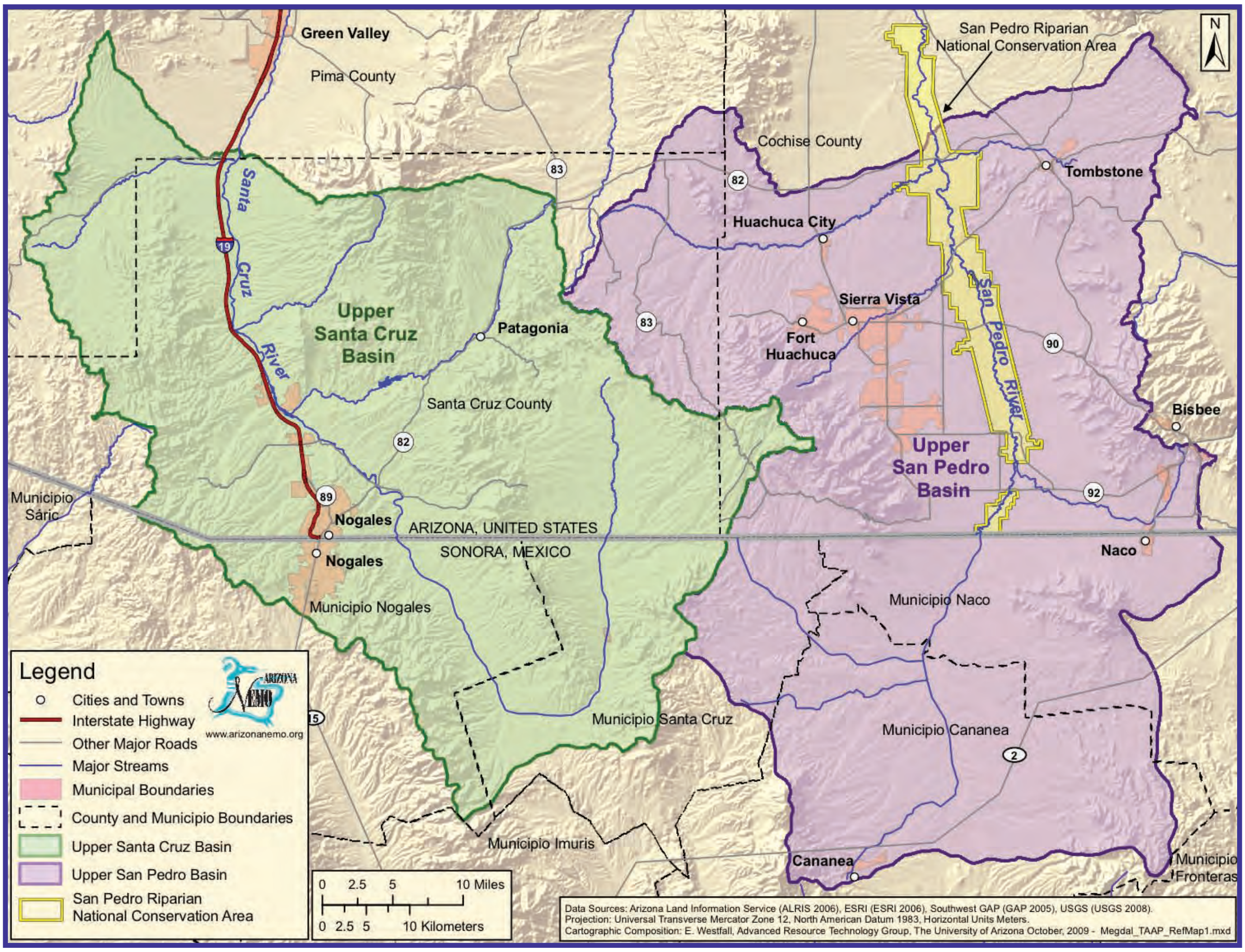
Sonora-Arizona Drylands region.

networks in the arid Americas that feature scientists, agency personnel, civil society, and decisionmakers who have initiated a sustained effort to reduce vulnerability and heighten adaptation through science-policy dialogues.[10] As evidenced by engagement of high-level decisionmakers and programmatic initiatives described in the following sections, both networks are making credible progress, although much remains to be done. Based on our ongoing experience, at least four conditions—*inclusivity*, *involvement*, *interaction*, and *influence*—are essential for successful science-policy dialogues.

The first network is a cross-border alliance of U.S. and Mexican stakeholders.[11] Over the past dozen years this binational community-of-practice has devised and helped implement responses to climate variability, water scarcity, loss of rural livelihoods, vulnerability of growing urban populations, conventional-energy insecurity, and degradation of transboundary ecosystems. A second, newer network comprises Chilean and Argentine researchers and policymakers. These partners are diagnosing human–environment trade-offs and complementarities, and in the process, applying the best available science to pressing challenges that are prioritized in dialogue with stakeholders.

In the United States–Mexico border area, the need for joint, that is, binational, management of shared transborder watersheds cuts across societal and environmental concerns.[12] Since the 1960s this region has experienced rapid population growth, especially in border cities; a spurt in the creation of assembly



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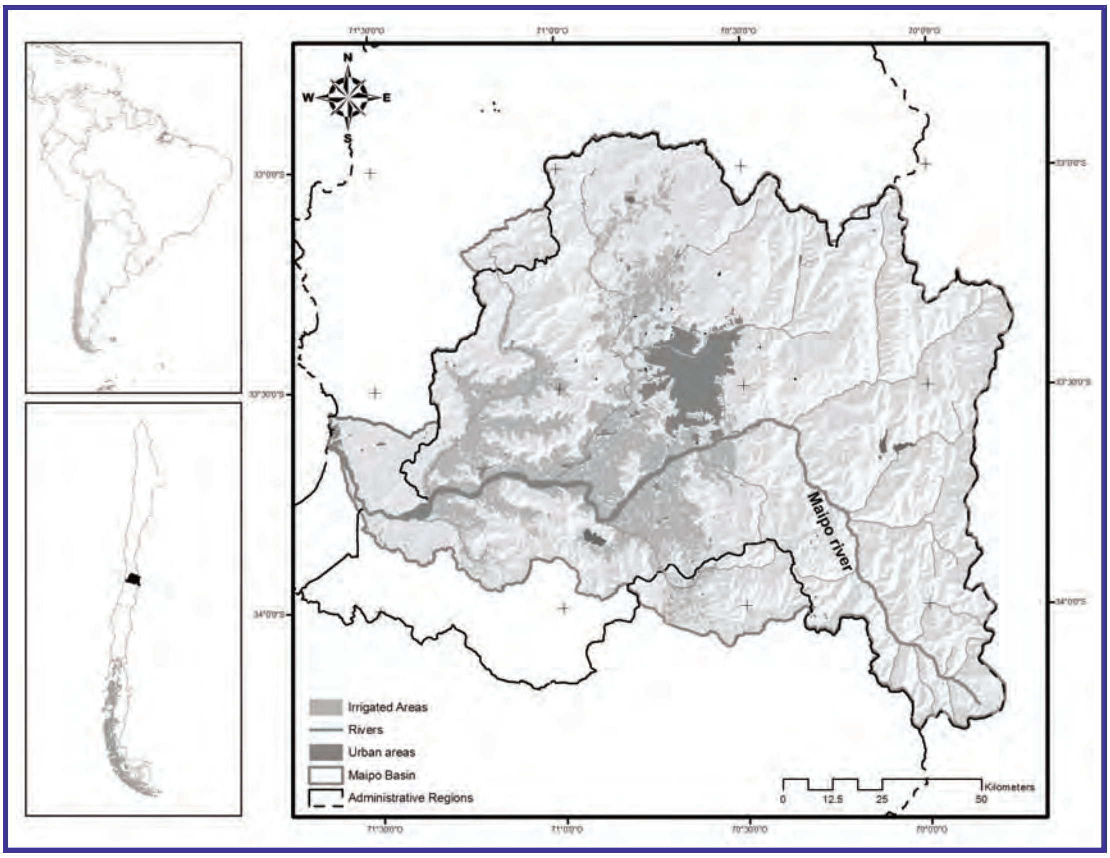
Upper San Pedro River Basin (right).

