Making Decision-Support Information Useful, Useable, and Responsive to Decision-Maker Needs

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KEY FINDINGS

Decision-support experiments that apply seasonal and interannual climate variability information to basin and regional water resource problems serve as test beds that address diverse issues faced by decision makers and scientists. They illustrate how to identify user needs, overcome communication barriers, and operationalize forecast tools. They also demonstrate how user participation can be incorporated into tool development.

Five major lessons emerge from these experiments and supporting analytical studies:

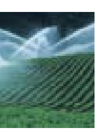
- The effective integration of seasonal-to-interannual climate information in decisions requires long-term collaborative research and application of decision support through identifying problems of mutual interest. This collaboration will require a critical mass of scientists and decision makers to succeed and there is currently an insufficient number of "integrators" of climate information for specific applications.
- Investments in long-term research-based relationships between scientists and decision makers must be adequately funded and supported. In general, progress on developing effective decision-support systems is dependent on additional public and private resources to facilitate better networking among decision makers and scientists at all levels as well as public engagement in the fabric of decision making.
- Effective decision-support tools must integrate national production of data and technologies to ensure efficient, cross-sector usefulness with customized products for local users. This requires that tool developers engage a wide range of participants, including those who generate tools and those who translate them, to ensure that specially-tailored products are widely accessible and are immediately adopted by users insuring relevancy and utility.
- The process of tool development must be inclusive, interdisciplinary, and provide ample dialogue among researchers and users. To achieve this inclusive process, professional reward systems that recognize people who develop, use and translate such systems for use by others are needed within water management and related agencies, universities and organizations. Critical to this effort, further progress is needed in boundary spanning—the effort to translate tools to a variety of audiences across institutional boundaries.
- Information generated by decision-support tools must be implementable in the short term for users to foresee progress and support further tool development. Thus, efforts must be made to effectively integrate public concerns and elicit public information through dedicated outreach programs.

4.1 INTRODUCTION

This Chapter examines a series of decision-support experiments that explore how information on seasonal-to-interannual (SI) climate variability is being used, and how various water management contexts serve as test beds for implementing decision-support outputs. We describe how these experiments are implemented and how SI climate information is used to assess potential impacts of and responses to climate variability and change. We also examine characteristics of effective decision-support systems, involving users in forecast and other tool development, and incorporating improvements.

Section 4.2 discusses a series of experiments from across the nation, and in a variety of contexts. Special attention is paid to the role of key leadership in organizations to empower employees, take risks, and promote inclusiveness. This Section highlights the role of organizational culture in building pathways for innovation related to boundary-spanning approaches.

Section 4.3 examines approaches to increasing user knowledge and enhancing capacity building. We discuss the role of two-way communication among multiple forecast and water resource sectors, and the importance of translation and integration skills, as well as operations staff incentives for facilitating such integration.



Section 4.4 discusses the development of measurable indicators of progress in promoting climate information access and effective use, including process measures such as consultations between agencies and potential forecast user communities. The role of efforts to enhance dialogue and exchange among researchers and users is emphasized.

Finally, Section 4.5 summarizes major findings, directions for further research, and recommendations, including: needs for better understanding of the role of decision-maker context for tool use, how to assess vulnerability to climate, communicating results to users, bottom-up as well as top-down approaches to boundary-spanning innovation, and applicability of lessons from other resource management sectors (*e.g.*, forestry, coastal zone management, hydropower) on decision-support use and decision maker/scientist collaboration.

We conclude that, at present, the weak conceptual grounding afforded by cases from the literature necessitates that we base measures to improve decision support for the water resources management sector, as it pertains to inclusion of climate forecasts and information, on best judgment extrapolated from case experience. Additional research is needed on effective models of boundary spanning in order to develop a strong, theoretically-grounded understanding of the processes that facilitate information dissemination, communication, use, and evaluation so that it is possible to generalize beyond single cases, and to have predictive value.

4.2 DECISION-SUPPORT TOOLS FOR CLIMATE FORECASTS: SERVING END-USER NEEDS, PROMOTING USER-ENGAGEMENT AND ACCESSIBILITY

This Section examines a series of decision-support experiments from across the United States. Our objective is to learn how the barriers to optimal decision making, including impediments to trust, user confidence, communication of information, product translation, operationalization of decision-support tools, and policy transformation discussed in Chapter 3, can be overcome. As shall be seen, all of these experiments share one characteristic: users have been involved, to some degree, in tool development—through active elicitation of their needs, involvement in tool design, evaluation of tool effectiveness (and feedback into product refinement as a result of tool use), or some combination of factors.

4.2.1 Decision-Support Experiments on Seasonal-to-Interannual Climate Variability

The following seven cases are important testbeds that examine how, and how effectively, decision-support systems have been used to manage diverse water management needs, including ecological restoration, riparian flow management, urban water supply, agricultural water availability, coastal zone issues, and fire management at diverse spatial scales: from cities and their surrounding urban concentrations (New York, Seattle), to regions (Northern California, South Florida, Intermountain West); a comprehensively-managed river basin (CALFED); and a resource (forest lands) scattered over parts of the U.S. West and Southwest. These cases also illustrate efforts to rely on temporally diverse information (*i.e.*, predictions of future variability in precipitation, sea-level rise, and drought as well as past variation) in order to validate trends.

Most importantly, these experiments represent the use of different ways of integrating information into water management to enable better decisions to be made, including neural networks[1] in combination with El Niño-Southern Oscillation (ENSO) forecasting; temperature, precipitation and sea-level rise prediction; probabilistic risk assessment; integrated weather, climate and hydrological models producing short- and longer-term forecasts; weather and streamflow station outputs; paleoclimate records of streamflow and hydroclimatic variability; and the use of climate change information on precipitation and sea-level rise to address shorter-term weather variability.

Experiment 1: How the South Florida Water Management District Uses Climate Information

The Experiment

In an attempt to restore the Everglades ecosystem of South Florida, a team of state and federal agencies is engaged in the world's largest restoration program (Florida Department of Environmental Protection and South Florida Water Management District, 2007). A cornerstone of this effort is the understanding that SI climate variability (as well as climate change) could have significant impacts on the region's hydrology over the program's 50-year lifetime.

[1] A neural network or "artificial neural network" is an approach to information processing paradigm that functions like a brain in processing information. The network is composed of a large number of interconnected processing elements (neurons) that work together to solve specific problems and, like the brain, the entire network learns by example.

The South Florida Water Management District (SFWMD) is actively involved in conducting and supporting climate research to improve the prediction and management of South Florida's complex water system (Obeysekera *et al.*, 2007). The SFWMD is significant because it is one of the few cases in which decade-scale climate variability information is being used in water resource modeling, planning, and operation programs.

Background/Context

Research relating climatic indices to South Florida climate started at SFWMD more than a decade ago (South Florida Water Management District, 1996). Zhang and Trimble (1996), Trimble *et al.* (1997), and Trimble and Trimble (1998) used neural network models to develop a better understanding of how ENSO and other climate factors influence net inflow to Lake Okeechobee. From that knowledge, Trimble (1998) demonstrated the potential for using ENSO and other indices to predict net inflow to Lake Okeechobee for operational planning. Subsequently, SFWMD was able to apply climate forecasts to its understanding of climate-water resources relationships in order to assess risks associated with seasonal and multi-seasonal operations of the water management system and to communicate the projected outlook to agency partners, decision makers, and other stakeholders (Cadavid *et al.*, 1999).

There are many different ways of integrating information into water management to enable better decisions.

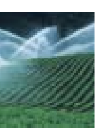
Implementation/Application

The SFWMD later established the Water Supply and Environment (WSE), a regulation schedule for Lake Okeechobee that formally uses seasonal and multi-seasonal climate outlooks as guidance for regulatory release decisions

(Obeysekera *et al.*, 2007). The WSE schedule uses states of ENSO and the Atlantic Multidecadal Oscillation (AMO) (Enfield *et al.,* 2001) to estimate the Lake Okeechobee net inflow outlook for the next six to 12 months. A decision tree with a climate outlook is a unique component of the WSE schedule and is considered a major advance over traditional hydrologic rule curves typically used to operate large reservoirs (Obeysekera *et al.*, 2007). Evaluation of the application of the WSE schedule revealed that considerable uncertainty in regional hydrology remains and is attributable to some combination of natural climatic variation, long-term global climate change, changes in South Florida precipitation patterns associated with drainage and development, and rainfall-runoff relationships altered by infrastructure changes (Obeysekera *et al.*, 2007).

Lessons Learned

From its experience with climate information and research, SFWMD has learned that to improve its modeling capabilities and contributions to basin management, it must improve its ability to: differentiate trends and discontinuities in basin flows associated with climate variation from those caused by water management; gauge the skill gained in using climate information to predict basin hydroclimatology; improve management; account for management uncertainties caused by climate variation and change; and evaluate how climate change projections may affect facility planning and operation of the SFWMD (Bras, 2006; Obeysekera *et al.*, 2007).



The district has also learned that, given the decades needed to restore the South Florida ecosystem, adaptive management is an effective way to incorporate SI climate variation into its modeling and operations decision-making processes, especially since longer term climate change is likely to exacerbate operational challenges. As previously stated, this experiment is also unique in being the only one that has been identified in which decadal climate status (*e.g.*, state of the AMO) is being used in a decision-support context.

Experiment 2: Long-Term Municipal Water Management Planning—New York City

The Experiment

Projections of long-term climate change, while characterized by uncertainty, generally agree that coastal urban areas will, over time, be increasingly threatened by a unique set of hazards. These include sea-level rise, increased storm surges, and erosion. Two important questions facing decision makers are: (1) How will long-term climate change increase these threats, which are already of concern to urban planners? and (2) Can information on the likely changes in recurrence intervals of extreme events (*e.g.*, tropical storms) be used in long term municipal water management planning and decision making?

Background and Context

Water management in coastal urban areas faces unique challenges due to vulnerabilities of much of the existing water supply and treatment infrastructure to storm surges, coastal erosion, coastal subsidence, and tsunamis (Jacobs *et al.*, 2007; OFCM, 2004). Not only are there risks due to extreme events under current and evolving climate conditions, but many urban areas rely on aging infrastructure that was built in the late nineteenth and early twentieth centuries. These vulnerabilities will only be amplified by the addition of global warming-induced sea-level rise due to thermal expansion of ocean water and the melting of glaciers, mountain ice caps and ice sheets (IPCC, 2007).

Water management in coastal urban areas faces unique challenges due to vulnerabilities of much of the existing water supply and treatment infrastructure to storm surges, coastal erosion, coastal subsidence, and tsunamis.

For example, observed global sea-level rise was ~1.8 millimeters (~0.07 inch) per year from 1961 to 2003, whereas from 1993 to 2003 the rate of sea-level rise was ~3.1 millimeters (~0.12 inch) per year (IPCC, 2007). The Intergovernmental Panel on climate Change (IPCC) projections for the twenty-first century (IPCC, 2007) are for an "increased incidence of extreme high sea level" which they define as the highest one percent of hourly values of observed sea level at a station for a given reference period. The New York City Department of Environmental Protection (NYCDEP) is one example of an urban agency that is adapting strategic and capital planning to take into account the potential effects of climate change—sea-level rise, higher temperature, increases in extreme events, and changing precipitation patterns—on the city's water systems. NYCDEP, in partnership with local universities and private sector consultants, is evaluating climate change projections, impacts, indicators, and adaptation and mitigation strategies to support agency decision making (Rosenzweig *et al.*, 2007).

Implementation/Application

In New York City (NYC), as in many coastal urban areas, many of the wastewater treatment plants are at elevations of 2 to 6 meters above present sea level and thus within the range of current surges for tropical storms and hurricanes and extra-tropical cyclones (or "Nor'easters") (Rosenzweig and Solecki, 2001; Jacobs, 2001). Like many U.S. cities along the northern Atlantic Coast, NYC's vulnerability to storm surges is predominantly from Nor'easters that occur largely between late November and March, and tropical storms and hurricanes that typically strike between July and October. Based on global warming-induced sea-level rise inferred from IPCC studies, the recurrence interval for the 100-year storm flood (probability of occurring in any given year = 1/100) may decrease to 60 years or, under extreme changes, a recurrence interval as little as four years (Rosenzweig and Solecki, 2001; Jacobs *et al.*, 2007).

Increased incidence of high sea levels and heavy rains can cause sewer back-ups and water treatment plant overflows. Planners have identified activities to address current and future concerns such as using sea-level rise forecasts as inputs to storm surge and elevation models to anticipate the impact of flooding on NYC coastal water resource-related facilities. Other concerns include potential water quality impairment from heavy rains that can increase pathogen levels and turbidity with the possible effects magnified by "first-flush" storms: heavy rains after weeks of dry weather. NYC water supply reservoirs have not been designed for rapid releases and any changes to operations to limit downstream damage through flood control measures will reduce water supply. In addition, adding filtration capacity to the water supply system would be a significant challenge.

Planners in NYC have begun to consider these issues by defining risks through probabilistic climate scenarios, and categorizing potential adaptations as related to (1) operations/management; (2) infrastructure; and (3) policy (Rosenzweig *et al.*, 2007). The NYCDEP is examining the feasibility of relocating critical control systems to higher floors/ground in low-lying buildings, building protective flood walls, modifying design criteria to reflect changing hydrologic processes, and reconfiguring outfalls to prevent sediment build-up and surging. Significant strategic decisions and capital investments for NYC water management will continue to be challenged by questions such as: How does the city utilize projections in ways that are robust to uncertainties? And, when designing infrastructure in the face of future uncertainty, how can these planners make infrastructure more robust and adaptable to changing climate, regulatory mandates, zoning, and population distribution?

Lessons Learned

When trends and observations clearly point to increasing risks, decision makers need to build support for adaptive action despite inherent uncertainties. The extent and effectiveness of adaptive measures will depend on building awareness of these issues among decision makers, fostering processes of interagency interaction and collaboration, and developing common standards (Zimmerman and Cusker, 2001).

New plans for regional capital improvements can be designed to include measures that will reduce vulnerability to the adverse effects of sea-level rise. Wherever plans are underway for

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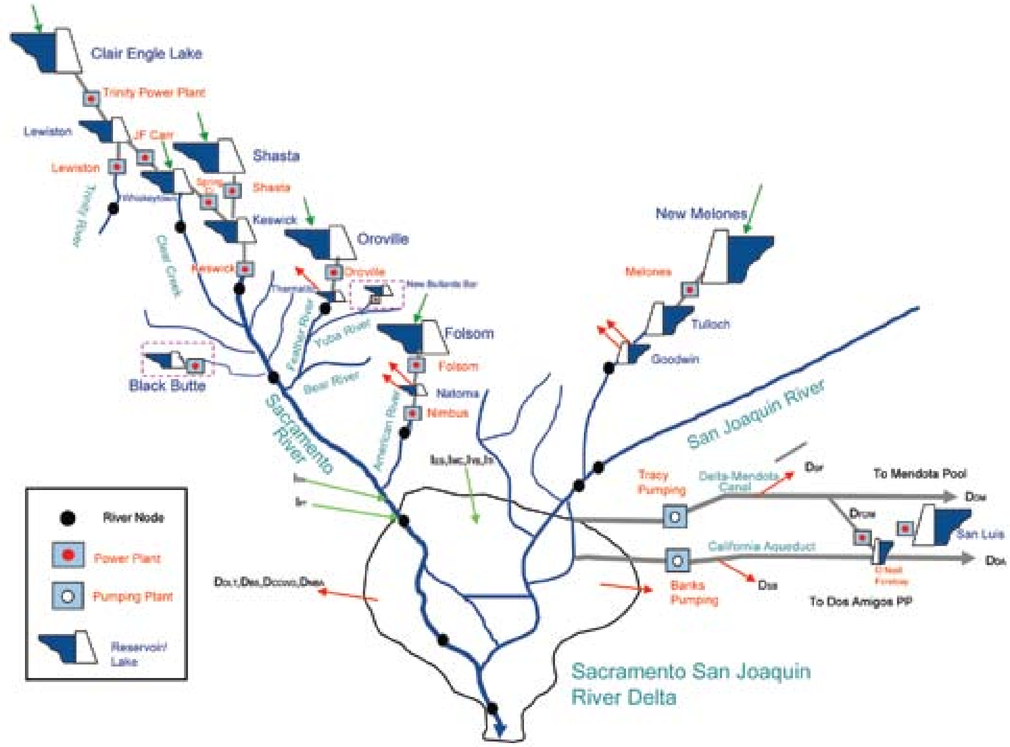
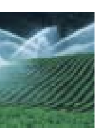


Figure 4.1 Map of Sacramento and San Joaquin River Delta.

upgrading or constructing new roadways, airport runways, or wastewater treatment plants, which may already include flood protection; project managers now recognize the need to consider sea-level rise in planning activities (*i.e.*, OFCM, 2002).

In order to incorporate new sources of risk into engineering analysis, the meteorological and hydrology communities need to define and communicate current and increasing risks clearly, and convey them coherently, with explicit consideration of the inherent uncertainties. Research needed to support regional stakeholders include: further reducing uncertainties associated with sea-level rise, providing more reliable predictions of changes in frequency and intensity of tropical and extra-tropical storms, and determining how saltwater intrusion will impact freshwater. Finally, regional climate model simulations and statistical techniques being used to predict long-term climate change impacts could be down-scaled to help manage projected SI climate variability. This could be especially useful for adaptation planning (OFCM, 2007a).



Experiment 3: Integrated Forecast and Reservoir Management (INFORM)—Northern California

The Experiment

The Integrated Forecast and Reservoir Management (INFORM) project aims to demonstrate the value of climate, weather, and hydrology forecasts in reservoir operations. Specific objectives are to: (1) implement a prototype integrated forecast-management system for the Northern California river and reservoir system in close collaboration with operational forecasting and management agencies, and (2) demonstrate the utility of meteorological/climate and hydrologic forecasts through near-real-time tests of the integrated system with actual data and management input.

Background and Context

The Northern California river system (Figure 4.1) encompasses the Trinity, Sacramento, Feather, American, and San Joaquin river systems, and the Sacramento-San Joaquin Delta (see: Experiment 7, CALFED)[2]. The Sacramento and San Joaquin Rivers join to form an extensive delta region and eventually flow out

[2] CA. Gov. Welcome to Calfed Bay-Deltas Program. http://calwater.ca.gov/index.aspx

into the Pacific Ocean. The Northern California river and reservoir system serves many vital water uses, including providing two-thirds of the state's drinking water, irrigating seven million acres of the world's most productive farmland, and providing habitat to hundreds of species of fish, birds, and plants. In addition, the system protects Sacramento and other major cities from flood disasters and contributes significantly to the production of hydroelectric energy. The Sacramento-San Joaquin Delta provides a unique environment and is California's most important fishery habitat. Water from the delta is pumped and transported through canals and aqueducts south and west serving the water needs of many more urban, agricultural, and industrial users.

An agreement between the U.S. Department of the Interior, U.S. Bureau of Reclamation, and California Department of Water Resources provides for the coordinated operation of the federal and state facilities (Agreement of Coordinated Operation-COA). The agreement aims to ensure that each project obtains its share of water from the San Joaquin Delta and protects other beneficial uses in the Delta and the Sacramento Valley. Coordination is structured around the necessity to meet in-basin use requirements in the Sacramento Valley and the San Joaquin Delta, including delta outflow and water quality requirements.

Implementation/Application

The INFORM Forecast-Decision system consists of a number of diverse elements for data handling, model runs, and output archiving and presentation. It is a distributed system with on-line and off-line components. The system routinely captures real-time National Center for Environmental Predictions (NCEP) ensemble forecasts and uses both ensemble synoptic forecasts from NCEP's Global Forecast System (GFS) and ensemble climate forecasts from NCEP's Climate Forecast System (CFS). The former produces real-time short-term forecasts, and the latter produce longer-term forecasts as needed (HRC-GWRI, 2006).

The INFORM DSS is designed to support the decision-making process, which includes multiple decision makers, objectives, and temporal scales. Toward this goal, INFORM DSS includes a suite of interlinked models that address reservoir planning and management at multi-decadal, interannual, seasonal, daily, and hourly time scales. The DSS includes models for each major reservoir in the INFORM region, simulation components for watersheds, river reaches, and the Bay Delta, and optimization components suitable for use with ensemble forecasts. The decision software runs off-line, as forecasts become available, to derive and assess planning and management strategies for all key system reservoirs. DSS is embedded in a user-friendly, graphical interface that links models with data and helps visualize and manage results.

Seasonal climate and hydrologic forecasts benefit reservoir management, provided that they are used in connection with adaptive dynamic decision methods that can explicitly account for and manage forecast uncertainty.

Development and implementation of the INFORM Forecast-Decision system was carried out by the Hydrologic Research Center (in San Diego) and the Georgia Water Resources Institute (in Atlanta), with funding from NOAA, CALFED, and the California Energy Commission. Other key participating agencies included U.S. National Weather Service California–Nevada River Forecast Center, the California Department of Water Resources, the U.S. Bureau of Reclamation Central Valley Operations, and the Sacramento District of the U.S. Army Corps of Engineers. Other agencies and regional stakeholders (*e.g.*, the Sacramento Flood Control Authority, SAFCA, and the California Department of Fish and Game) participated in project workshops and, indirectly, through comments conveyed to the INFORM Oversight and Implementation Committee.

Lessons Learned

The INFORM approach demonstrates the value of advanced forecast-decision methods for water resource decision making, attested to by participating agencies who took part in designing the experiments and who are now proceeding to incorporate the INFORM tools and products in their decision-making processes.

From a technical standpoint, INFORM served to demonstrate important aspects of integrated forecast-decision systems, namely that (1) seasonal climate and hydrologic forecasts benefit reservoir management, provided that they are used in connection with adaptive dynamic decision methods that can explicitly account for and manage forecast uncertainty;

(2) ignoring forecast uncertainty in reservoir regulation and water management decisions leads to costly failures; and (3) static decision rules cannot take full advantage of and handle forecast uncertainty information. The extent to which forecasts benefit the management process depends on their reliability, range, and lead time, in relation to the management systems' ability to regulate flow, water allocation, and other factors.

Ignoring forecast uncertainty in reservoir regulation and water management decisions leads to costly failures.

Experiment 4: How Seattle Public Utility District Uses Climate Information to Manage Reservoirs

The Experiment

Seattle Public Utilities (SPU) provides drinking water to 1.4 million people living in the central Puget Sound region of Washington. SPU also has instream (*i.e.*, river flow), resource management, flood control management and habitat responsibilities on the Cedar and South Fork Tolt Rivers, located on the western slopes of the Cascade Mountains. Over the past several years SPU has taken numerous steps to improve the incorporation of climate, weather, and hydrologic information into the real-time and SI management of its mountain water supply system.

Implementation/Application

Through cooperative relationships with agencies such as NOAA's National Weather Service, U.S. Department of Agriculture, Natural Resource Conservation Service, and the U.S. Geological Survey (USGS), SPU has secured real-time access to numerous SNOTEL sites[3], streamflow gages and weather stations in and around Seattle's watersheds. SPU continuously monitors weather and climate data across the maritime Pacific derived from all these above sources. Access to this information has helped to reduce the uncertainty associated with making real-time and seasonal tactical and strategic operational decisions, and enhanced the inherent flexibility of management options available to SPU's water supply managers as they adjust operations for changing weather and hydrologic conditions, including abnormally low levels of snowpack or precipitation.

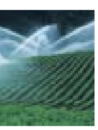
Among the important consequences of this synthesis of information has been SPU's increasing ability to undertake reservoir operations with higher degrees of confidence than in the past. As an example, SPU was well served by this information infrastructure during the winter of 2005 when the lowest snowpack on record was realized in its watersheds. The consequent reduced probability of spring flooding, coupled with their ongoing understanding of local and regional climate and weather patterns, enabled SPU water managers to safely capture more water in storage earlier in the season than normal. As a result of SPU's ability to continuously adapt its operations, Seattle was provided with enough water to return to normal supply conditions by early summer despite the record low snowpack.

SPU is also using conclusions from a SPU-sponsored University of Washington study that examined potential impacts of climate change on SPU's water supply. To increase the rigor of the study, a set of fixed reservoir operating rules was used and no provisions were made to adjust these to account for changes projected by the study's climate change scenarios. From these conclusions, SPU has created two future climate scenarios, one for 2020 and one for 2040, to examine how the potential impacts of climate change may affect decisions about future supply. While these scenarios indicated a reduction in yield, SPU's existing sources of supply were found to be sufficient to meet official demand forecasts through 2053.

Lessons Learned

SPU has actually incorporated seasonal climate forecasts into their operations and is among the

[3] The SNOTEL network of weather stations is a snowfall depth monitoring network established by the USGS.



leaders in considering climate change. SPU is a "receptive audience" for climate tools in that it has a wide range of management and long-term capital investment responsibilities that have clear connections to climate conditions. Further, SPU is receptive to new management approaches due to public pressure and the risk of legal challenges related to the protection of fish populations who need to move upstream to breed.

Specific lessons include: (1) access to skillful seasonal forecasts enhances credibility of using climate information in the Pacific Northwest, even with relatively long lead times; (2) monitoring of snowpack moisture storage and mountain precipitation is essential for effective decision making and for detecting long-term trends that can affect water supply reliability; and (3) while SPU has worked with the research community and other agencies, it also has significant capacity to conduct in-house investigations and assessments. This provides confidence in the use of information.

Experiment 5: Using Paleoclimate Information to Examine Climate Change Impacts

The Experiment

Can an expanded estimate of the range of natural hydrologic variability from tree ring reconstructions of streamflow, a climate change research tool, be used effectively as a decision-support resource for better understanding SI climate variability and water resource planning? Incorporation of tree ring reconstructions of streamflow into decision making was accomplished through partnerships between researchers and water managers in the intermountain West.

Background and Context

Although water supply forecasts in the intermountain West have become increasingly sophisticated in recent years, water management planning and decision making have generally depended on instrumental gage records of flow, most of which are less than 100 years in length. Drought planning in the Intermountain West has been based on the assumption that the 1950s drought, the most severe drought in the instrumental record, adequately represents the full range of natural variability and, thus, a likely worst-case scenario.

The recent prolonged drought in the western United States prompted many water managers to consider that the observational gage records of the twentieth century do not contain the full range of natural hydroclimatic variability possible. Gradual shifts in recent decades to more winter precipitation as rain and less as snow, earlier spring runoff, higher temperatures, and unprecedented population growth have resulted in an increase in vulnerability of limited water supplies to a variable and changing climate. The paleoclimate records of streamflow and hydroclimatic variability provide an extended, albeit indirect, record (based on more than 1000 years of record from tree rings in some key watersheds) for assessing the potential impact of a more complete range of natural variability as well as for providing a baseline for detecting possible regional impacts of global climate change.

Implementation/Application

Several years of collaborations between scientists and water resource partners have explored possible applications of tree ring reconstructed flows in water resource management to assess the potential impacts of drought on water systems. Extended records of hydroclimatic variability from tree ring based reconstructions reveal a wider range of natural variability than in gage records alone, but how to apply this information in water management planning has not been obvious. The severe western drought that began in 2000 and peaked in 2002 provided an excellent opportunity to work with water resource providers and agencies on how to incorporate paleoclimate drought information in planning and decision making. These partnerships with water resource managers have led to a range of applications evolving from a basic change in thinking about drought, to the use of tree ring reconstructed flows to run a complex water supply model to assess the impacts of drought on water systems.

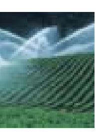
The extreme five-year drought that began in 2002 motivated water managers to ask these questions: How unusual was 2002, or the 2000-2004 drought? How often do years or droughts like this occur? What is the likelihood

Several years of collaborations between scientists and water resource partners have explored possible applications of tree ring reconstructed flows in water resource management to assess the potential impacts of drought on water systems.

of it happening again in the future (should we plan for it, or is there too low a risk to justify infrastructure investments)? And, from a long term perspective, is the twentieth and twenty-first century record an adequate baseline for drought planning?

The first three questions could be answered with reconstructed streamflow data for key gages, but to address planning, a critical step is determining how tree ring streamflow reconstruction could be incorporated into water supply modeling efforts. The tree ring streamflow reconstructions have annual resolution, whereas most water system models required weekly or daily time steps, and reconstructions are generated for a few gages, while water supply models typically have multiple input nodes. The challenge has been spatially and temporally disaggregating the reconstructed flow series into the time steps and spatial scales needed as input into models. A variety of analogous approaches have successfully addressed the temporal scale issue, while the spatial challenges have been addressed statistically using nearest neighbor or other approaches.

Improvements in El Niño–Southern Oscillation-based climate forecasting, and research on interactions between climate and wildland fire occurrence, have generated opportunities for improving use of seasonal-to-interannual climate forecasts by fire managers.



Another issue addressed has been that the streamflow reconstructions explain only a portion of the variance in the gage record, and the most extreme values are often not fully replicated. Other efforts have focused on characterizing the uncertainty in the reconstructions, the sources of uncertainty, and the sensitivity of the reconstruction to modeling choices. In spite of these many challenges, expanded estimates of the range of natural hydrologic variability from tree ring reconstructions have been integrated into water management decision support and allocation models to evaluate operating policy alternatives for efficient management and sustainability of water resources, particularly during droughts in California and Colorado.

Lessons Learned

Roadblocks to incorporating tree ring reconstructions into water management policy and decision making were overcome through prolonged, sustained partnerships with researchers working to make their scientific findings relevant, useful, and usable to users for planning and management, and water managers willing to take risk and invest time to explore the use of non-traditional information outside of their comfort zone. The partnerships focused on formulating research questions that led to applications addressing institutional constraints within a decision process addressing multiple timescales.

Workshops requested by water managers have resulted in expansion of application of the tree ring based streamflow reconstructions to drought planning and water management <http://wwa.colorado.edu/resources/paleo/>. In addition, an online resource called TreeFlow <http://wwa.colorado.edu/resources/paleo/data.html> was developed to provide water managers interested in using tree ring streamflow reconstructions access to gage and reconstruction data and information, and a tutorial on reconstruction methods for gages in Colorado and California.

Experiment 6
Climate, Hydrology, and Water Resource Issues in Fire-Prone United States Forests

The Experiment

Improvements in ENSO-based climate forecasting, and research on interactions between climate and wildland fire occurrence, have generated opportunities for improving use of seasonal-to-interannual climate forecasts by fire managers. They can now better anticipate annual fire risk, including potential damage to watersheds over the course of the year. The experiment, consisting of annual workshops to evaluate the utility of climate information for fire management, were initiated in 2000 to inform fire managers about climate forecasting tools and to enlighten climate forecasters about the needs of the fire management community. These workshops have evolved into an annual assessment of conditions and production of pre-season fire-climate forecasts.