factories; large-scale agriculture; and increased tourism. Much of the water needed to sustain this activity has relied on aquifers, most of those transnational. This has occasioned steep declines in groundwater tables, to levels well below those needed for replenishment of streamflow, such as in the cross-border San Pedro River, a partially protected, biodiverse riparian corridor.[13]

Similarly, in the Andes (see map, above) decreasing water supply, with rising uncertainty under climate change, threatens growing urban, rural, and ecosystem demands for water. In the Maipo valley in Chile, where the capital, Santiago, is located, farmers' water rights have come under stress from expanding urban water-supply needs. Across the mountains and border to the east, the Mendoza valley in Argentina is dominated by a multimillion-dollar commercial wine and fruit industry. This enteprise depends on water supplied via Argentina's most extensive irrigation system, where agriculture and urban development also compete for scarce water. Glacial and snow melt from the Andes critically affects both sides of the mountain range.

Water Vulnerability and Responses

Even if hydroclimatic variability—such as drought, flooding, and other natural phenomena—were not at play, human-induced impacts that affect water and the environment are key concerns. These include historical land-use and water-use changes caused by human settlement, colonialism, economic development, public policies, and management regimes. Impacts are both direct (from water diversions, reservoir impoundments, groundwater pumping, generation of wastewater and pollution, soil salinization, and water needs of human-altered ecosystems) and indirect (inequitable access to water or heightened investment in infrastructure with inadequate consideration of longer term consequences).[14] These challenges, in developed and developing countries alike, heighten the need for sound planning, effective use of information, and anticipatory and adaptive management.[15] The science-policy dialogues we describe (Figure 3) build social and



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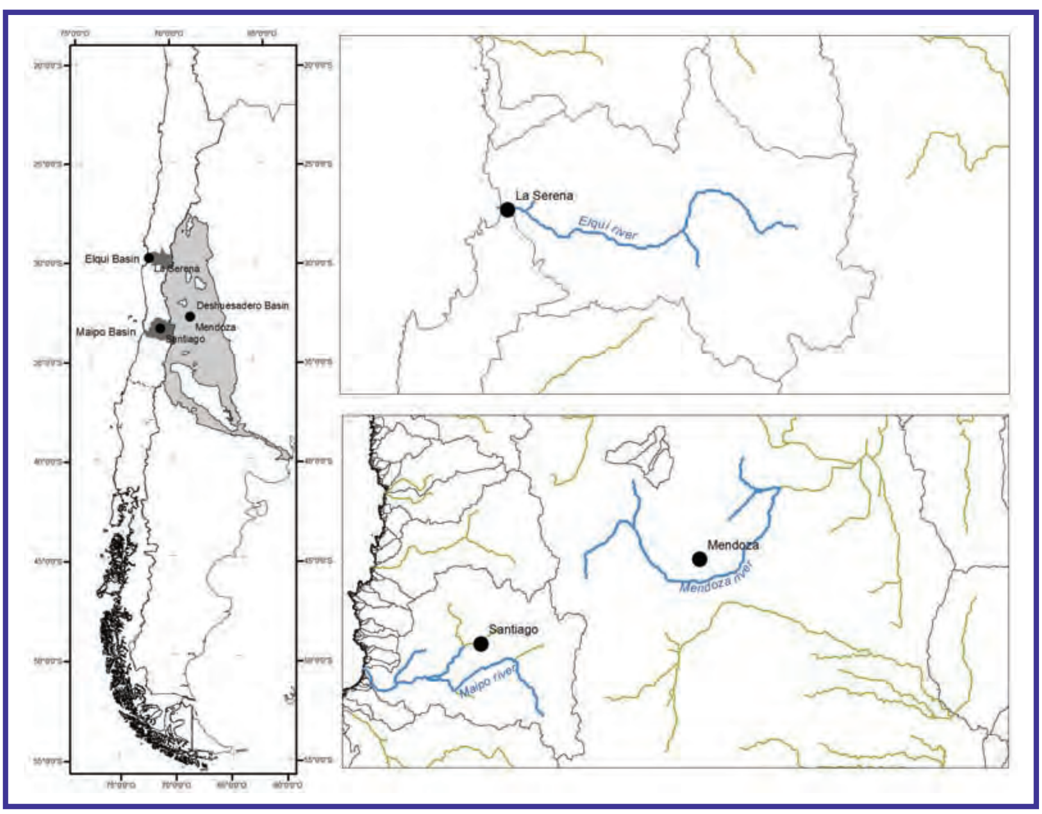
Central Andes region locator map and Maipo River Basin.



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Central Andes region locator map; Elqui, Maipo, and Mendoza River Basins.