Background and Context

Large wildfire activity in the U.S. West and Southeast has increased substantially since the mid-1980s, an increase that has largely been attributed to shifting climate conditions (Westerling *et al.*, 2006). Recent evidence also suggests that global or regional warming trends and a positive phase of the AMO are likely to lead to an even greater increase in risk for ecosystems and communities vulnerable to wildfire in the western United States (Kitzberger *et al.,* 2007). Aside from the immediate impacts of a wildfire (*e.g.*, destruction of biomass, substantial altering of ecosystem function), the increased likelihood of high sediment deposition in streams and flash flood events can present post-fire management challenges including impacts to soil stability on slopes and mudslides (*e.g.*, Bisson *et al*., 2003). While the highly complex nature and substantially different ecologies of fire-prone systems precludes one-size-fits-all fire management approaches (Noss *et al*., 2006), climate information can help managers plan for fire risk in the context of watershed management and post-fire impacts, including impacts on water resources. One danger is inundation of water storage and treatment facilities with sediment-rich water, creating potential for significant expense for pre-treatment of water or for facilities repair. Post-fire runoff can also raise nitrate concentrations to levels that exceed the federal drinking water standard (Meixner and Wohlgemuth, 2004).

Work by Kuyumjian (2004), suggests that coordination among fire specialists, hydrologists, climate specialists, and municipal water managers may produce useful warnings to downstream water treatment facilities about significant ash- and sediment-laden flows. For example, in the wake of the 2000 Cerro Grande fire in the vicinity of Los Alamos, New Mexico, catastrophic floods were feared, due to the fact that 40 percent of annual precipitation in northern New Mexico is produced by summer monsoon thunderstorms (*e.g.*, Earles *et al.*, 2004). Concern about water quality and about the potential for contaminants carried by flood waters from the grounds of Los Alamos Nuclear Laboratory to enter water supplies prompted a multi-year water quality monitoring effort (Gallaher and Koch, 2004). In the wake of the 2002 Bullock Fire and 2003 Aspen Fire in the Santa Catalina Mountains adjacent to Tucson, Arizona, heavy rainfall produced floods that destroyed homes and caused one death in Canada del Oro Wash in 2003 (Ekwurzel, 2004), destroyed structures in the highly popular Sabino Canyon recreation area and deposited high sediment loads in Sabino Creek in 2003 (Desilets *et al.,* 2006). A flood in 2006 wrought a major transformation to the upper reaches of the creek (Kreutz, 2006). Residents of Summerhaven, a small community located on Mt. Lemmon, continues to be concerned about the impacts of future fires on their water resources. In all of these situations, climate information can be helpful in assessing vulnerability to both flooding and water quality issues.

Implementation/Application

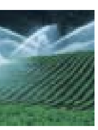
Little published research specifically targets interactions among climate, fire, and watershed dynamics (OFCM, 2007b). Publications on fire-climate interactions, however, provide a useful entry point for examining needs for and uses of climate information in decision processes involving water resources. A continuing effort to produce fire-climate outlooks was initiated through a workshop held in Tucson, Arizona, in late winter 2000. One of the goals of the workshop was to identify the climate information uses and needs of fire managers, fuel managers, and other decision makers. Another was to actually produce a fire-climate forecast for the coming fire season. The project was initiated through collaboration involving researchers at the University of Arizona, the NOAA-funded Climate Assessment for the Southwest Project (CLIMAS), the Center for Ecological and Fire Applications (CEFA) at the Desert Research Institute in Reno, Nevada and the National Interagency Fire Center (NIFC) located in Boise, Idaho (Morehouse, 2000). Now called the National Seasonal Assessment Workshop (NSAW), the process continues to produce annual fire-climate outlooks (*e.g.*, Crawford *et al.*, 2006). The seasonal fire-climate forecasts produced by NSAW have been published through NIFC since 2004. During this same time period,

Westerling *et al.* (2002) developed a long-lead statistical forecast product for areas burned in western wildfires.

Lessons Learned

The experimental interactions between climate scientists and fire managers clearly demonstrated the utility of climate information for managing watershed problems associated with wildfire. Climate information products used in the most recently published NSAW Proceedings (Crawford *et al.*, 2006), for example, include the following: NOAA Climate Prediction Center (CPC) seasonal temperature and precipitation outlooks, historical temperature and precipitation data, *e.g.*, High Plains Regional Climate Center, National drought conditions, from National Drought Mitigation Center, 12-month standardized precipitation index, spring and summer streamflow forecasts and departure from average greenness.

The use of climate forecast information in fire management began because decision makers within the wildland fire management community were open to new information, due to legal challenges, public pressure, and a "landmark" wildfire season in 2000.



Based on extensive interactions with fire managers, other products are also used by some fire ecologists and managers, including climate history data from instrumental and paleo (especially tree ring) records and hourly to daily and weekly weather forecasts, (*e.g.*, temperature, precipitation, wind, relative humidity).

Products identified as potentially improving fire management (*e.g.*, Morehouse, 2000; Garfin and Morehouse, 2001) include: improved monsoon forecasts and training in how to use them, annual to decadal (AMO, Pacific Decadal Oscillation) projections, decadal to centennial climate change model outputs, downscaled to regional/finer scales, and dry lightning forecasts.

This experiment is one of the most enduring we have studied. It is now part of accepted practice by agencies, and has produced spin-off activities managed and sustained by the agencies and new participants. The use of climate forecast information in fire management began because decision makers within the wildland fire management community were open to new information, due to legal challenges, public pressure, and a "landmark" wildfire season in 2000. The National Fire Plan (2000) and its associated 10-year Comprehensive Strategy reflected a new receptiveness for new ways of coping with vulnerabilities, calling for a community-based approach to reducing wildland fires that is proactive and collaborative rather than prior approaches entered on internal agency activities.

Annual workshops became routine forums for bringing scientists and decision makers together to continue to explore new questions and opportunities, as well as involve new participants, new disciplines and specialties, and to make significant progress in important areas (*e.g.*, lightning climatologies, and contextual assessments of specific seasons), quickly enough to fulfill the needs of agency personnel (National Fire Plan, 2000).

Experiment 7: The CALFED—Bay Delta Program: Implications of Climate Variability

The Experiment

The Sacramento-San Joaquin River Delta, which flows into San Francisco Bay, is the focus of a broad array of environmental issues relating to endangered fish species, land use, flood control and water supply. After decades of debate about how to manage the delta to export water supplies to southern California while managing habitat and water supplies in the region, and maintaining endangered fish species, decision makers are involved in making major long-term decisions about rebuilding flood control levees and rerouting water supply networks through the region. Incorporating the potential for climate change impacts on sea level rise and other regional changes are important to the decision-making process (Hayhoe *et al.*, 2004; Knowles *et al.*, 2006; Lund *et al.*, 2007).

Background and Context

Climate considerations are critical for the managers of the CALFED program, which oversees the 700,000 acres in the Sacramento-San Joaquin Delta. 400,000 acres have been subsiding due to microbial oxidation of peat soils that have been used for agriculture. A significant number of the islands are below sea level, and protected from inundation by dikes that are in relatively poor condition. Continuing sea-level rise and regional climate change are expected to have additional major impacts such as flooding and changes in seasonal precipitation patterns. There are concerns that multiple islands would be inundated in a "10-year storm event", which represents extreme local vulnerability to flooding.

In the central delta, there are five county governments in addition to multiple federal and state agencies and non-governmental organizations whose perspectives need to be integrated into the management process, which is one of the purposes of the CALFED program. A key decision being faced is whether delta interests should invest in trying to build up and repair levies to protect subsided soils. What are the implications for other islands when one island floods? Knowing the likelihood of sea-level rise of various magnitudes will significantly constrain the answers to these questions. For example, if the rise is greater than one foot in the next 50 to 100 years, that could end the debate about whether to use levee improvements to further protect these islands. Smaller amounts of sea-level rise will make this decision less clear-cut. Answers are needed in order to support decisions about the delta in the near term.

Implementation/Application
Hundreds of millions of dollars of restoration work has been done in the delta and associated watersheds, and more investment is required. Where should money be invested for effective long-term impact? There is a need to invest in restoring lands at intertidal and higher elevations so that wetlands can evolve uphill while tracking rising sea level (estuarine progression). Protecting only "critical" delta islands (those with major existing infrastructure) to endure a 100-year flood will cost around $2.6 billion.

Another way that climate change-related information is critical to delta management is in estimating volumes and timing of runoff from the Sierra Nevada mountain range (Knowles *et al.*, 2006). To the extent that snowpack will be diminished and snowmelt runoff occurs earlier, there are implications for flood control, water supply and conveyance, and seawater intrusion—all of which affect habitat and land use decisions. One possible approach to water shortages is more recent aggressive management of reservoirs to maximize water supply benefits, thereby possibly increasing flood

risk. The State Water Project is now looking at a ten percent failure rate operating guideline at Oroville rather than a 5 percent failure rate operating guideline; this would provide much more water supply flexibility.

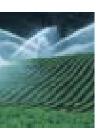
Lessons Learned
Until recently the implications of climate change and sea-level rise were not considered in the context of solutions to the Bay Delta problem—particularly in the context of climate variability. These implications are currently considered to be critical factors in infrastructure planning, and the time horizon for future planning has been extended to to over 100 years (Delta Vision Blue Ribbon Task Force, 2008). The relatively rapid shift in perception of the urgency of climate change impacts was not predicted, but does demand renewed consideration of adaptive management strategies in the context of incremental changes in understanding (as opposed to gradual increases in accumulation of new facts, which is the dominant paradigm in adaptive management).

4.2.2 Organizational and Institutional Dimensions of Decision-Support Experiments

These seven experiments illuminate the need for effective two-way communication among tool developers and users, and the importance of organizational culture in fostering collaboration. An especially important lesson they afford is in underscoring the significance of boundary-spanning entities to enable decision-support transformation. Boundary spanning, discussed in Section 4.3, refers to the activities of special scientific/stakeholder committees, agency coordinating bodies, or task forces that facilitate bringing together tool developers and users to exchange information, promote communication, propose remedies to problems, foster frequent engagement, and jointly develop decision-support systems to address user needs. In the process, they provide incentives for innovation—frequently noted in the literature—that facilitate the use of climate science information in decisions (*e.g.*, NRC, 2007; Cash and Buizer, 2005; Sarewitz and Pielke, 2007). Before outlining how these seven experiments illuminate boundary spanning, it is important to consider problems identified in recent research.

While there is widespread agreement that decision support involves translating the products of climate science into forms useful for decision makers and disseminating the translated products, there is disagreement over precisely what constitutes translation (NRC, 2008). One view is that climate scientists know which products will be useful to decision makers and that potential users will make appropriate use of decision-relevant information once it is made available. Adherents of this view typically emphasize the importance of developing "decision-support tools", such as models, maps, and other technical products intended to be relevant to certain classes of decisions that, when created, complete the task of decision support. This approach, also called a "translation model", (NRC, 2008) has not proved useful to many decision makers—underscored by the fact that, in our seven cases, greater weight was given to "creating conditions that foster the appropriate use of information" rather than to the information itself (NRC, 2008).

There is a need to incorporate public concerns and develop communication outreach methods, particularly about risk, that are clear and coherent.



A second view is that decision-support activities should enable climate information producers and users to jointly develop information that addresses users' needs—also called "co-production" of information or reconciling information "supply and demand" (NRC, 1989, 1996, 1999, 2006; McNie, 2007; Sarewitz and Pielke, 2007; Lemos and Morehouse, 2005). Our seven cases clearly delineate the presumed advantages of the second view.

In the SFWMD case, an increase in user trust was a powerful inducement to introduce, and then continue, experiments leading to development of a Water Supply and Environment schedule, employing seasonal and multi-seasonal climate outlooks as guidance for regulatory releases. As this tool began to help reduce operating system uncertainty, decision-maker confidence in the use of model outputs increased, as did further cooperation between scientists and users—facilitated by SFWMD's communication and agency partnership networks.

In the case of INFORM, participating agencies in California worked in partnership with scientists to design experiments that would allow the state to integrate forecast methods into planning for uncertainties in reservoir regulation. Not only did this set of experiments demonstrate the practical value of such tools, but they built support for adaptive measures to manage risks, and reinforced the use, by decision makers, of tool output in their decisions. Similar to the SFWMD case, through demonstrating how forecast models could reduce operating uncertainties—especially as regards increasing reliability and lead time for crucial decisions—cooperation among partners seems to have been strengthened.

Because the New York City and Seattle cases both demonstrate use of decision-support information in urban settings, they amplify another set of boundary-spanning factors: the need to incorporate public concerns and develop communication outreach methods, particularly about risk, that are clear and coherent. While conscientious efforts to support stakeholder needs for reducing uncertainties associated with sea-level rise and infrastructure relocation are being made, the New York case highlights the need for further efforts to refine communication, tool dissemination, and evaluation efforts to deliver information on potential impacts of climate change more effectively. It also illustrates the need to incorporate new risk-based analysis into existing decision structures related to infrastructure construction and maintenance. The Seattle public utility has had success in conveying the importance of employing SI climate forecasts in operations, and is considered a national model for doing so, in part because of a higher degree of established public support due to: (1) litigation over protection of endangered fish populations and (2) a greater in-house ability to test forecast skill and evaluate decision tools. Both served as incentives for collaboration. Access to highly-skilled forecasts in the region also enhanced prospects for forecast use.

Although not an urban case, the CALFED experiment's focus on climate change, sea-level rise, and infrastructure planning has numerous parallels with the Seattle and New York City cases. In this instance, the public and decision makers were prominent in these cases, and their involvement enhanced the visibility and importance of these issues and probably helped facilitate the incorporation of climate information by water resource managers in generating adaptation policies.

The other cases represent variations of boundary spanning whose lessons are also worth noting. The tree ring reconstruction case documents impediments of a new data source to incorporation into water planning. These impediments were overcome through prolonged and sustained partnerships between researchers and users that helped ensure that scientific findings were relevant, useful, and usable for water resources planning and management, and water managers who were willing to take some risk. Likewise, the case of fire-prone forests represented a different set of impediments that also required novel means of boundary spanning to overcome. In this instance, an initial workshop held among scientists and decision makers itself constituted an experiment on how to: identify topics of mutual interest across the climate and wildland fire management communities at multiple scales; provide a forum for exploring new questions and opportunities; and constitute a vehicle for inviting diverse agency personnel, disciplinary representatives, and operation, planning, and management personnel to facilitate new ways of thinking about an old set of problems. In all cases, the goal is to facilitate successful outcomes in the use of climate information for decisions, including faster adaptation to more rapidly changing conditions.

Before turning to analytical studies on the importance of such factors as the role of key leadership in organizations to empower employees, organizational climate that encourages risk and promote inclusiveness, and the ways organizations encourage boundary innovation (Section 4.3), it is important to reemphasize the distinguishing feature of the above experiments: they underscore the importance of process as well as product outcomes in developing, disseminating and using information. We return to this issue when we discuss evaluation in Section 4.4.

4.3 APPROACHES TO BUILDING USER KNOWLEDGE AND ENHANCING CAPACITY BUILDING

The previous section demonstrated a variety of contexts where decision-support innovations are occurring. This Section analyzes six factors that are essential for building user knowledge and enhancing capacity in decision-support systems for integration of SI climate variability information, and which are highlighted in the seven cases above: (1) boundary spanning, (2) knowledge-action systems through inclusive organizations, (3) decision-support needs are user driven, (4) proactive leadership that champions change; (5) adequate funding and capacity building, and (6) adaptive management.

4.3.1 Boundary-Spanning Organizations as Intermediaries Between Scientists and Decision Makers

Boundary-spanning organizations perform translation and mediation functions between producers of information and their users.

As noted in Section 4.2.2, boundary-spanning organizations link different social and organizational worlds (*e.g.*, science and policy) in order to foster innovation across boundaries, provide two-way communication among multiple sectors, and integrate production of science with user needs. More specifically, these organizations perform translation and mediation functions between producers of information and their users (Guston, 2001; Ingram and Bradley, 2006; Jacobs, *et al.*, 2005). Such activities include convening forums that provide common vehicles for conversations and training, and for tailoring information to specific applications.

Ingram and Bradley (2006) suggest that boundary organizations span not only disciplines, but different conceptual and organizational divides (*e.g.*, science and policy), organizational missions and philosophies, levels of governance, and gaps between experiential and professional ways of knowing. This is important because effective knowledge transfer systems cultivate individuals and/or institutions that serve as intermediaries between nodes in the system, most notably between scientists and decision makers. In the academic community and within agencies, knowledge, including the knowledge involved in the production of climate forecast information, is often produced in "stove-pipes" isolated from neighboring disciplines or applications.

Boundary organizations enhance communication among stakeholders.

Evidence for the importance of this proposition—and for the importance of boundary spanning generally—is provided by those cases, particularly in Chapter 3 (*e.g.*, the Apalachicola–Chattahoochee–Flint River basin dispute), where the absence of a boundary spanning entity created a void that made the deliberative consideration of various decision-maker needs all but impossible to negotiate. Because the compact organization charged with managing water allocation among the states of Alabama, Florida, and Georgia would not actually take effect until an allocation formula was agreed upon, the compact could not serve to bridge the divides between decision making and scientific assessment of flow, meteorology, and riverine hydrology in the region.

Boundary spanning organizations are important to decision-support system development in three ways. First, they "mediate" communication between supply and demand functions for particular areas of societal concern. Sarewitz and Pielke (2007) suggest, for example, that the IPCC serves as a boundary organization for connecting the science of climate change to its use in society—in effect, satisfying a "demand" for science implicitly contained in such international processes for negotiating and implementing climate treaties as the U.N. Framework Convention on Climate Change and Kyoto Protocol. In the United States, local irrigation district managers and county extension agents often serve this role in mediating between scientists (hydrological modelers) and farmers (Cash *et al.*, 2003). In the various cases we explored in Section 4.2.1, and in Chapter 3 (*e.g.*, coordinating committees, post-event "technical sessions" after the Red River floods, and comparable entities), we saw other boundary spanning entities performing mediation functions.

Second, boundary organizations enhance communication among stakeholders. Effective tool development requires that affected stakeholders be included in dialogue, and that data from local resource managers (blended knowledge) be used to ensure credible communication. Successful innovation is characterized by two-way communication between producers and users of

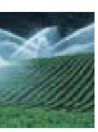


Table 4.1 Examples of Boundary Organizations for Decision-Support Tool Development.

Cooperative Extension Services: Housed in land-grant universities in the United States, they provide large networks of people who interact with local stakeholders and decision makers within certain sectors (not limited to agriculture) on a regular basis. In other countries, this agricultural extension work is often done with great effectiveness by local government (*e.g.*, Department of Primary Industries, Queensland, Australia).
Watershed Councils: In some U.S. states, watershed councils and other local planning groups have developed, and many are focused on resolving environmental conflicts and improved land and water management (particularly successful in the State of Oregon).
Natural Resource Conservation Districts: Within the U.S. Department of Agriculture, these districts are highly networked within agriculture, land management, and rural communities.
Non-governmental organizations (NGOs) and public interest groups: Focus on information dissemination and environmental management issues within particular communities. They are good contacts for identifying potential stakeholders, and may be in a position to collaborate on particular projects. Internationally, a number of NGOs have stepped forward and are actively engaged in working with stakeholders to advance use of climate information in decision making (*e.g.*, Asian Disaster Preparedness Center (ADPC), in Bangkok, Thailand).
Federal agency and university research activities: Expanding the types of research conducted within management institutions and local and state governments is an option to be considered—the stakeholders can then have greater influence on ensuring that the research is relevant to their particular concerns.

knowledge, as well as development of networks that allow close and ongoing communication among multiple sectors. Likewise, networks must allow close communication among multiple sectors (Sarewitz and Pielke, 2007).

Third, boundary organizations contribute to tool development by serving the function of translation more effectively than is conceived in the Loading Dock Model of climate products. In relations between experts and decision makers, understanding is often hindered by jargon, language, experiences, and presumptions; *e.g.*, decision makers often want deterministic answers about future climate conditions, while scientists can often only provide probabilistic information, at best. As noted in Chapter 3, decision makers often mistake probabilistic uncertainty as a kind of failure in the utility and scientific merit of forecasts, even though uncertainty is a characteristic of science (Brown, 1997).

One place where boundary spanning can be important with respect to translation is in providing a greater understanding of uncertainty and its source. This includes better information exchange between scientists and decision makers on, for example, the decisional relevance of different aspects of uncertainties, and methods of combining probabilistic estimates of events through simulations, in order to reduce decision-maker distrust, misinterpretation of forecasts, and mistaken interpretation of models (NRC, 2005).

Effective boundary organizations facilitate the co-production of knowledge—generating information or technology through the collaboration of scientists/engineers and nonscientists who incorporate values and criteria from both communities. This is seen, for example, in the collaboration of scientists and users in producing models, maps, and forecast products. Boundary organizations have been observed to work best when accountable to the individuals or interests on both sides of the boundary they bridge, in order to avoid capture by either side and to align incentives such that interests of actors on both sides of the boundary are met.

Jacobs (2003) suggests that universities can be good locations for the development of new ideas and applications, but they may not be ideal for sustained stakeholder interactions and services, in part because of funding issues and because training cycles for graduate students, who are key resources at universities, do not always allow a long-term commitment of staff. Many user groups and stakeholders either have no contact with universities or may not encourage researchers to participate in or observe decision-making processes. University reward systems rarely recognize interdisciplinary work, outreach efforts, and publications outside of academic journals. This limits incentives for academics to participate in real-world problem solving and collaborative efforts. Despite these limitations, many successful boundary organizations are located within universities.

In short, boundary organizations serve to make information from science useful and to keep information flowing (in both directions) between producers and users of the information. They foster mutual respect and trust between users and producers. Within such organizations there is a need for individuals simultaneously capable of translating scientific results for practical use and framing the research questions from the perspective of the user of the information. These key intermediaries in boundary organizations need to be capable of integrating disciplines and defining the research question beyond the focus of the participating individual disciplines. Table 4.1 depicts a number of boundary organization examples for climate change decision-support tool development. Section 4.3.2 considers the type of organizational leaders who facilitate boundary spanning.

Boundary organizations serve to make information from science useful and to keep information flowing (in both directions) between producers and users of the information.

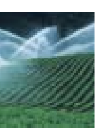
An oft-cited model of the type of boundary-spanning organization needed for the transfer and translation of decision-support information on climate variability is the Regional Integrated Science and Assessment (RISA) teams supported by NOAA. These teams "represent a new collaborative paradigm in which decision makers are actively involved in developing research agendas" (Jacobs, 2003). The eight RISA teams, located within universities and often involving partnerships with NOAA laboratories throughout the United States, are focused on stakeholder-driven research agendas and long-term relationships between scientists and decision makers in specific regions. RISA activities are highlighted in the sidebar below.

BOX 4.1: Comparative Examples of Boundary Spanning—Australia and the United States

In Australia, forecast information is actively sought both by large agribusiness and government policymakers planning for drought because "the logistics of handling and trading Australia's grain commodities, such as wheat, are confounded by huge swings in production associated with climate variability. Advance information on likely production and its geographical distribution is sought by many industries, particularly in the recently deregulated marketing environment" (Hammer, *et al.*, 2001). Forecast producers have adopted a systems approach to the dissemination of seasonal forecast information that includes close interaction with farmers, use of climate scenarios to discuss the incoming rainfall season and automated dissemination of seasonal forecast information through the RAINMAN interactive software.

In the U.S. Southwest, forecast producers organized stakeholder workshops that refined their understanding of potential users and their needs. Because continuous interaction with stakeholder was well funded and encouraged, producers were able to 'customize' their product—including the design of user friendly and interactive Internet access to climate information—to local stakeholders with significant success (Hartmann, *et al.*, 2002; Pagano, *et al.*, 2002; Lemos and Morehouse, 2005). Such success stories seem to depend largely on the context in which seasonal climate forecasts were deployed—in well-funded policy systems, with adequate resources to customize and use forecasts, benefits can accrue to the local society as a whole. From these limited cases, it is suggested that where income, status, and access to information are more equitably distributed in a society, the introduction of seasonal forecasts may create winners; in contrast, when pre-existing conditions are unequal, the application of seasonal climate forecasts may create more losers by exacerbating those inequities (Lemos and Dilling, 2007). The consequences can be costly both to users and seasonal forecast credibility.

A true dialogue between end users of scientific information and those who generate data and tools is rarely achieved.



This is followed by another sidebar on comparative examples of boundary spanning which emphasizes the "systemic" nature of boundary spanning—that boundary organizations produce reciprocity of benefits to various groups.

One final observation can be made at this juncture concerning boundary spanning and the dissemination of climate information and knowledge. Some suggest a three-pronged process of outreach consisting of "missionary work", "co-discovery", and "persistence". Missionary work is directed toward potential users of climate information who do not fully understand the potential of climate variation and change and the potential of climate information applications. Such non-users may reject science not because they believe it to be invalid, but because they do not envision the strategic threat to their water use, or water rights, through non-application of climate information. Co-discovery, by contrast, is the process of co-production of knowledge aimed at answering questions of concern to both managers and scientists, as we have discussed. Overcoming resistance to using information, in the first case, and ensuring co-production in the second instance— both depend on persistence: the notion that effective introduction of climate applications may require long-term efforts to establish useful relationships, particularly where there is disbelief in the science of climate change or where there is significant asymmetry of access to information and other resources (*i.e.*, Chambers, 1997; Weiner, 2004).

4.3.2 Regional Integrated Science and Assessment Teams (RISAs) —An Opportunity for Boundary Spanning, and a Challenge

A true dialogue between end users of scientific information and those who generate data and tools is rarely achieved. The eight Regional Integrated Science and Assessment (RISA) teams that are sponsored by NOAA and activities sponsored by the Environmental Protection Agency's Global Change Research Program are among the leaders of this experimental endeavor, and represent a new collaborative paradigm in which decision makers are actively involved in developing research agendas. RISAs explicitly seek to work at the boundary of science and decision making.

There are five principal approaches RISA teams have learned that facilitate engagement with stakeholders and design of climate-related decision-support tools for water managers. First, RISAs employ a "stakeholder-driven research" approach that focuses on performing research on both the supply side (*i.e.*, information development) and demand side (*i.e.*, the user and her/his needs). Such reconciliation efforts require robust communication in which each side informs the other with regard to decisions, needs, and products—this communication cannot be intermittent; it must be robust and ongoing.

Second, some RISAs employ an "information broker" approach. They produce little new scientific information themselves, due to resource limitations or lack of critical mass in a particular scientific discipline. Rather, the RISAs' primary role is providing a conduit for information and facilitating the development of information networks.

Third, RISAs generally utilize a "participant/advocacy" or "problem-based" approach, which involves focusing on a particular problem or issue and engaging directly in solving that problem. They see themselves as part of a learning system and promote the opportunity for joint learning with a well-defined set of stakeholders who share the RISA's perspective on the problem and desired outcomes.

Fourth, some RISAs utilize a "basic research" approach in which the researchers recognize particular gaps in the fundamental knowledge needed in the production of context sensitive, policy-relevant information. Any RISA may utilize many or most of these approaches at different times depending upon the particular context of the problem. The more well-established RISAs have more formal processes and procedures in place to identify stakeholder needs and design appropriate responses, as well as to evaluate the effectiveness of decision-support tools that are developed.

Finally, a critical lesson for climate science policy from RISAs is that, despite knowing what is needed to produce, package, and disseminate useful climate information—and the well-recognized success of the regional partnerships with stakeholders, RISAs continue to struggle for funding while RISA-generated lessons are widely acclaimed. To a large extent, they have not influenced federal climate science policy community outside of the RISAs themselves, though progress has been made in recent years. Improving feedback between RISA programs and the larger research enterprise need to be enhanced so lessons learned can inform broader climate science policy decisions—not just those decisions made on the local problem-solving level (McNie *et al.*, 2007).

In April 2002, the House Science Committee held a hearing to explore the connections of climate science and the needs of decision makers. One question it posed was the following: "Are our climate research efforts focused on the right questions"? (<http://www.house.gov/science/hearings/full02/apr17/full_charter_041702.htm>). The Science Committee found that the RISA program is a promising means to connect decision-making needs with the research prioritization process, because "(it) attempts to build a regional-scale picture of the interaction between climate change and the local environment from the ground up. By funding research on climate and environmental science focused on a particular region, [the RISA] program currently supports interdisciplinary research on climate-sensitive issues in five selected regions around the country. Each region has its own distinct set of vulnerabilities to climate change, *e.g.*, water supply, fisheries, agriculture, *etc.*, and RISA's research is focused on questions specific to each region".

Decision makers do not always find seasonal-to-interannual forecast products, and related climate information, to be useful for the management of water resources.

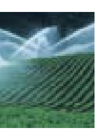
4.3.3 Developing Knowledge-Action Systems—a Climate for Inclusive Management

Research suggests that decision makers do not always find seasonal-to-interannual forecast products, and related climate information, to be useful for the management of water resources—this is a theme central to this entire Product (*e.g.*, Weiner, 2004). As our case study experiments suggest, in order to ensure that information is useful, decision makers must be able to affect the substance of climate information production and the method of delivery so that information producers know what are the key questions to respond to in the broad and varied array of decisional needs different constituencies require (Sarewitz and Pielke, 2007; Callahan *et al.*, 1999; NRC, 1999). This is likely the most effective process by which true decision-support activities can be made useful.

Efforts to identify factors that improve the usability of SI climate information have found that effective "knowledge-action" systems focus on promoting broad, user-driven risk management objectives (Cash and Buizer, 2005). These objectives, in turn, are shaped by the decision context, which usually contains multiple stresses and management goals. Research on water resource decision making suggests that goals are defined very differently by agencies or organizations dedicated to managing single-issue problems in particular sectors (*e.g.*, irrigation, public supply) when compared to decision makers working in political jurisdictions or watershed-based entities designed to comprehensively manage and coordinate several management objectives simultaneously (*e.g.*, flood control and irrigation, power generation, and in-stream flow). The latter entities face the unusual challenge of trying to harmonize competing objectives, are commonly accountable to numerous users, and require "regionally and locally tailored solutions" to problems (Water in the West, 1998; Kenney and Lord, 1994; Grigg, 1996).

Knowledge systems need to engage a range of participants including those who generate scientific tools and data, those who translate them into predictions for use by decision makers, and the decision makers themselves.