Global Water Stress and Climate Change

Across the planet the amount of water available from rain, snow, glaciers, or groundwater is modulated by fluctuation over time and space in physical processes and human activities. Additionally, since a seminal piece by Milly et al. in *Science* in 2008, most environmental scientists now recognize that past climate, once considered "stationary" (i.e., unvarying within fixed and known bounds of extremes), is a poor guide for future variability resulting from climate change.[a]

Reconstructions of more than 1,000 years of past hydroclimatic variability, using proxy data from tree rings along with paleolimnological and glaciological records for many sites, confirm that precipitation and streamflow have never exhibited stationarity. Tree-ring data indicate, for example, extended droughts in Mexico during the Maya, Toltec, and Aztec civilizations,[b] and in Pre-Incan societies on the Bolivian Altiplano.[c,d] Similarly, global-circulation-model downscaling and disaggregation techniques have been refined for our regions of interest.[e] And using climate scenarios, hydrologic process models are now better able to predict the flow, availability, and timing of surface water and groundwater. These and similar sophisticated techniques are uncovering trends that have major implications for water management and for strategies to mitigate vulnerability and enhance adaptation.[a] Over shorter—that is, annual and decadal—periods, hydroclimatic variability in the arid Americas is very strongly affected by the El Niño Southern Oscillation with marked seasonal effects.[f] Less widely known is the Pacific Decadal Oscillation that influences snowpack and streamflow, as demonstrated for rivers in the Central Andes.[g]

Hydroclimatic extremes, typically floods and droughts, heighten water vulnerability. In northwestern Mexico and the southwestern United States, the North American Monsoon brings considerable summer rains, but observers note that past trends in summer versus winter precipitation are changing.[h] Tropical cyclones constitute a wildcard in the region's water vulnerability; they wreak havoc, but can be a water resources lifeline.[i] At the other extreme, drought cycles appear to be intensifying with more frequent heat waves and prolonged periods of moisture stress, increasing incidence and severity of wildfires, and dust storms.[j] Heightened variability and uncertainty of water availability in rivers and lakes have triggered growing and generally unsustainable use of groundwater to meet human demands. Subsurface water in many basins accumulates from very-long-term storage. Meanwhile, recharge processes, which are subject to hydroclimatic variability, do not keep pace with pumping that is reaching unprecedented levels.[k] Access to this sort of state-of-the-art information is crucial to effective adaptation planning and decisionmaking.

[a] P. C. D. Milly, J. Betancourt, M. Falkenmark, R. M. Hirsch, Z. W. Kundzewicz, D. P. Lettenmaier, and R. J. Stouffer, "Stationarity Is Dead: Whither Water Management?," *Science* 319, no. 5863 (2008), 573–574.

[b] D. W. Stahle, J. Villanueva Diaz, D. J. Burnette, J. Cerano Paredes, R. R. Heim, Jr., F. K. Fye, R. Acuna Soto, M. D. Therrell, M. K. Cleaveland, and D. K. Stahle, "Major Mesoamerican Droughts of the Past Millennium," *Geophysical Research Letters* 38 (2011): l05703, doi:10.1029/2010gl046472.

[c] C. Solíz, R. Villalba, J. Argollo , M. S. Morales, D. A. Christie, J. Moya, and J. Pacajes, "Spatio-Temporal Variations in *Polylepis tarapacana* Annual Growth Across the Bolivian Altiplano (17–23°S)," *Palaeogeography, Palaeoclimatology, Palaeoecology* 281 (2009): 296–308.

[d] IAI, "Did Pre-Incans Fight Over Water? Tree Ring Research Unravels How Water Scarcity Triggered Historic Conflicts," *Science Snapshots* 11 (2011).

[e] F. Dominguez, J. Cañon, and J. Valdes, "IPCC-AR4 Climate Simulations for the Southwestern US: The Importance of Future ENSO Projections," *Climatic Change* 99 (2010): 499–514.

[f] F. J. Meza, "Variability of Reference Evapotranspiration and Water Demands. Association to ENSO in the Maipo River Basin, Chile," *Global and Planetary Change* 47 (2005): 212–220.

[g] M. H. Masiokas, R. Villalba, B. Luckman, and S. Mauget, "Intra- to Multidecadal Variations of Snowpack and Streamflow Records in the Andes of Chile and Argentina Between 30° and 37°S," *Journal of Hydrometeorology* 11 (2010): 822–831. doi: 10.1175/2010JHM1191.1

[h] A. R. Coles and C. A. Scott, "Vulnerability and Adaptation to Climate Change and Variability in Semi-Arid Rural Southeastern Arizona, USA," *Natural Resources Forum* 33 (2009): 297–309.

[i] L. M. Farfán, R. Romero-Centeno, and G. B. Raga, "Observations and Forecasts From the Landfall of Tropical Cyclones John, Lane, and Paul (2006) Over Northwestern Mexico," *Weather and Forecasting* (in review).

[j] E. R. Cook, C. A. Woodhouse, C. M. Eakin, D. M. Meko, and D. W. Stahle, "Long-Term Aridity Changes in the Western United States," *Science* 306, no. 5698 (2004): 1015–1018.

[k] C. A. Scott, "The Water-Energy-Climate Nexus: Resources and Policy Outlook for Aquifers in Mexico," *Water Resources Research* 47 (2011): W00L04, doi:10.1029/2011WR010805.

institutional capacity to cope with current challenges, address uncertainty and change, and strengthen global-change adaptation initiatives—local to transnational.

Numerous approaches—broadly characterized as water governance[16]—exist to reconcile multiple demands for water in the context of physical and human drivers of scarcity and vulnerability. Systems to allocate water, assign rights, establish priority uses, and balance human and ecosystem needs differ with historical, political, and institutional context. Flexibility in decisionmaking, particularly to incorporate new information and changing priorities, enhances adaptation. Conversely, rigid approaches—particularly those that externalize "unintended consequences"—tend to be maladaptive.

In northwestern Mexico and the southwestern United States, groundwater buffers against climate-driven variability in surface-water supplies for agriculture and for urban and industrial use.[17] In some cases, fossil-water reservoirs are tapped, which is dangerous, as the water amounts removed over periods of only a few years may take decades to millennia to be replenished.[18] Nor can groundwater use be considered adaptive when (1) declines in groundwater levels occur under excessive extraction rates and are not compensated for by either natural hydrological or artificially engineered recharge; (2) groundwater-quality degradation or increased salinity is observed; (3) inequity in groundwater access is associated with social class (wealth, income, gender), is spatially and regionally mediated (e.g., high-demand regions dewatering their surroundings), or is temporal (i.e., intergenerational); or (4) shallow groundwater capture interferes with surface-water bodies, with possible negative impacts for ecosystem water requirements.

C. Scott

U.S.-Mexico binational technical committee meeting on transboundary groundwater, Nogales, Arizona (2012).

Meeting new demands for increasingly scarce water proves to be a major challenge in both urban and rural settings, from water-resource and institutional perspectives. Private-sector commercial activities in the United States–Mexico and Andean regions—especially export-oriented agriculture, mining, and associated electric-power generation—all require water. Allocating available quantities, monitoring environmental impacts, and abating pollution have historically been the purview of government agencies. But with rising decentralization in both regions, businesses and communities are expected to assume a growing responsibility to ensure water security by minimizing social vulnerabilities and environmental risks resulting from their operations. For example, Mexico's expanding virtual-water[19] exports in the trade of agricultural goods bound for distant markets—both domestic and international—will need to be addressed by more efficient water-use strategies, policies that fix or reduce the total irrigated area, and establishment of groundwater-allocation procedures that include participatory mechanisms.