Effective knowledge-action systems should be designed for learning rather than knowing; the difference being that the former emphasizes the process of exchange between decision makers and scientists, constantly evolving in an iterative fashion, rather than aiming for a one-time-only completed product and structural permanence. Learning requires that knowledge-action systems have sufficient flexibility of processes and institutions to effectively produce and apply climate information (Cash and Buizer, 2005), encourage diffusion of boundary-spanning innovation, be self-innovative and responsive, and develop "operating criteria that measure responsiveness to changing conditions and external advisory processes" (Cash and Buizer, 2005). Often, nontraditional institutions that operate outside of "normal" channels, such as nongovernmental organizations (NGOs) or regional coordinating entities, are less constrained by tradition or legal mandate and thus more able to innovate.



To encourage climate forecast and information producers and end-users to better communicate with one another, they need to be engaged in a long-term dialogue about each others' needs and capabilities. To achieve this, knowledge producers must be committed to establishing opportunities for joint learning. When such communication systems have been established, the result has been the gaining of knowledge by users. The discovery that climate information must be part of a larger suite of information can help producers understand the decision context, and better appreciate that users manage a broad array of risks. Lead innovators within the user community can lay the groundwork for broader participation of other users and greater connection between producers and users (Cash and Buizer, 2005).

Such tailoring or conversion of information requires organizational settings that foster communication and exchange of ideas between users and scientists. For example, a particular user might require a specific type of precipitation forecast or even a different type of hydrologic model to generate a credible forecast of water supply volume. This producer-user dialogue must be long term, it must allow users to independently verify the utility of forecast information, and finally, must provide opportunities for verification results to "feed back" into new product development (Cash and Buizer, 2005; Jacobs *et al.*, 2005).

Studies of this connection refer to it as an "end-to-end" system to suggest that knowledge systems need to engage a range of participants including those who generate scientific tools and data, those who translate them into predictions for use by decision makers, and the decision makers themselves. A forecast innovation might combine climate factor observations, analyses of climate dynamics, and SI forecasts. In turn, users might be concerned with varying problems and issues such as planting times, instream flows to support endangered species, and reservoir operations.

As Cash and Buizer note, "Often entire systems have failed because of a missing link between the climate forecast and these ultimate user actions. Avoiding the missing link problem varies according to the particular needs of specific users (Cash and Buizer, 2005). Users want useable information more than they want answers—they want an understanding of things that will help them explain, for example, the role of climate in determining underlying variation in the resources they manage. This includes a broad range of information needed for risk management, not just forecasting particular threats.

Organizational measures to hasten, encourage, and sustain these knowledge-action systems must include practices that empower people to use information through providing adequate training and outreach, as well as sufficient professional reward and development opportunities. Three measures are essential. First, organizations must provide incentives to produce boundary objects, such as decisions or products that reflect the input of different perspectives. Second, they must involve participation from actors across boundaries. And finally, they must have lines of accountability to the various organizations spanned (Guston, 2001).

Introspective evaluations of the organizations' ability to learn and adapt to the institutional and knowledge-based changes around them should be combined with mechanisms for feedback and advice from clients, users, and community leaders. However, it is important that a review process not become an end in itself or be so burdensome as to affect the ability of the organization to function efficiently. This orientation is characterized by a mutual recognition on the part of scientists and decision makers of the importance of social learning—that is, learning by doing or by experiment, and refinement of forecast products in light of real-world experiences and previous mistakes or errors—both in forecasts and in their application. This learning environment also fosters an emphasis on adaptation and diffusion of innovation (*i.e.*, social learning, learning from past mistakes, long-term funding).

4.3.4 The Value of User-Driven Decision Support

Studies of what makes climate forecasts useful have identified a number of common characteristics in the process by which forecasts are generated, developed, and taught to—and disseminated among—users (Cash and Buizer, 2005). These characteristics (some previously described) include:

- Ensuring that the problems forecasters address are driven by forecast users;
- Making certain that knowledge-action systems (the process of interaction between scientists and users that produces forecasts) are end-to-end inclusive;
- Employing "boundary organizations" (groups or other entities that bridge the communication void between experts and users) to perform translation and mediation functions between the producers and consumers of forecasts;
- Fostering a social learning environment between producers and users (*i.e.*, emphasizing adaptation); and
- Providing stable funding and other support to keep networks of users and scientists working together.

As noted earlier, "users" encompass a broad array of individuals and organizations, including farmers, water managers, and government agencies; while "producers" include scientists and engineers and those "with relevant expertise derived from practice" (Cash and Buizer, 2005). Complicating matters is that some "users" may, over time, become "producers" as they translate, repackage, or analyze climate information for use by others.

There is an emerging consensus that the utility of information intended to make possible sustainable environmental decisions depends on the "dynamics of the decision context and its broader social setting".

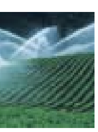
In effective user-driven information environments, the agendas of analysts, forecasters, and scientists who generate forecast information are at least partly set by the users of the information. Moreover, the collaborative process is grounded in appreciation for user perspectives regarding the decision context in which they work, the multiple stresses under which they labor, and their goals so users can integrate climate knowledge into risk management. Most important, this user-driven outlook is reinforced by a systematic effort to link the generation of forecast information with needs of users through soliciting advice and input from the latter at every step in the generation of information process.

Effective knowledge-action systems do not allow particular research or technology capabilities (*e.g.*, ENSO forecasting) to drive the dialogue. Instead, effective systems ground the collaborative process of problem definition in user perspectives regarding the decision context, the multiple stresses bearing on user decisions, and ultimate goals that the knowledge-action system seeks to advance. For climate change information, this means shifting the focus toward "the promotion of broad, user-driven risk-management objectives, rather than advancing the uptake of particular forecasting technologies" (Cash and Buizer, 2005; Sarewitz and Pielke, 2007).

In sum, there is an emerging consensus that the utility of information intended to make possible sustainable environmental decisions depends on the "dynamics of the decision context and its broader social setting" (Jasanoff and Wynne, 1998; Pielke *et al.*, 2000; Sarewitz and Pielke, 2007). Usefulness is not inherent in the knowledge generated by forecasters—the information generated must be "socially robust". Robustness is determined by how well it meets three criteria: (1) is it valid outside, as well as inside the laboratory; (2) is validity achieved through involving an extended group of experts, including lay "experts;" and 3) is the information (*e.g.*, forecast models) derived from a process in which society has participated as this ensures that the information is less likely to be contested (Gibbons, 1999).

User-driven information in regard to seasonal-to-interannual climate variability for water resources decision making must be salient, credible, and legitimate.

Finally, a user-driven information system relies heavily on two-way communication. Such communication can help bridge gaps between what is produced and what is likely to be used, thus ensuring that scientists produce products that are recognized by the users, and not just the producers, as useful. Effective user-oriented two-way communication can increase users' understanding of how they could use climate information and enable them to ask questions about information that is uncertain or in dispute. It also affords an opportunity to produce "decision-relevant" information that might otherwise not be produced because scientists may not have understood completely what kinds of information would be most useful to water resource decision makers (NRC, 2008).



In conclusion, user-driven information in regard to seasonal-to-interannual climate variability for water resources decision making must be salient (*e.g.*, decision-relevant and timely), credible (viewed as accurate, valid, and of high quality), and legitimate (uninfluenced by pressures or other sources of bias) (see NRC, 2008; NRC, 2005). In the words of a recent National Research Council report, broad involvement of "interested and affected parties" in framing scientific questions helps ensure that the science produced is useful ("getting the right science") by ensuring that decision-support tools are explicit about any simplifying assumptions that may be in dispute among the users, and accessible to the end-user (NRC, 2008).

4.3.5 Proactive Leadership—Championing Change

Organizations—public, private, scientific, and political—have leaders: individuals charged with authority, and span of control, over important personnel, budgetary, and strategic planning decisions, among other venues. Boundary organizations require a kind of leadership called inclusive management practice by its principal theorists (Feldman and Khademian, 2004). Inclusive management is defined as management that seeks to incorporate the knowledge, skills, resources, and perspectives of several actors and seeks to avoid creating "winners and losers" among stakeholders.

While there is an enormous literature on organizational leadership, synthetic studies—those that take various theories and models about leaders and try to draw practical, even anecdotal, lessons for organizations—appear to coalesce around the idea that inclusive leaders have context-specific skills that emerge through a combination of tested experience within a variety of organizations, and a knack for judgment (Bennis, 2003; Feldman and Khademan, 2004; Tichy and Bennis, 2007). These skills evolve through trial and error and social learning. Effective "change-agent" leaders have a guiding vision that sustains them through difficult times, a passion for their work and an inherent belief in its importance, and a basic integrity toward the way in which they interact with people and approach their jobs (Bennis, 2003).

While it is difficult to discuss leadership without focusing on individual leaders (and difficult to disagree with claims about virtuous leadership), inclusive management also embraces the notion of "process accountability": that leadership is embodied in the methods by which organizations make decisions, and not in charismatic personality alone. Process accountability comes not from some external elected political principle or body that is hierarchically superior, but instead infuses through processes of deliberation and transparency. All of these elements make boundary organizations capable of being solution focused and integrative and, thus, able to span the domains of climate knowledge production and climate knowledge for water management use.

Adaptive and inclusive management practices are essential to fulfilling these objectives. These practices must empower people to use information through providing adequate training and outreach, as well as sufficient professional reward and development opportunities; and they must overcome capacity-building problems within organizations to ensure that these objectives are met, including adequate user support. The cases discussed below—on the California Department of Water Resources' role in adopting climate variability and change into regional water management, and the efforts of the Southeast consortium and its satellite efforts—are examples of inclusive leadership which illustrate how scientists as well agency managers can be proactive leaders. In the former case, decision makers consciously decided to develop relationships with other western states' water agencies and partnership (through a Memorandum of Understanding [MOU]) with NOAA. In the latter, scientists ventured into collaborative efforts—across universities, agencies, and states—because they shared a commitment to exchanging information in order to build institutional capacity among the users of the information themselves.

Case Study A: Leadership in the California Department of Water Resources

The deep drought in the Colorado River Basin that began with the onset of a La Niña episode in 1998 has awakened regional water resources managers to the need to incorporate climate variability and change into their plans and reservoir forecast models. Paleohydrologic estimates of streamflow, which document extended periods of low flow and demonstrate greater streamflow variability than the information found in the gage record, have been particularly persuasive examples of the non-stationary behavior of the hydroclimate system (Woodhouse *et al.*, 2006; Meko *et al.*, 2007). Following a 2005 scientist-stakeholder workshop on the use of paleohydrologic data in water resource management <http://www.climas.arizona.edu/calendar/details.asp?event_id=21>, NOAA RISA and California Department of Water Resources (CDWR) scientists developed strong relationships oriented toward improving the usefulness and usability of science in water management. Since the 2005 workshop, CDWR, whose mission in recent years includes preparation for potential impacts of climate change on California's water resources, has led western states' efforts in partnering with climate scientists to co-produce hydroclimatic science to inform decision making. CDWR led the charge to clarify scientific understanding of Colorado River Basin climatology and hydrology, past variations, projections for the future, and impacts on water resources, by calling upon the National Academy of Sciences to convene a panel to study the aforementioned issues (NRC, 2007). This occurred, and in 2007, CDWR developed a Memorandum of Agreement with NOAA, in order to better facilitate cooperation with scientists in NOAA's RISA program and research laboratories (CDWR, 2007a).

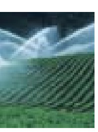
Case Study B: Cooperative Extension Services, Watershed Stewardship: The Southeast Consortium

Developing the capacity to use climate information in resource management decision making requires both outreach and education, frequently in an iterative fashion that leads to two-way communication and builds partnerships. The Cooperative Extension Program has long been a leader in facilitating the integration of scientific information into decision maker of practice in the agricultural sector. Cash (2001) documents an example of successful

Cooperative Extension leadership in providing useful water resources information to decision makers confronting policy changes in response to depletion of groundwater in the High Plains aquifer. Cash notes the Cooperative Extension's history of facilitating dialogue between scientists and farmers, encouraging the development of university and agency research agendas that reflect farmers' needs, translating scientific findings into site-specific guidance, and managing demonstration projects that integrate farmers into researchers' field experiments.

Climate information is only valuable when both the potential response and benefits of using the information are clearly defined.

In the High Plains aquifer example, the Cooperative Extension's boundary-spanning work was motivated from a bottom-up need of stakeholders for credible information on whether water management policy changes would affect their operations. By acting as a liaison between the agriculture and water management decision making communities, and building bridges between many levels of decision makers, Kansas Cooperative Extension was able to effectively coordinate information flows between university and USGS modelers, and decision makers. The result of their effort was collaborative development of a model with characteristics needed by agriculturalists (at a sufficient spatial resolution) and that provided credible scientific information to all parties. Kansas Cooperative Extension effectiveness in addressing groundwater depletion and its impact on farmers sharply contrasted with the Cooperative Extension efforts in other states where no effort was made to establish multi-level linkages between water management and agricultural stakeholders.



The Southeast Climate Consortium RISA (SECC), a confederation of researchers at six universities in Alabama, Georgia, and Florida, has used more of a top-down approach to developing stakeholder capacity to use climate information in the Southeast's $33 billion agricultural sector (Jagtap *et al.*, 2002). Early in its existence, SECC researchers recognized the potential to use knowledge of the impact of the El Niño-Southern Oscillation on local climate to provide guidance to farmers, ranchers, and forestry sector stakeholders on yields and changes to risk (*e.g.*, frost occurrence). Through a series of needs and vulnerability assessments (Hildebrand *et al.*, 1999, Jagtap *et al.*, 2002), SECC researchers determined that the potential for producers to benefit from seasonal forecasts depends on factors that include the flexibility and willingness to adapt farming operations to the forecast, and the effectiveness of the communication process—and not merely documenting the effects of climate variability and providing better forecasts (Jones *et al.*, 2000). Moreover, Fraisse *et al.* (2006) explain that climate information is only valuable when both the potential response and benefits of using the information are clearly defined. SECC's success in championing integration of new information is built upon a foundation of sustained interactions with agricultural producers in collaboration with extension agents. Extension specialists and faculty are integrated as members of the SECC research team. SECC engages agricultural stakeholders through planned communication and outreach, such as monthly video conferences, one-on-one meetings with extension agents and producers, training workshops designed for extension agents and resource managers to gain confidence in climate decision tool use and to identify opportunities for their application, and by attending traditional extension activities (*e.g.*, commodity meetings, field days) (Fraisse *et al.*, 2005). SECC is able to leverage the trust engendered by Cooperative Extension's long service to the agricultural community and Extension's access to local knowledge and experience, in order to build support for its AgClimate online decision-support tool <http://www.agclimate.org> (Fraisse *et al.*, 2006). This direct engagement with stakeholders provides feedback to improve the design of the tool and to enhance climate forecast communication (Breuer *et al.*, 2007).

Yet another Cooperative Extension approach to integrating scientific information into decision making is the Extension's Master Watershed Steward (MWS) programs. MWS was first developed at Oregon State University <http://seagrant.oregonstate.edu/wsep/index.html>. In exchange for 40 hours of training on aspects of watersheds that range from ecology to water management, interested citizen volunteers provide service to their local community through projects, such as drought and water quality monitoring, developing property management plans, and conducting riparian habitat restoration. Arizona's MWS program includes training in climate and weather (Garfin and Emanuel, 2006); stewards are encouraged to participate in drought impact monitoring through Arizona's Local Drought Impact Groups (GDTF, 2004; Garfin, 2006). MWS enhances the capacity for communities to deploy new climate information and to build expertise for assimilating scientific information into a range of watershed management decisions.

4.3.6 Funding and Long-Term Capacity Investments Must Be Stable and Predictable

Provision of a stable funding base, as well as other investments, can help to ensure effective knowledge-action systems for climate change. Stable funding promotes long-term stability and trust among stakeholders because it allows researchers to focus on user needs over a period of time, rather than having to train new participants in the process. Given that these knowledge-action systems produce benefits for entire societies, as well as for particular stakeholders in a society, it is not uncommon for these systems to be thought of as producing both public and private goods, and thus, needing both public and private sources of support (Cash and Buizer, 2005). Private funders could include, for example, farmers whose risks are reduced by the provision of climate information (as is done in Queensland, Australia, where the individual benefits of more profitable production are captured by farmers who partly support drought-warning systems). In less developed societies, by contrast, it would not be surprising for these systems to be virtually entirely supported by public sources of revenue (Cash and Buizer, 2005).

Experience suggests that a public-private funding balance should be shaped on the basis of user needs and capacities to self-tailor knowledge-action systems. More generic systems that could afterwards be tailored to users' needs might be most suitable for public support, while co-funding with particular users can then be pursued for developing a collaborative system that more effectively meets users' needs. Funding continuity is essential to foster long-term relationship building between users and producers. The key point here is that—regardless of who pays for these systems, continued funding of the social and economic investigations of the use of scientific information is essential to ensure that these systems are used and are useful (Jacobs *et al.*, 2005).

Other long-term capacity investments relate to user training—an important component that requires drawing upon the expertise of "integrators". Integrators are commonly self-selected managers and decision makers with particular aptitude or training in science, or scientists who are particularly good at communication and applications. Training may entail curriculum development, career and training development for users as well as science integrators, and continued mid-career in-stream retraining and re-education. Many current integrators have evolved as a result of doing interdisciplinary and applied research in collaborative projects, and some have been encouraged by funding provided by NOAA's Climate Programs Office (formerly Office of Global Programs) (Jacobs, *et al.*, 2005).

4.3.7 Adaptive Management for Water Resources Planning—Implications for Decision Support

Since the 1970s, an "adaptive management paradigm" has emerged that is characterized by: greater public and stakeholder participation in decision making; an explicit commitment to environmentally sound, socially just outcomes; greater reliance upon drainage basins as planning units; program management via spatial and managerial flexibility, collaboration, participation, and sound, peer-reviewed science; and finally, embracing of ecological, economic, and equity considerations (Hartig *et al.*, 1992; Landre and Knuth, 1993; Cortner and Moote, 1994; Water in the West, 1998; May *et al.*, 1996; McGinnis, 1995; Miller *et al.*, 1996; Cody, 1999; Bormann *et al.*, 1993; Lee, 1993). Adaptive management traces its roots to a convergence of intellectual trends and disciplines, including industrial relations theory, ecosystems management, ecological science, economics, and engineering. It also embraces a constellation of concepts such as social learning, operations research, environmental monitoring, precautionary risk avoidance, and many others (NRC, 2004).

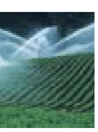
Adaptive management can be viewed as an alternative decision-making paradigm that seeks

Regardless of who pays for these systems, continued funding of the social and economic investigations of the use of scientific information is essential to ensure that these systems are used and are useful.

insights into the behavior of ecosystems utilized by humans. In regard to climate variability and water resources, adaptive management compels consideration of questions such as the following: What are the decision-support needs related to managing in-stream flows/low flows? How does climate variability affect runoff? What is the impact of increased temperatures on water quality or on cold-water fisheries' (*e.g.*, lower dissolved oxygen levels)? What other environmental quality parameters does a changing climate impact related to endangered or threatened species? And, what changes to runoff and flow will occur in the future, and how will these changes affect water uses among future generations unable to influence the causes of these changes today? What makes these questions particularly challenging is that they are interdisciplinary in nature[4].

An adaptive management approach is one that is flexible and subject to adjustment in an iterative, social learning process.

While a potentially important concept, applying adaptive management to improving decision support requires that we deftly avoid a number of false and sometimes uncritically accepted suppositions. For example, adaptive management does not postpone actions until "enough" is known about a managed ecosystem, but supports actions that acknowledge the limits of scientific knowledge, "the complexities and stochastic behavior of large ecosystems", and the uncertainties in natural systems, economic demands, political institutions, and ever-changing societal social values (NRC, 2004; Lee, 1999). In short, an adaptive management approach is one that is flexible and subject to adjustment in an iterative, social learning process (Lee, 1999). If treated in such a manner, adaptive management can encourage timely responses by: encouraging protagonists involved in water management to bound disputes; investigating environmental uncertainties; continuing to constantly learn and improve the management and operation of environmental control systems; learning from error; and "reduc(ing) decision-making gridlock by making it clear…that there is often no 'right' or 'wrong' management decision, and that modifications are expected" (NRC, 2004).



The four cases discussed below illustrate varying applications, and context specific problems, of adaptive management. The discussion of Integrated Water Resource Planning stresses the use of adaptive management in a variety of local political contexts where the emphasis is on reducing water use and dependence on engineered solutions to provide water supply. The key variables are the economic goals of cost savings coupled with the ability to flexibly meet water demands. The Arizona Water Institute case illustrates the use of a dynamic organizational training setting to provide "social learning" and decisional responsiveness to changing environmental and societal conditions. A key trait is the use of a boundary-spanning entity to bridge various disciplines.

The Glen Canyon and Murray–Darling Basin cases illustrate operations-level decision making aimed at addressing a number of water management problems that, over time, have become exacerbated by climate variability, namely: drought, streamflow, salinity, and regional water demand. On one hand, adaptive management has been applied to "re-engineer" a large reservoir system. On the other, a management authority that links various stakeholders together has attempted to instill a new set of principles into regional river basin management. It should be borne in mind that transferability of lessons from these cases depends not on some assumed "randomness" in their character (they are not random; they were chosen because they are amply studied), but on the similarity between their context and that of other cases. This is a problem also taken up in Section 4.5.2.

4.3.8 Integrated Water Resources Planning—Local Water Supply and Adaptive Management

A significant innovation in water resources management in the United States that affects climate information use is occurring in the

[4] Underscored by the fact that scholars concur, adaptive management entails a broad range of processes to avoid environmental harm by imposing modest changes on the environment, acknowledging uncertainties in predicting impacts of human activities on natural processes, and embracing social learning (*i.e.*, learning by experiment). In general, it is characterized by managing resources by learning, especially about mistakes, in an effort to make policy improvements using four major strategies that include: (1) modifying policies in the light of experience, (2) permitting such modifications to be introduced in "mid-course, (3) allowing revelation of critical knowledge heretofore missing and analysis of management outcomes, and (4) incorporating outcomes in future decisions through a consensus-based approach that allows government agencies and NGOs to conjointly agree on solutions (Bormann, *et al.*, 1993; Lee, 1993; Definitions of Adaptive Management, 2000).

local water supply sector: the growing use of integrated water resource planning (or IWRP) as an alternative to conventional supply-side approaches for meeting future demands. IWRP is gaining acceptance in chronically water-short regions such as the Southwest and portions of the Midwest, including Southern California, Kansas, Southern Nevada, and New Mexico (*e.g.*, Beecher, 1995; Warren *et al.*, 1995; Fiske and Dong, 1995; Wade, 2001).

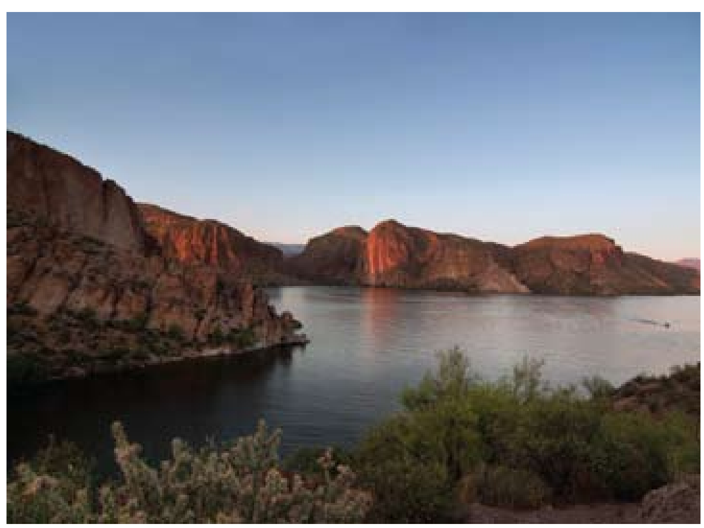
IWRP's goal is to "balanc(e) water supply and demand management considerations by identifying feasible planning alternatives that meet the test of least cost without sacrificing other policy goals" (Beecher, 1995). This can be variously achieved through depleted aquifer recharge, seasonal groundwater recharge, conservation incentives, adopting growth management strategies, wastewater reuse, and/or applying least cost planning principles to large investor-owned water utilities. The latter may encourage IWRP by demonstrating the relative efficiency of efforts to reduce demand as opposed to building more supply infrastructure. A particularly challenging alternative is the need to enhance regional planning among water utilities in order to capitalize on the resources of every water user, eliminate unnecessary duplication of effort, and avoid the cost of building new facilities for water supply (Atwater and Blomquist, 2002).

In some cases, short-term applications of least cost planning may increase long-term project costs, especially when environmental impacts, resource depletion, and energy and maintenance costs are included. The significance of least cost planning is that it underscores the importance of long- and short-term costs (in this case, of water) as an influence on the value of certain kinds of information for decisions. Models and forecasts that predict water availability under different climate scenarios can be especially useful to least cost planning and make more credible efforts to reducing demand. Specific questions IWRP raises for decision support given a changing climate include: How precise must climate information be to enhance long-term planning? How might predicted climate change provide an incentive for IWRP strategies? and, What climate information is needed to optimize decisions on water pricing, re-use, shifting from surface to groundwater use, and conservation?

Case Study C: Approaches to Building User Knowledge and Enhancing Capacity Building—the Arizona Water Institute

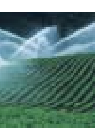
The Arizona Water Institute was initiated in 2006 to focus the resources of the State of Arizona's university system on the issue of water sustainability. Because there are 400 faculty and staff members in the three Arizona universities who work on water-related topics, it is clear that asking them and their students to assist the state in addressing the major water quantity and quality issues should make a significant contribution to water sustainability. This is particularly relevant given that the state budget for supporting water resources related work is exceedingly small by comparison to many other states, and the fact that Arizona is one of the fastest-growing states in the United States. In addition to working towards water sustainability, the Institute's mission includes water-related technology transfer from the universities to the private sector to create and develop economic opportunities, as well as build capacity, to enhance the use of scientific information in decision making.

The Institute was designed from the beginning as a "boundary organization" to build pathways for innovation between the universities and state agencies, communities, Native American tribal representatives, and the private sector. In addi-



In some cases, short-term applications of least cost planning may increase long-term project costs, especially when environmental impacts, resource depletion, and energy and maintenance costs are included.

tion, the Institute is specifically designed as an experiment in how to remove barriers between groups of researchers in different disciplines and across the universities. The Institute's projects involve faculty members from more than one of the universities, and all involve true engagement with stakeholders. The faculty is provided incentives to engage both through small grants for collaborative projects and through the visibility of the work that the Institute supports. Further, the Institute's structure is unique, in that there are high level Associate Directors of the Institute whose assignment is to build bridges between the universities and the three state agencies that are the Institute's partners: Water Resources, Environmental Quality, and Commerce. These Associate Directors are physically located inside the state agencies that they serve. The intent is to build trust between university researchers (who may be viewed as "out of touch with reality" by agency employees), and agency or state employees (whom researchers may believe are not interested in innovative ideas). Physical proximity of workspaces and daily engagement has been shown to be an ingredient of trust building.



A significant component of the Institute's effort is focused on: capacity building, training students through engagement in real-world water policy issues, providing better access to hydrologic data for decision makers, assisting them in visualizing the implications of the decisions that they make, workshops and training programs for tribal entities, joint definition of research agendas between stakeholders and researchers, and building employment pathways to train students for specific job categories where there is an insufficient supply of trained workers, such as water and wastewater treatment plant operators. Capacity-building in interdisciplinary planning applications such as combining land use planning and water supply planning to focus on sustainable water supplies for future development is emerging as a key need for many communities in the state.

The Institute is designed as a "learning organization" in that it will regularly revisit its structure and function, and redesign itself as needed to maintain effectiveness in the context of changing institutional and financial conditions.

Case Study D: Murray–Darling Basin—Sustainable Development and Adaptive Management

The Murray-Darling Basin Agreement (MDBA), formed in 1985 by New South Wales, Victoria, South Australia and the Commonwealth, is an effort to provide for the integrated and conjoint management of the water and related land resources of the world's largest catchment system. The problems initially giving rise to the agreement included rising salinity and irrigation-induced land salinization that extended across state boundaries (SSCSE, 1979; Wells, 1994). However, embedded in its charter was a concern with using climate variability information to more effectively manage drought, runoff, riverine flow and other factors in order to meet the goal of "effective planning and management for the equitable, efficient and sustainable use of the water, land and environmental resources (of the basin)" (MDBC, 2002).

Some of the more notable achievements of the MDBA include programs to promote the management of point and non-point source pollution; balancing consumptive and in-stream uses (a decision to place a cap on water diversions was adopted by the commission in 1995); the ability to increase water allocations—and rates of water flow—in order to mitigate pollution and protect threatened species (applicable in all states except Queensland); and an explicit program for "sustainable management". The latter hinges on implementation of several strategies, including a novel human dimension strategy adopted in 1999 that assesses the social, institutional and cultural factors impeding sustainability; as well as adoption of specific policies to deal with salinity, better manage wetlands, reduce the frequency and intensity of algal blooms by better managing the inflow of nutrients, reverse declines in native fisheries populations (a plan which, like that of many river basins in the United States, institutes changes in dam operations to permit fish passage), and preparing floodplain management plans.

Moreover, a large-scale environmental monitoring program is underway to collect and analyze basic data on pressures upon the basin's resources as well as a "framework for evaluating and reporting on government and community investment" efforts and their effectiveness. This self-evaluation program is a unique adaptive management innovation rarely found in other basin initiatives. To support these activities, the Commission funds its own research program and engages in biophysical and social science investigations. It also establishes priorities for investigations based, in part, on the severity of problems, and the knowledge acquired is integrated directly into commission policies through a formal review process designed to assure that best management practices are adopted.

From the standpoint of adaptive management, the Murray–Darling Basin Agreement seeks to integrate quality and quantity concerns in a single management framework; has a broad mandate to embrace social, economic, environmental and cultural issues in decisions; and has considerable authority to supplant, and supplement, the authority of established jurisdictions in implementing environmental and water development policies. While water quality policies adopted by the Basin Authority are recommended to states and the federal government for approval, generally, the latter defer to the commission and its executive arm. The MDBA also promotes an integrated approach to water resources management. Not only does the Commission have responsibility for functions as widely varied as floodplain management, drought protection, and water allocation, but for coordinating them as well. For example, efforts to reduce salinity are linked to strategies to prevent waterlogging of floodplains and land salinization on the Murray and Murrumbidgee Valleys (MDBC, 2002). Also, the Basin commission's environmental policy aims to utilize water allocations not only to control pollution and benefit water users, but to integrate its water allocation policy with other strategies for capping diversions, governing in-stream flow, and balancing in-stream needs and consumptive (*i.e.*, agricultural irrigation) uses. Among the most notable of MDBC's innovations is its community advisory effort.