In rural areas, mining, ranching, and agriculture are the largest consumers of water. Prolonged droughts since the mid-1990s have intensified chronic water shortages. In the immediate term, diminishing surface-water supplies—enhanced by monumental water diversion schemes dating from the early 20th century—have been met by growing reliance on subsurface water. But as these fragile and nonrenewable sources are depleted, politicians and planners have called for new sources of water—the "next bucket." Much attention is being paid to desalination, which, in spite of its high energy needs and cost, is seen by many decisionmakers as a potentially "limitless" water supply.[20] Energy-intensive and infrastructure-dependent adaptation strategies such as desalination can have long-term environmental consequences, even as they alleviate water scarcity in the short term.[21] While desalination can reduce uncertainty over future water supply, relying on the technology alone risks enhancing vulnerabilities related to equity and affordability of water.

P. Vandervoet

U.S.-Mexico stakeholder workshop in Tucson, Arizona (2009), on transboundary groundwater, including U.S. and Mexican federal, state, and local officials; NGO representatives; and researchers.

The central Andean region similarly faces water scarcity and allocation challenges. The Chilean water-allocation system, for example, permanently grants water-use rights based on minimum streamflow estimates. Under global-change scenarios, this system's stability may not be guaranteed, requiring significant adaptations in how water rights are allocated and ecological water needs determined.[22] In the Río Maipo basin, where average precipitation is 12 inches (300 mm) per year, the reliability of the urban water-supply system will be severely affected. Under current conditions the failure rate is around 6 percent to 20 percent; under certain climate change scenarios, this could increase to 40 percent. Also, projections show that agriculture in the Maipo basin would be more vulnerable to climate-driven water scarcity than the urban sector; however, with the river as the only water source, potable water availability to cities may become more limited.[23]

In Mendoza, Argentina, transnational wine-production and export firms arrived in the 1990s and situated their water demands upstream of the irrigated oases where the aquifers recharge. Relying solely on groundwater, this additional water demand has caused irreversible agro-ecological change in the low-lying reaches of the oases, where producers of longer standing are located. As a further complication, groundwater users are state subsidized and poorly regulated. Because Mendoza's water law dates from the 1880s, when there was no groundwater pumping, a legal and regulatory vacuum allows for continued aquifer overexploitation. Groundwater use, in particular, is currently caught in an intergenerational equity trap: that is, near-term gains of export-oriented agriculture trade off against the longer term strategic value of groundwater for multiple societal demands including urban water supply.

In the Andes, dryland river-basin communities have developed over centuries of deliberate water-management regimes, in which social order controls a hostile environment through extensive water-resources manipulation. Because political-power distributions are aligned with water-management structures, communities without access to power retain very limited control over water—a connection that holds particularly when global environmental-change vulnerabilities are superimposed on older institutional vulnerabilities. In such settings, social relationships depend on water appropriation.

In Mendoza, equity considerations are critical. To illustrate, indigent goat herders—most of them descendants of indigenous Huarpes—depend on rainfall for their grazing lands. When there is drought, they are forced to migrate with their herds; they simply do not gain access to water from the irrigation system. Peasants like these herders did not obtain water rights when water use was legislated in 1884 by the agriculturally oriented "water tamers." Today, scattered in nonirrigated locations downstream of the irrigated oases, either these groups rely on the meager and erratic 3 inches (80 mm) per year average rainfall and leftover agricultural runoff or they have settled and work for agribusinesses. As herders, they depended on rainfall; as wage earners, their livelihood now hinges on the river-based supply of water coming from remote regions. But river flows have been diminishing due to upstream consumption and are now threatened by climate change.

The preceding examples illustrate the sorts of vulnerabilities characteristic of water-short regions. Given the multidimensional nature of vulnerability, where climate interacts with many other stressors, adaptation ought to feature in national and regional development priorities. Next, we explore ways to strengthen adaptive capacity so as to reduce climatic, economic, and social exposures while simultaneously addressing physical and human drivers of vulnerability.

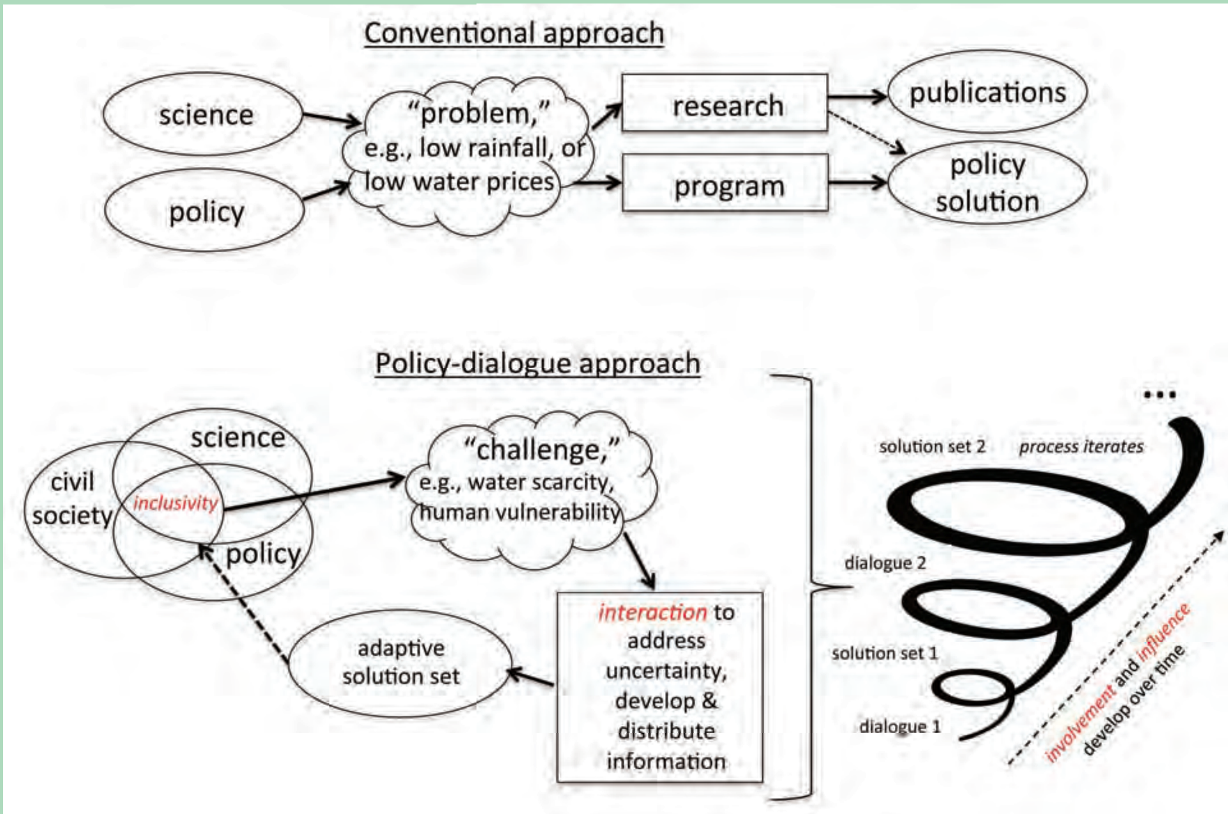
There is growing recognition that adaptation also must consider "internal" changes, such as those occuring within geographical regions as a consequence of the adaptation practices of others.

Adaptation Through Science-Policy Dialogues[24]

In both the United States–Mexico and Andean cases, cross-border cooperation among scientific, civil-society, and governmental stakeholders is critical for adaptation to environmental change. Binational approaches to transboundary water and climate challenges are commonly understood as responses to "external" conditions or forces, that is, climate change. There is growing recognition that adaptation also must consider "internal" changes, such as those occuring within geographical regions as a consequence of the adaptation practices of others. Adaptation is conditioned by capacity, which includes adequate funding, trained personnel, and access to and an ability to use relevant information. Further, adaptive capacity is constrained or enhanced by institutional context—social customs, laws, and the roles of government agencies, nongovernmental organizations (NGOs), and private entities. We explore capacity and institutions as important ingredients of adaptation and as determinants of its outcomes.

We are particularly concerned with the efficacy of science-policy networks to increase the capacity of institutions to mitigate potential vulnerabilities via water management and disaster relief and prevention. Figure 1 conceptually contrasts conventional approaches with

Figure 1: Conventional adaptive approaches tend to offer less robust solutions than sustained science-policy dialogues.



Authors

the iterative, science-policy approach of our examples. While many conventional institutions are capable of providing satisfactory adaptive responses to incremental changes, planning for vulnerabilities caused by extreme water scarcity or climate-related disasters requires much stronger efforts. The problem more often than not is lack of capacity (funds, staff, or knowledge). Thus, we consider science-policy dialogues an important stimulus for building institutional adaptive capacity.

To evaluate science-policy dialogues and their effectiveness, we consider four elements: (1) *inclusivity*, the degree to which key scientists, decision-makers, and other stakeholders participate in the dialogue and represent an appropriate range of viewpoints; (2) *involvement*, the commitment and staying power of dialogue participants to incorporate changes in water-resources management; (3) *interaction*, the degree to which participants discuss, assimilate, exchange, create, and disseminate relevant information among each other and to those outside the process; and (4) *influence*, the ability of the dialogue to effect institutional changes, such as policies, laws, interagency or intra-agency practices, intergovernmental or international agreements, and so on.

Before characterizing and evaluating the United States–Mexico and Andean-region dialogues, we offer a brief assessment of participants' own views on the value of dialogues. The degrees of development of the two processes are asymmetrical: The former is more mature and elaborated than the latter. The United States–Mexico case is noteworthy for the sustained participation of a broad spectrum of stakeholders. And because of the expressly binational character of the dialogues, involvement of federal agencies remains high over time while state, municipal, NGO, and corporate stakeholders respond to specific, often-changing local challenges. Our research team has pioneered dialogue processes to address decision-makers' concerns. Each of these initiatives is joined by growing numbers of scientists interested, but poorly trained, in stakeholder engagement.

The Andean networks have capitalized on specific "policy windows." In Chile, the national government's climate policy expressly mandates robust adaptation planning, and the dialogue process is working to meet that need and influence policy. The Argentinian network takes advantage of a more formal institutional setting—the Mendoza Strategic Development Plan—but

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"Hands off the glaciers"—Public protest brings a broad range of opinion to bear on adaptation planning, Mendoza, Argentina (2011).

as a result is somewhat constrained in its flexibility to *inclusively* address all stakeholders' interests. Such comparative assessment of the North and South American dialogues supports our current goal of better integrating the two.

Stakeholders representing an *inclusive* range of interests have participated in the dialogues. Chief among these are local, state, regional, and national agency personnel, binational and international organizations, NGOs and other civil society organizations, farmers associations, and researchers. With programmatic support from multiple U.S., Mexican, and international sources,[25] the dialogue process has strengthened, allowing us to convene major workshops and meetings.[26] The entire process has involved some 30 dialogues or related events attended by 30 to 40 researchers and some 300 different stakeholders. Our team has been less successful in *involving* private-sector participants; however, we recently brokered an urban water governance exchange between entrepreneurs serving on the advisory council of the Sonoran state capital (Hermosillo) and the Tucson water utility. We have preferred day-long, workshop-style meetings, usually in Mexico, to encourage interactions among active, working officials and stakeholders. These are often supplemented by longer (two- or three-day) meetings of researchers to compare findings and strategize how best to influence policy. Team members are directly involved in regional drought taskforce planning, serve on the board of state water infrastructure projects, coordinate or attend binational collaborative programs and technical committees, and are linked with broader regional climate and water initiatives.

In Chile, where the dialogue process is more recent, the team has conducted an annual dialogue meeting beginning in early 2008, when our core research team met with 70 stakeholders at an information-dissemination meeting, followed by a dialogue attended by 25 persons. Subsequent meetings were held with smaller groups, for example, five researchers and a dozen stakeholders from the national water service, irrigation commission, and environment ministry.

Since the first Chilean dialogue, there have been notable increases in inclusivity and quality of stakeholder participation. Research has been presented to Aguas Andinas, Santiago's main water utility, where decisionmakers have shown interest in climate-change impact assessment, water-allocation system reliability, and water-sector adaptation evaluation. The dialogues have proven seminal for developing additional studies incorporating uncertainty in evaluating irrigation projects and future reservoir operations. Over the five-year process to date, technical and management studies have been generated and are actively being disseminated.[27]

The process has fostered ongoing interaction with government agencies dealing with climate change, the development of two major science-policy projects (one to strengthen climate-change coping capacities; the second to develop vulnerability-assessment tools for irrigated agriculture). In addition, reflecting their influence with senior decisionmakers, the researchers were invited to present a synthesis of climate change impacts to the Environmental Commission of the Chilean Congress.