In 1990, the ministerial council for the MDBC adopted a Natural Resources Management Strategy that provides specific guidance for a community-government partnership to develop plans for integrated management of the Basin's water, land and other environmental resources on a catchment basis. In 1996, the ministerial council put in place a Basin Sustainability Plan that provides a planning, evaluation and reporting framework for the Strategy, and covers all government and community investment for sustainable resources management in the basin.

According to Newson (1997), while the policy of integrated management has "received wide endorsement", progress towards effective implementation has fallen short—especially in the area of floodplain management. This has been attributed to a "reactive and supportive" attitude as opposed to a proactive one. Despite such criticism, it is hard to find another initiative of this scale and sophistication that has attempted adaptive management based on community involvement.

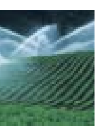
Case Study E: Adaptive Management in Glen Canyon, Arizona and Utah

Glen Canyon Dam was constructed in 1963 to provide hydropower, water for irrigation, flood control, and public water supply—and to ensure adequate storage for the upper basin states of the Colorado River Compact (*i.e.*, Utah, Wyoming, New Mexico, and Colorado). Lake Powell, the reservoir created by Glen Canyon Dam, has a storage capacity equal to approximately two years flow of the Colorado River. Critics of Glen Canyon Dam have insisted that its impacts on the upper basin have been injurious almost from the moment it was completed. The flooding of one of the West's most beautiful canyons under the waters of Lake Powell increased rates of evapotranspiration and other forms of water loss (*e.g.*, seepage of water into canyon walls) and eradicated historical flow regimes. The latter has been the focus of recent debate. Prior to Glen Canyon's closure, the Colorado River, at this location, was highly variable with flows ranging from 120,000 cubic feet per second (cfs) to less than 1,000 cfs.

When the dam's gates were closed in 1963, the Colorado River above and below Glen Canyon was altered by changes in seasonal variability. Once characterized by muddy, raging floods, the river became transformed into a clear, cold stream. Annual flows were stabilized and

replaced by daily fluctuations by as much as 15 feet. A band of exotic vegetation colonized a river corridor no longer scoured by spring floods; five of eight native fish species disappeared; and the broad sand beaches of the pre-dam river eroded away. Utilities and cities within the region came to rely on the dam's low cost power and water, and in-stream values were ignored (Carothers and Brown, 1991).

Attempts to abate or even reverse these impacts came about in two ways. First, in 1992, under pressure from environmental organizations, Congress passed the Grand Canyon Protection Act that mandated Glen Canyon Dam's operations coincide with protection, migration, and improvement of the natural and cultural resources of the Colorado River. Second, in 1996, the Bureau of Reclamation undertook an experimental flood to restore disturbance and dynamics to the river ecosystem. Planners hoped that additional sand would be deposited on canyon beaches and that backwaters (important rearing areas for native fish) would be revitalized. They also hoped the new sand deposits would stabilize eroding cultural sites while high flows would flush some exotic fish species out of the system (Moody, 1997; Restoring the Waters, 1997). The 1996 flood created over 50 new sandbars, enhanced existing ones, stabilized cultural sites, and helped to restore some downstream sport fisheries. What made these changes possible was a consensus developed through a six-year process led by the Bureau that brought together diverse stakeholders on a regular basis. This process developed a new operational plan for Lake Powell, produced an environmental impact statement for the project, and compelled the Bureau (working with the National Park Service) to implement an adaptive management approach that encouraged wide discussion over all management decisions.



While some environmental restoration has occurred, improvement to backwaters has been less successful. Despite efforts to restore native fisheries, the long-term impact of exotic fish populations on the native biological community, as well as potential for long-term recovery of native species, remains uncertain (Restoring the Waters, 1997). The relevance for climate variability decision support in the Glen Canyon case is that continued drought in the Southwest is placing increasing stress on the land and water resources of the region, including agriculture lands. Efforts to restore the river to conditions more nearly approximating the era before the dam was built will require changes in the dam's operating regime that will force a greater balance between instream flow considerations and power generation and offstream water supply. This will also require imaginative uses of forecast information to ensure that these various needs can be optimized.

4.3.9 Measurable Indicators of Progress to Promote Information Access and Use

These cases, and our previous discussion about capacity building, point to four basic measures that can be used to evaluate progress in providing equitable access to decision-support-generated information. First, the overall process of tool development should be inclusive. This could be measured and documented over time by the interest of groups to continue to participate and to be consulted and involved. Participants should view the process of collaboration as fair and effective—this could be gauged by elicitation of feedback from process participants.

Second, there should be progress in developing an interdisciplinary and interagency environment of collaboration, documented by the presence of dialogue, discussion, and exchange of ideas and data among different professions—in other words, documented boundary-spanning progress and building of trusted relationships. One documentable measure of interdisciplinary, boundary-spanning collaboration is the growth, over time, of professional reward systems within organizations that reward and recognize people who develop, use, and translate such systems for use by others.

Third, the collaborative process must be viewed by participants as credible. This means that participants feel it is believable and trustworthy and that there are benefits to all who engage in it. Again, this can be documented by elicitation of feedback from participants. Finally, outcomes of decision-support tools must be implementable in the short term, as well as longer-term. It is necessary to see progress in assimilating and using such systems in a short period of time in order to sustain the interest, effort, and participatory conviction of decision makers in the process. Table 4.2 suggests some specific,

Outcomes of decision-support tools must be implementable in the short term, as well as longer-term.

Table 4.2 Promoting Access to Information and its Use Between Scientists and Decision Makers–A Checklist (adopted from: Jacobs, 2003).

Information Integration
• Was information received by stakeholders and integrated into decision makers' management framework or world view?
• Was capacity built? Did the process lead to a result where institutions, organizations, agencies, officials can use information generated by decision-support experts? Did experts who developed these systems rely upon the knowledge and experience of decision makers—and respond to their needs in a manner that was useful?
• Will stakeholders continue to be invested in the program and participate in it over the long term?
Stakeholder Interaction/Collaboration
• Were contacts/relationships sustained over time and did they extend beyond individuals to institutions?
• Did stakeholders invest staff time or money in the activity?
• Was staff performance evaluated on the basis of quality or quantity of interaction?
• Did the project take on a life of its own, become at least partially self-supporting after the end of the project?
• Did the project result in building capacity and resilience to future events/conditions rather than focus on • mitigation?
• Was quality of life or economic conditions improved due to use of information generated or accessed through the project?
• Did the stakeholders claim or accept partial ownership of final product?
Tool Salience/Utility
• Are the tools actually used to make decisions; are they used by high-valued uses and users?
• Is the information generated/provided by these tools accurate/valid?
• Are important decisions made on the basis of the tool?
• Does the use of these tools reduce vulnerabilities, risks, and hazards?
Collaborative Process Efficacy
• Was the process representative (all interests have a voice at the table)?
• Was the process credible (based on facts as the participants knew them)?
• Were the outcomes implementable in a reasonable time frame (political and economic support)?
• Were the outcomes disciplined from a cost perspective (*i.e.*, there is some relationship between total costs and total benefits)?
• Were the costs and benefits equitably distributed, meaning there was a relationship between those who paid and those who benefited?

discrete measures that can be used to assess progress toward effective information use.

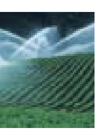
4.3.10 Monitoring Progress

An important element in the evaluation of process outcomes is the ability to monitor progress. A recent National Academy report (NRC, 2008) on NOAA's Sectoral Applications Research Program (SARP), focusing on climate-related information to inform decisions, encourages the identification of process measures that can be recorded on a regular basis, and of outcome measures tied to impacts of interest to NOAA and others that can also be recorded on a comparable basis.

The ability to consult with agencies, water resource decision makers, and a host of other potential forecast user communities can be an invaluable means of providing "mid-course" or interim indicators of progress in integrating forecast use in decisions.

These metrics can be refined and improved on the basis of research and experience, while consistency is maintained to permit time-series comparisons of progress (NRC, 2008). An advantage of such an approach includes the ability to document learning (*e.g.*, Is there progress on the part of investigators in better project designs? Should there be a redirection of funding toward projects that show a large payoff in benefits to decision makers?).

Finally, the ability to consult with agencies, water resource decision makers, and a host of other potential forecast user communities can be an invaluable means of providing "mid-course" or interim indicators of progress in integrating forecast use in decisions. The Transition of Research Applications to Climate Services Program (TRACS), also within the NOAA Climate Program Office, has a mandate to support users of climate information and forecasts at multiple spatial and geographical scales—the transitioning of "experimentally mature climate information tools, methods, and processes, including computer-related applications (*e.g.* web interfaces, visualization tools), from research mode into settings where they may be applied in an operational and sustained manner" (TRACS, 2008). While TRACS primary goal is to deliver useful climate information products and services to local, regional, national, and even international policy makers, it is also charged with learning from its partners how to better accomplish technology transition processes. NOAA's focus is to infer how effectively transitions of research applications (*i.e.* experimentally developed and tested, end-user-friendly information to support decision making), and climate services (*i.e.* the routine and timely delivery of that information, including via partnerships) are actually occurring.



While it is far too early to conclude how effectively this process of consultation has advanced, NOAA has established criteria for assessing this learning process, including clearly identifying decision makers, research, operations and extension partners, and providing for post-audit evaluation (*e.g.*, validation, verification, refinement, maintenance) to determine at the end of the project if the transition of information has been achieved and is sustainable. Effectiveness will be judged in large part by the partners, and will focus on the developing means of communication and feedback, and on the deep engagement with the operational and end-user communities (TRACS, 2008).

The Southeast Climate Consortium case discussed below illustrates how a successful process of ongoing stakeholder engagement can be developed through the entire cycle (from development, introduction, and use) of decision-support tools. This experiment affords insights into how to elicit user community responses in order to refine and improve climate information products, and how to develop a sense of decision-support ownership through participatory research and modeling. The Potomac River case focuses on efforts to resolve a long-simmering water dispute and the way collaborative processes can themselves lead to improved decisions. Finally, the Upper San Pedro Partnership exemplifies the kind of sustained partnering efforts that are possible when adequate funding is made available, politicization of water management questions is prevalent, and climate variability has become an important issue on decision-makers' agenda, while the series of fire prediction workshops illustrate the importance of a highly-focused problem—one that requires improvements to information processes, as well as outcomes, to foster sustained collaboration.

Case Study F: Southeast Climate Consortium Capacity Building, Tool Development

The Southeast Climate Consortium is a multidisciplinary, multi-institutional team, with members from Florida State University, University of Florida, University of Miami, University of Georgia, University of Auburn and the University of Alabama-Huntsville. A major part of the Southeast Climate Consortium's (SECC) effort is directed toward developing and providing climate and resource management information through AgClimate <http://www.agclimate.org/>, a decision-support system (DSS) introduced for use by Agricultural Extension, agricultural producers, and resource managers in the management of agriculture, forests, and water resources. Two keys to SECC's progress in promoting the effective use of climate information in agricultural sector decision making are (1) iterative ongoing engagement with stakeholders, from project initiation to decision-support system completion and beyond (further product refinement, development of ancillary products, *etc.*) (Breuer *et al.*, 2007; Cabrera *et al.*, 2007), and (2) co-developing a stakeholder sense of decision-support ownership through participatory research and modeling (Meinke and Stone, 2005; Breuer *et al.*, 2007; Cabrera *et al.*, 2007).

The SECC process has begun to build capacity for the use of climate information with a rapid assessment to understand stakeholder perceptions and needs regarding application of climate information that may have benefits (*e.g.*, crop yields, nitrogen pollution in water) (Cabrera *et al.*, 2006). Through a series of engagements, such as focus groups, individual interviews, research team meetings (including stakeholder advisors), and prototype demonstrations, the research team assesses which stakeholders are most likely adopt the decision-support system and communicate their experience with other stakeholders (Roncoli *et al.*, 2006), as well as stakeholder requirements for decision support (Cabrera *et al.*, 2007). Among the stakeholder requirements gleaned from more than six years of stakeholder engagements, are: present information in an uncomplicated way (often deterministic), but allow the option to view probabilistic information; provide information timed to allow users to take revised or preventative actions; include an economic component (because farmer survival, *i.e.* cost of practice adoption, takes precedence over stewardship concerns); and allow for confidential comparison of model results with proprietary data.

The participatory modeling approach used in the development of DyNoFlo, a whole-farm decision-support system to decrease nitrogen leaching while maintaining profitability under variable climate conditions (Cabrera *et al.*, 2007), engaged federal agencies, individual producers, cooperative extension specialists, and consultants (who provided confidential data for model verification). Cabrera *et al.* (2007) report that the dialogue between these players, as equals, was as important as the scientific underpinning and accuracy of the model in improving adoption. They emphasize that the process, including validation (defined as occurring when researchers and stakeholders agree the model fits real or measured conditions adequately) is a key factor in developing stakeholder sense of ownership and desire for further engagement and decision-support system enhancement. These findings concur with recent examples of the adoption of climate data, predictions and information to improve water supply model performance by Colorado River Basin water managers (Woodhouse and Lukas, 2006).

Water wars, traditionally seen in the West, are spreading to the Midwest, East, and South.

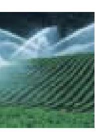
Case Study G: The Potomac River Basin

Water wars, traditionally seen in the West, are spreading to the Midwest, East, and South. The

"Water Wars" report (Council of State Governments, 2003) underlines the stress a growing resident population is imposing on a limited natural resource, and how this stress is triggering water wars in areas formerly with plentiful water. An additional source of concern would be the effect on supply and the increase in demand due to climate variability and change. Although the study by Hurd *et al.* (1999) indicated that the Northeastern water supply would be less vulnerable to the effect of climate change, the Interstate Commission on the Potomac River Basin (ICPRB) periodically studies the impact of climate change on the supply reliability to the Washington metropolitan area (WMA). (See also: *Restoring the Waters*. 1997, Boulder, CO, Natural Resources Law Center, the University of Colorado School of Law, May.)

Almost two decades of research into the associations between climate and fire demonstrate a high potential to predict various measures of fire activity, based on direct influences, such as drought, and indirect influences, such as growth of fire fuels such as grasses and shrubs.

The ICPRB was created in 1940 by the States of Maryland and West Virginia, the Commonwealths of Virginia and Pennsylvania, and the District of Columbia. The ICPRB was recognized by the United States Congress, which also provided a presence in the Commission. The ICPRB's purpose is "regulating, controlling, preventing, or otherwise rendering unobjectionable and harmless the pollution of the waters of said Potomac drainage area by sewage and industrial and other wastes".



The Potomac River constitutes the primary source of water for the WMA. Out of the five reservoirs in the WMA, three are in the Potomac River Basin. Every five years, beginning in April, 1990, the Commission evaluates the adequacy of the different sources of water supply to the Metropolitan Washington area. The latest report, (Kame'enui *et al.*, 2005), includes a report of a study by Steiner and Boland (1997) of the potential effects of climate variability and change on the reliability of water supply for that area.

The ICPRB inputs temperature, precipitation from five general circulation models (GCMs), and soil moisture capacity and retention, to a water balance model, to produce monthly average runoff records. The computed Potential Evapotranspiration (PET) is also used to estimate seasonal water use in residential areas.