In Argentina, natural resources are managed at the provincial level, situating governance more locally. In particular, Mendoza faces a growing water-allocation challenge that has spawned popular demonstrations. Formal institutional arrangements do not adequately address public concerns, particularly those of the weaker players. For example, NGOs, students, and other stakeholders oppose a gold mine, planned for development in the high Andes—with implications for adjoining glaciers and watercourses seen as common property. "Hands off the glaciers," "Water is more valuable than gold," and "No means no," they claim, taking to the streets to underscore their position in dialogues.

Especially when politics are turbulent, science contributes credibility and strengthens constructive dialogue among parties not always willing to negotiate. In Mendoza, natural scientists and social scientists played a cornerstone role in the 2010–2011 Mendoza Strategic Development Plan.[28] This process included representatives of over 100 local organizations to discuss developmental goals and priorities for the region. The dialogue prioritized water allocation and irrigated-land use, attracting interest of state agencies, civil-society organizations, the private sector, and the public eager not to be excluded from the process. Scientists first explained water and climate issues from natural-science and social-science perspectives, but their primary role was legitimizing and providing credibility to the process initiated by political decisionmakers. Furthermore, social scientists applied methods for working step-by-step through an inclusive and interactive planning process with numerous opposing claims. The Mendoza Strategic Development Plan, now completed and under a new government, also addresses land-use planning. This historical initiative illustrates scientists' influence in integrating the interests of political decisionmakers and the local community.

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"Water is more valuable than gold," Mendoza, Argentina (2011).

These North American and South American dialogue processes are now being linked. They are receiving programmatic support from the Inter-American Institute for Global Change Research (IAI), a treaty organization sponsoring science-for-policy research and outreach across the Americas through networks such as those presented here. An initial hemisphere-wide dialogue with 30 scientists and decisionmakers from Chile, Argentina, Brazil, Mexico, the United States, and Canada was held in 2011 in Los Cabos, Mexico. This led to the conceptual de-

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"No means no," Mendoza, Argentina (2011).

velopment of AQUASEC, the IAI Center of Excellence for Water Security (www.aquasec.org)—a pan-Americas knowledge-brokering platform—with further operational development occurring at early-2012 dialogue meetings in Santiago, Chile, and Tucson, Arizona.

Synthesizing from our ongoing experience, at least four conditions are essential for successful science-policy dialogues:

1. *Inclusivity* of an integrated, transdisciplinary research team and multisectoral stakeholder representation. Robust science for policy requires the participation of multiple institutions with team members who are multinational, multilingual (in the United States–Mexico case), and broadly interdisciplinary (especially strong on social sciences and policy, and physical sciences attuned to decisionmaking). Effective researchers in science-policy networks are nonprescriptive, eager to understand global-change conditions and context, and conduct "applied, on-the-ground" work. They appreciate the integrated nature of the sectors involved (water, climate, livelihoods, land use, planning, and especially policymaking and implementation), and understand vulnerability and adaptation. Decisionmakers who attend commit time and often travel, predisposing them to learn and engage with researchers. Other characteristics we have observed include amenability to bi- (or multi-) national approaches and solutions; willingness to express views orally and in response to surveys; ability to partition dialogue participation from overt political imperatives (given changes in personnel, government, and policy); and finally, willing to dispense with protocol, meet informally, and meet without official sanction.

2. *Involvement* and commitment of an array of stakeholders, particularly agency staff, civil society representatives, and, increasingly, the private sector. An essential ingredient is building trust. Dialogues are most effective when scientists pursue open and participatory biophysical data collection and modeling, and when decisionmakers eschew their own preference for predetermined outcomes.

3. *Interaction* and information exchange with the dialogue process. While there exist no off-the-shelf approaches, researchers develop initial agendas and seek input from other scientists, often in other countries. The in-country hosts responsible for organizing the dialogue see to political sensitivities. Meetings usually involve a few policy-relevant scientific presentations, with programmatic remarks by officials, followed by open, moderated discussion. Staff members, usually advanced graduate students, take extensive notes. Recent innovations have involved administering brief surveys with results transmitted immediately, and seeking feedback on scientific work and outputs generated jointly with and for decisionmakers.

4. *Influence* on the capacity of institutions and policy outcomes. Operational-agency staff members greatly expand their professional networks through the science-policy process and in many instances gain access to cutting-edge science. Conversely, the process also allows scientists working on policy-relevant research to "get it right" by communicating their results to decisionmakers. Furthermore, the dialogue process also supports training of graduate students and junior professionals within agencies, for example, at week-long capacity-building events run by scientists from world-renowned research institutes. The mutual exchange of scientific information and decisionmaking priorities allows both researchers and stakeholders to enhance understanding and capacity to respond to global-change challenges.

Policy Outcomes

Processes do not lend themselves easily to metrics, yet we can identify numerous achievements stemming from our efforts. For example, we believe open meetings since 1998 on the San Pedro contributed to the creation of the Upper San Pedro Partnership, which continues to function and is officially recognized by the U.S. federal government as the party responsible for maintaining sustainable use of the aquifer. The team tried, beginning in 2002, to spur the creation of an analogue, bottom-up watershed council in Mexico, but internal politics—specifically, the influence of the copper mining industry—inhibited this process.[29] Relatedly, the University of Arizona's long involvement in groundwater issues in the cross-border San Pedro and Santa Cruz Basins was a factor in the establishment of the United States–Mexico Transboundary Aquifer Assessment Program[30] (TAAP), resulting in the commitment of funds by the Mexican federal government (via CONAGUA, Mexico's national water commission, and CILA, the Mexican section of the International Boundary and Water Commission).

The dialogues have also prompted the establishment by the Mexican national meteorological service (SMN) of a regional climate center for the northwest. Top SMN officials were active participants of dialogue meetings and workshops from 2005 to 2010. The team is hesitant to claim that its work has raised awareness among Mexican water managers of the importance of considering long-term climate change. But their willingness to attend dialogues, coauthor papers with us,[31] and invite us to serve on steering committees for professional meetings and as resource persons for national and global climate action programs all demonstrate policy influence.

In the Andean case, outcomes have included (1) ongoing interaction and collaboration with government offices dealing with climate change. These South American agencies appear to be more disposed to adaptation initiatives than those in the United States–Mexico case, in part because disappearing glaciers as a manifestation of climate change in the Andes have greater symbolic value than the "creeping crisis" of drought as the principal challenge for the United States–Mexico region we consider; (2) development of two major projects to strengthen capacities to cope with climate change has develop tools for vulnerability assessment in irrigated agriculture with the participation of the private and public sectors on the projects' executive boards; (3) an invitation to present a synthesis of climate-change impacts to the Environmental Commission of Chile's *Cámara de Diputados* (Congress); and (4) a public-policy paper on the relevance of uncertainty assessment and the incorporation of climate-change projections for the evaluation of future reservoirs, several extension publications, and presentations to raise climate-change awareness in the agricultural community

In general, we find that important ingredients of policy impact include: (1) participation of top, director-level, officials; (2) participation of, and ongoing communication with, senior, deputy-director-level, staff members responsible for program implementation; (3) word-of-mouth transmission from attendees to superiors, colleagues, and constituents; (4) press coverage; (5) jointly authored publications; (6) presentations at conferences, professional meetings, workshops, and so on; (7) securing externally funded, joint, multinational research that broadly benefits researchers and stakeholders, and thereby supports adaptation planning; (8) promoting future exchanges of students and personnel; and (9) lateral linkages with allied initiatives pursued by other researchers and stakeholders.

Our experiences in North and South America have shown that science-policy dialogues hold considerable potential for informing and influencing climate-related water-management decisions. With a suitable mix of talented and context-sensitive scientists, earnest and open-minded interlocutors from the policy sector, and a carefully thought out and well-designed process, relevant scientific findings can find their way into real-world situations.

Processes do not lend themselves easily to metrics, yet we can identify numerous achievements stemming from our efforts.

Conclusions and Broader Relevance

We examined two arid regions in the Americas, reviewing key challenges for adaptation to water-related risks caused by physical and human forces. For the North American and Andean cases presented, as elsewhere, hydroclimatic variability and water vulnerability are both physical and social in nature. Accordingly, water decisionmakers and administrators should be encouraged to include social and economic considerations to promote equity and accessibility of adaptation support.[32]

In water and climate forecasts, we note that further attention is needed to consider more adequately the full palette of possible future extremes and reflect complex social and economic developments and changes in public behavior. Improved adaptation planning and outcomes can be gained from funding at higher and more reliable levels for operational agencies, enhanced interagency coordination, awareness campaigns, knowledge exchange, and capacity building.[33] Based on the extensive experiences of the research teams in the southwestern United States and Mexico, and the still burgeoning process in Chile and Argentina, we find that approaches that feature functioning science-policy dialogues are well positioned to benefit from new scientific developments and social-science-based approaches.

Our examples suggest that institutions tasked with adaptation to water risks may gain a comparative advantage by fostering communities of practice with scientists and stakeholders. Close collaboration among all concerned parties can be strengthened via the sort of dialogue process we have described. The resulting partnerships tend to foster proactive, integrated responses to sustainable resource governance and thereby lead to enhanced adaptive capacity and outcomes. The approach we describe draws fundamentally from but goes beyond traditional strategies that favor hydroclimatological sciences, infrastructures, and technologies to address vulnerabilities and strengthen water security.

Most scholars and observers agree that the world's dryland areas share numerous risks associated with growing demand for water in the face of large-scale environmental change.[34] The examples we have explored include both developing and developed economies. And while context will always determine specific challenges, we believe that science-policy dialogues that aim to address vulnerability and promote adaptive capacity can be designed to improve environmental decisionmaking in most settings.

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NOTES

1. Intergovernmental Panel on Climate Change, *Climate Change 2001: Impacts, Adaptation, and Vulnerability Technical Summary, A Report of Working Group II of the Intergovernmental Panel on Climate Change* (Cambridge: Cambridge University Press, 2001).

2. Exposure, in the context of global change, was defined in 2008 by R. M. Leichenko and K. L. O'Brien (in *Environmental Change and Globalization: Double Exposures* [Oxford: Oxford University Press]) as "prone or sensitive to change." Sensitivity leads to vulnerability, that is, the "negative outcomes from stresses and shocks." This conceptualization of global change in terms of context, response, and outcome explicitly considers social and environmental outcomes.

3. B. Smit and J. Wandel, "Adaptation, Adaptive Capacity and Vulnerability," *Global Environmental Change* 16 (2006): 282–292.

4. W. N. Adger and P. M. Kelly, "Social Vulnerability to Climate Change and the Architecture of Entitlements," *Mitigation and Adaptation Strategies for Global Change* 4 (1999): 253–266.

5. Arid (including hyperarid) areas receive less than 250 mm of preciptation per year; semiarid areas receive 250 to 500 mm. C. F. Hutchinson, R. G. Varady, and S. Drake, "Old and New: Changing Paradigms in Arid Lands Water Management," in G. Schneier-Madanes and M. F. Courel, eds., *Water and Sustainability in Arid Regions* (Dordrecht, the Netherlands: Springer, 2009), pp. 311–332. We use "arid" to include semiarid, in that both imply water-short conditions.

6. The Water Center for Arid and Semi-Arid Zones in Latin America and the Caribbean (http://www.cazalac.org/eng/mision_eng.php, accessed on 19 January 2012) notes that aridity characterizes some 4.5 million sq km from Mexico to South America, where decisionmakers lack appropriate knowledge on water management and preservation.

7. World Economic Forum Water Initiative, *Water Security: The Water-Food-Energy-Climate Nexus* (Washington, DC: Island Press, 2011).

8. "Humans shoulder at least half the blame," according to Diana Liverman's reading of the 2007 Intergovernmental Panel on Climate Change report, "From Uncertain to Unequivocal," in *Environment* 49, no. 8 (2007): 28–32.

9. H. Eakin and M. C. Lemos, "Institutions and Change: The Challenge of Building Adaptive Capacity in Latin America," *Global Environmental Change* 20 (2010): 1–3.

10. Ongoing support is provided by the Inter-American Institute for Global Change Research (http://www.iai.int).

11. See related article: W. Laird-Benner and H. Ingram, "Sonoran Desert Network Weavers," *Environment* 53, no. 1 (2011): 6–16.

12. B. J. Morehouse, D. Ferguson, G. Owen, A. Browning-Aiken, P. Wong-Gonzales, N. Pineda, and R. G. Varady," Science and Socio-Ecological Sustainability: Examples From the Arizona-Sonora Border," *Environmental Science and Policy* 11, no. 3 (2008): 272–284.

13. G. Saliba and K. L. Jacobs, "Saving the San Pedro River: Science, Collaboration, and Water Sustainability in Arizona," *Environment* 50, no. 6(2008): 30–32. See also R. G. Varady, M. A. Moote, and R. Merideth, "Water Allocation Options for the Upper San Pedro Basin: Assessing the Social and Institutional Landscape," *Natural Resources Journal* 40, no. 2 (2000): 223–235.

14. R. G. Varady and E. Ward, "Transboundary Conservation in Context: What Drives Environmental Change?," in L. Lopez-Hoffman, E. McGovern, R. G. Varady, and K. W. Flessa, eds., *Conservation of Shared Environments: Learning From the United States and Mexico* (Tucson: University of Arizona Press, 2009), pp. 9–22. A. K. Gerlak and M. Wilder, "Exploring the Textured Landscape of Water Insecurity and the Human Right to Water," *Environment 54, no. 2 (2012):* (in press).

15. C. Pahl-Wostl, "The Implications of Complexity For Integrated Resources Management," *Environmental Modelling & Software* 22 (2007): 561–569.

16. R. E. Saunier and R. A. Meganck, *Dictionary and Introduction to Global Environmental Governance* (London: Earthscan, 2007).

17. C. A. Scott, S. Dall'erba, and R. Díaz, "Groundwater Rights in Mexican Agriculture: Spatial Distribution and Social and Economic Determinants," *Professional Geographer* 62, no. 1 (2010): 1–15.

18. H. A. Loaiciga, "Climate Change and Ground Water," *Annals of the Association of American Geographers* 93, no. 1 (2003): 30–41.

19. "Virtual water" is embedded or hidden water, as in irrigation to grow crops. The concept was developed by J. A. Allan in 1993. See Allan, J. A. "Virtual water - the water, food and trade nexus: useful concept or misleading metaphor?" *Water International*, 28 (2003): 4-11.

20. M. Wilder, C. A. Scott, N. Pineda Pablos, R. G. Varady, G. M. Garfin, and J. McEvoy, "Adapting Across Boundaries: Climate Change, Social Learning, and Resilience in the U.S.–Mexico Border Region," *Annals of the Association of American Geographers* 100, no. 4 (2010): 917–928.

21. C. A. Scott and M. J. Pasqualetti, "Energy and Water Resources Scarcity: Critical Infrastructure for Growth and Economic Development in Arizona and Sonora," *Natural Resources Journal* 50, no. 3 (2010): 645–682.

22. C. J. Bauer, "Dams and Markets: Rivers and Electric Power in Chile," *Natural Resources Journal* 49 (2009): 583–651.

23. F. J. Meza, D. S. Wilks, L. Gurovich, and N. Bambach, "Impacts of Climate Change on Irrigated Agriculture in the Maipo Basin, Chile: Reliability of Water Rights and Changes in the Demand for Irrigation," *Journal of Water Resources Planning and Management* (in press).

24. The critical need to "reconnect science and policy" is highlighted in a recent report by the United Nations Environment Programme (UNEP, 21 Issues for the 21st Century: Results of the UNEP Foresight Process on Emerging Environmental Issues, Alcamo, J., Leonard, S.A. (Eds.). United Nations Environment Programme (UNEP), Nairobi, Kenya, 56pp., 2012). Based on an extensive survey of scientists, decisionmakers, and other stakeholders, the report calls for "a new look at... how the science-society-policy interface can be improved." In addition, it addresses numerous key issues that the dialogue process presented in this article also focuses on, including freshwater, climate change, food, biodiversity, land, and energy.

25. These science-policy interactions have been generously funded by the Inter-American Institute for Global Change Research, U.S. National Oceanic and Atmospheric Administration (NOAA), National Science Foundation, U.S. Geological Survey, Dialogue on Water and Climate (The Netherlands), and Morris K. and Stewart L. Udall Foundation. In Mexico the workshops were supported by the national water commission (CONAGUA), the Univesity of Sonora, El Colegio de Sonora, the national water research institute (IMTA), the national meteorological service (SMN), the Sonoran state water agency, and local governments.

26. Dialogues have been held in Hermosillo (2006, 2008, 2010), Guaymas (2006), Cuernavaca (2009), Mexico City (2005, 2006), Puerto Peñasco (2009), Tucson (2009, 2010), and Cabos (2011). Findings were promulgated at the World Water Forums (2003, 2006, and 2009), Hydrology for the Environment, Life and Policy meetings (Tucson 1999, 2008; Kalmar [Sweden] 2002; Dundee [Scotland] 2001, 2004; Guayaquil [Ecuador] 2005; Panama 2011), Internationally Shared Aquifer Resources Management Program (Paris 2010), and other fora.

27. See F. J. Meza, "Variability of Reference Evapotranspiration and Water Demands. Association to ENSO in the Maipo River Basin, Chile," *Global and Planetary Change* 47 (2005): 212–220; Meza et al. (in press), note 23, above. See also: http://cambioglobal.uc.cl/index.php?option=com_content&view=article&id=81&Itemid=62&lang=en

28. See http://www.planestrategico.mendoza.gob.ar.

29. R. G. Varady and A. Browning-Aiken, "The Birth of a Mexican Watershed Council in the San Pedro Basin in Sonora," in C. Fuentes-Flores and S. Peña-Medina, eds., *Planeación y Cooperación Transfronteriza en la Frontera México-Estados Unidos* (*Transboundary Planning and Cooperation in the U.S.-Mexico Border Region*) (Ciudad Juárez, Mexico: El Colegio de la Frontera Norte & Universidad Autónoma de Ciudad Juárez, Ambiente y Desarrollo, 2005), pp. 165–183.

30. U.S. Public Law 109-448, the United States–Mexico Transboundary Aquifer Assessment Act, was approved in late 2006 and authorized up to $50 million; to date, $2 million has been appropriated. The intent is to provide scientific information useful to policymakers and water managers.

31. R. G. Varady, R. Salmón Castillo, and S. Eden, "Key Issues, Institutions, and Strategies for Managing Transboundary Water Resources in the Arizona–Mexico Border Region," in S. B. Megdal, R. G. Varady, and S. Eden, eds. *Shared Borders, Shared Waters: Israeli-Palestinian and Colorado River Basin Water Challenges* (Delft, The Netherlands: UNESCO-IHE Press in collaboration with Taylor & Francis, in press); C. A. Scott, S. Megdal, L. A. Oroz, J. Callegary, and P. Vandervoet, "Climate Change and Population Growth Impacts on the Transboundary Santa Cruz Aquifer," *Climate Research 51* (2012):159-170, doi: 10.3354/cr01061. 51: 159–170, doi: 10.3354/cr01061

32. G. Young, H. Zavala, J. Wandel, B. Smit, S. Salas, E. Jimenez, M. Fiebig, R. Espinoza, H. Diaz, and J. Cepeda, "Vulnerability and Adaptation in a Dryland Community of the Elqui Valley, Chile," *Climatic Change* 98 (2010): 245–276, doi: 10.1007/s10584-009-9665-4; E. Montaña, "Central Andean Foothill Farmers Facing Global Environmental Change," *IHDP Update* 2 (2008): 36–39. See http://www.ihdp.unu.edu/file/get/7724.

33. Young et al. (2010), note 32, above.

34. G. Schneier-Madanes and M. F. Courel, "Introduction," in G. Schneier-Madanes and M. F. Courel, eds., *Water and Sustainability in Arid Regions* (Dordrecht, the Netherlands: Springer, 2010), pp. xvii–xxii.