The results of the 2005 study indicated that, depending on the climate change scenario, the demand in the Washington metropolitan area in 2030 could be 74 to 138 percent greater than that of 1990. According to the report, "resources were significantly stressed or deficient" at that point. The water management component of the model helped determine that, with aggressive plans in conservation and operation policies, existing resources would be sufficient through 2030. In consequence, the study recommended "that water management consider the need to plan for mitigation of potential climate change impacts" (Kame'enui *et al.*, 2005; Steiner and Boland, 1997).

Case Study H: Fire Prediction Workshops as a Model for a Climate Science-Water Management Process to Improve Water Resources Decision Support

Fire suppression costs the United States about $1 billion each year. Almost two decades of research into the associations between climate and fire (*e.g.*, Swetnam and Betancourt, 1998), demonstrate a high potential to predict various measures of fire activity, based on direct influences, such as drought, and indirect influences, such as growth of fire fuels such as grasses and shrubs (*e.g.*, Westerling *et al.*, 2002; Roads *et al.*, 2005; Preisler and Westerling, 2007). Given strong mutual interests in improving the range of tools available to fire management, with the goals of reducing fire related damage and loss of life, fire managers and climate scientists have developed a long-term process to improve fire potential prediction (Garfin *et al.*, 2001; Wordell and Ochoa, 2006) and to better estimate the costs and most efficient deployment of fire fighting resources. The strength of collaborations between climate scientists, fire ecologists, fire managers, and operational fire weather forecasters, is based upon mutual learning and meshing of both complementary knowledge (*e.g.*, atmospheric science and forestry science) and expertise (*e.g.*, dynamical modeling and command and control operations management) (Garfin, 2005). The emphasis on process, as well as product, may be a model for climate science in support of water resources management decision making. Another key facet in maintaining this collaboration and direct application of climate science to operational decision-making has been the development of strong professional relationships between the academic and operational partners. Aspects of developing these relationships that are germane to adoption of this model in the water management sector include:

- Inclusion of climate scientists as partners in annual fire management strategic planning meetings;
- Development of knowledge and learning networks in the operational fire management community;
- Inclusion of fire managers and operational meteorologists in academic research projects and development of verification procedures (Corringham *et al*., 2008)
- Co-location of fire managers at academic institutions (Schlobohm *et al*., 2003).

Case Study I: Incentives to Innovate—Climate Variability and Water Management along the San Pedro River

The San Pedro River, though small in size, supports one of the few intact riparian systems remaining in the Southwest. Originating in Sonora, Mexico, the stream flows northward into rapidly urbanizing southeastern Arizona, eventually joining with the Gila River, a tributary of the Lower Colorado River. On the American side of the international boundary, persistent conflict plagues efforts to manage local water resources in a manner that supports demands generated at Fort Huachuca Army Base and the nearby city of Sierra Vista, while at the same time preserving the riparian area. Located along a major flyway for migratory birds and providing habitat for a wide range of avian and other species, the river has attracted major interest from an array of environmental groups that seek its preservation. Studies carried out over the past decade highlight the vulnerability of the river system to climate variability. Recent data indicate that flows in the San Pedro have declined significantly due, in part, to ongoing drought. More controversial is the extent to which intensified groundwater use is depleting water that would otherwise find its way to the river.

The highly politicized issue of water management in the upper San Pedro River Basin has led to establishment of the Upper San Pedro Partnership, whose primary goal is balancing water demands with water supply in a manner that does not compromise the region's economic viability, much of which is directly or indirectly tied to Fort Huachuca Army base. Funding from several sources, including, among others, several NOAA programs and the Netherlands-based Dialogue on Climate and Water, has supported ongoing efforts to assess vulnerability of local water resources to climate variability on both sides of the border. These studies, together with experience from recent drought, point toward escalating vulnerability to climatic impacts, given projected increases in demand and likely diminution of effective precipitation over time in the face of rising temperatures and changing patterns of winter *versus* summer rainfall (IPCC, 2007). Whether recent efforts to reinforce growth dynamics by enhancing the available supply through water reuse or water importation from outside the basin will buffer impacts on the riparian corridor remains to be seen. In the meantime, climatologists, hydrologists, social scientists, and engineers continue to work with members of the Partnership and others in the area to strengthen capacity and interest in using climate forecast products. A relatively recent decision to include climate variability and change in a decision-support model being developed by a University of Arizona engineer in collaboration with members of the Partnership constitutes a significant step forward in integrating climate into local decision processes.

Effective integration of climate information in decisions requires identifying topics of mutual interest to sustain long-term collaborative research and application of decision-support outcomes.

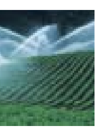
The incentives for engagement in solving the problems in the San Pedro include both a "carrot" in the form of federal and state funding for the San Pedro Partnership, and a newly formed water management district, and a "stick" in the form of threats to the future of Fort Huachuca. Fort Huachuca represents a significant component of the economy of southern Arizona, and its existence is somewhat dependent on showing that endangered species in the river, and the water rights of the San Pedro Riparian Conservation Area, are protected.

4.4 SUMMARY FINDINGS AND CONCLUSIONS

The decision-support experiments discussed here and in Chapter 3, together with the analytical discussion, have depicted several barriers to use of decision-support experiment information on SI climate conditions by water resource managers. The discussion has also pinpointed a number of ways to overcome these barriers and ensure effective communication, transfer, dissemination, and use of information. Our major findings are as follows.

While forecasts vary in their skill, multiple forecasts that examine various factors are most useful because they provide decision makers more access to data that they can manipulate themselves.

Effective integration of climate information in decisions requires identifying topics of mutual interest to sustain long-term collaborative research and application of decision-support outcomes: Identifying topics of mutual interest, through forums and other means of formal collaboration, can lead to information penetration into agency (and stakeholder group) activities, and produce self-sustaining, participant-managed spin-off activities. Long-term engagement also allows time for the evolution of scientist/decision-maker collaborations, ranging from understanding the roles of various players to connecting climate to a range of decisions, issues, and adaptation strategies—and building trust.



Tools must engage a range of participants, including those who generate them, those who translate them into predictions for decision-maker use, and the decision makers who apply the products. Forecast innovations might combine climate factor observations, analyses of climate dynamics, and SI forecasts. In turn, users are concerned with varying problems and issues such as planting times, instream flows to support endangered species, and reservoir operations. While forecasts vary in their skill, multiple forecasts that examine various factors (*e.g.*, snow pack, precipitation, temperature variability) are most useful because they provide decision makers more access to data that they can manipulate themselves.

A critical mass of scientists and decision makers is needed for collaboration to succeed: Development of successful collaborations requires representation of multiple perspectives, including diversity of disciplinary and agency-group affiliation. For example, operations, planning, and management personnel should all be involved in activities related to integrating climate information into decision systems; and there should be sound institutional pathways for information flow from researchers to decision makers, including explicit responsibility for information use. Cooperative relationships that foster learning and capacity building within and across organizations, including restructuring organizational dynamics, are important, as is training of "integrators" who can assist stakeholders with using complex data and tools.

What makes a "critical mass" critical? Research on water resource decision making suggests that agencies and other organizations define problems differently depending on whether they are dedicated to managing single-issue problems in particular sectors (*e.g.*, irrigation, public supply) or working in political jurisdictions or watershed-based entities designed to comprehensively manage and coordinate several management objectives simultaneously (*e.g.*, flood control and irrigation, power generation, and in-stream flow). The latter entities face the unusual challenge of trying to harmonize competing objectives, are commonly accountable to numerous users, and require "regionally and locally tailored solutions" to problems (Water in the West, 1998; also, Kenney and Lord, 1994; Grigg, 1996). A lesson that appears to resonate in our cases is that decision makers representing the affected organizations should be incorporated into collaborative efforts.

Forums and other means of engagement must be adequately funded and supported. Discussions that are sponsored by boundary organizations and other collaborative institutions allow for co-production of knowledge, legitimate pathways for climate information to enter assessment processes, and a platform for building trust. Collaborative products also give each community something tangible that can be used within its own system (*i.e.*, information to support decision making, climate service, or academic research products). Experiments that effectively incorporate seasonal forecasts into operations generally have long-term financial support, facilitated, in turn, by high public concern over potential adverse environmental and/or economic impacts. Such concern helps generate a receptive audience for new tools and ideas. Flexible and appropriate sources of funding must be found that recognize benefits received by various constituencies on the one hand, and ability to pay on the other. A combination of privately-funded, as well as publicly-supported revenue sources may be appropriate in many cases—both because of the growing demands on all sources of decision-support development, and because such a balance better satisfies demands that support for these experiments be equitably borne by all who benefit from them (Cash and Buizer, 2005). Federal agencies within CCSP can help in this effort by developing a database of possible funding sources from all sectors, public and private (CDWR, 2007b).

There is a need to balance national decision-support tool production against customizable, locally specific conditions. Given the diversity of challenges facing decision makers, the diverse needs and aspirations of stakeholders, and the diversity of decision-making authorities, there is little likelihood of providing comprehensive climate services or "one-stop-shop" information systems to support all decision making or risk assessment. Support for tools to help communities and other self-organizing groups develop their own capacity and conduct their own assessments within a regional context is essential.

There is a growing push for smaller scale products that are tailored to specific users, as well as private sector tailored products (*e.g.*, "Weatherbug"). However, private sector products are generally available only to specific paying clients, and may not be equitable to those who lack access to publicly-funded information sources. Private observing systems also generate issues related to trustworthiness of information and quality control. What are the implications of this push for proprietary vs. public domain controls and access? This problem is well-documented in policy studies of risk-based information in the fields of food labeling, toxic pollutants, medical and pharmaceutical information, and other forms of public disclosure programs (Graham, 2002).

4.5 FUTURE RESEARCH NEEDS AND PRIORITIES

Six major research needs are at the top of our list of priorities for investigations by government agencies, private sector organizations, universities, and independent researchers. These are:

1. Better understanding the decision context within which decision support tools are used,
2. Understanding decision-maker perceptions of climate risk and vulnerability;
3. Improving the generalizability/transferability of case studies on decision-support experiments,
4. Understanding the role of public pressures and networks in generating demands for climate information,
5. Improving the communication of uncertainties, and
6. Sharing lessons for collaboration and partnering with other natural resource areas.

Better understanding of the decision-maker context for tool use is needed. While we know that the institutional, political and economic context has a powerful influence on the use of tools, we need to learn more about how to promote user interactions with researchers at all junctures within the tool development process.

Those most likely to use weather and climate information are individuals who have experienced weather and climate problems in the past.

The institutional and cultural circumstances of decision makers and scientists are important to determining the level of collaboration, Among the topics that need to be addressed are the following:

- understanding how organizations engage in transferring and developing climate variability information,
- defining the decision space occupied by decision makers,
- determining ways to encourage innovation within institutions, and
- understanding the role of economics and chain-of-command in the use of tools.

Access to information is an equity issue: large water management agencies may be able to afford sophisticated modeling efforts, consultants to provide specialized information, and a higher quality of data management and analysis, while smaller or less wealthy stakeholders generally do not have the same access or the consequent ability to respond (Hartmann, 2001). This is especially true where there are no alternatives to private competitive markets where asymmetries of economic buying power may affect information access. Scientific information that is not properly disseminated can inadvertently result in windfall profits for some and disadvantage others (Pfaff *et al.*, 1999; Broad and Agrawalla, 2000; Broad *et al.,* 2002). Access and equity issues also need to be explored in more detail.

Much more needs to be known about how to make decision makers aware of their possible vulnerability from climate variability impacts to water resources.

4.5.1 Understanding Decision-Makers' Perceptions of Climate Vulnerability

Much more needs to be known about how to make decision makers aware of their possible vulnerability from climate variability impacts to water resources. Research on the influence of climate science on water management in western Australia, for example, (Power *et al.*, 2005) suggests that water resource decision makers can be persuaded to act on climate variability information if a strategic program of research in support of specific decisions (*e.g.*, extended drought) can be wedded to a dedicated, timely risk communication program.

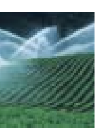
While we know, based on research in specific applications, that managers who find climate forecasts and projections to be reliable may be more likely to use them, those most likely to use weather and climate information are individuals who have experienced weather and climate problems in the recent past. The implication of this finding is that simply delivering weather and climate information to potential users may be insufficient in those cases in which the manager does not perceive climate to be a hazard—at least in humid, water-rich regions of the United States that we have studied[5].

We also need to know more about how the financial, regulatory, and management contexts influence perceptions of usefulness (Yarnal *et al.*, 2006; Dow *et al.*, 2007). Experience suggests that individual responses, in the aggregate, may have important impacts on one's capacity to use, access, and interpret information. Achieving a better understanding of these factors and of the informational needs of resource managers will require more investigation of their working environments and intimate understanding of their organizational constraints, motivations, and institutional rewards.

4.5.2 Possible Research Methodologies

Case studies increase understanding of how decisions are made by giving specific examples of decisions and lessons learned. A unique

[5] Additional research on water system manager perceptions is needed, in regions with varying hydrometeorological conditions, to discern if this finding is universally true.



strength offered by the case study approach is that "…only when we confront specific facts, the raw material on the basis of which decisions are reached—not general theories or hypotheses—do the limits of public policy become apparent (Starling, 1989)". In short, case studies put a human face on environmental decision making by capturing, even if only in a temporal "snapshot", the institutional, ethical, economic, scientific, and other constraints and factors that influence decisions.

4.5.3 Public Pressures, Social Movements and Innovation

The extent to which public pressures can compel innovation in decision-support development and use is an important area of prospective research. As has been discussed elsewhere in this Product, knowledge networks—which provide linkages between various individuals and interest groups that allow close, ongoing communication and information dissemination among multiple sectors of society involved in technological and policy innovations—can be sources of non-hierarchical movement to impel innovation (Sarewitz and Pielke, 2007; Jacobs, 2005). Such networks can allow continuous feedback between academics, scientists, policymakers, and NGOs in at least two ways:
(1) by cooperating in seeking ways to foster new initiatives, and (2) providing means of encouraging common evaluative and other assessment criteria to advance the effectiveness of such initiatives.

Since the late 1980s, there has arisen an extensive collection of local, state (in the case of the United States) and regional/sub-national climate change-related activities in an array of developed and developing nations. These activities are wide-ranging and embrace activities inspired by various policy goals, some of which are only indirectly related to climate variability. These activities include energy efficiency and conservation programs; land use and transportation planning; and regional assessment. In some instances, these activities have been enshrined in the "climate action plans" of so-called Annex I nations to the UN Framework Convention on Climate Change (UNCED, 1992; Rabe, 2004).

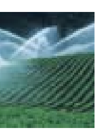
An excellent example of an important network initiative is the International Council of Local Environmental Initiatives, or ICLEI is a Toronto, Canada-based NGO representing local governments engaged in sustainable development efforts worldwide. Formed in 1990 at the conclusion of the World Congress of Local Governments involving 160 local governments, it has completed studies of urban energy use useful for gauging growth in energy production and consumption in large cities in developing countries (*e.g.*, Dickinson, 2007; ICLEI, 2007). ICLEI is helping to provide a framework of cooperation to evaluate energy, transportation, and related policies and, in the process, may be fostering a form of "bottom-up" diffusion of innovation processes that function across jurisdictions—and even entire nation-states (Feldman and Wilt, 1996; 1999). More research is needed on how, and how effectively networks actually function and whether their efforts can shed light on the means by which the diffusion of innovation can be improved and evaluated.

While uncertainty is an inevitable factor in regards to climate variability and weather information, the communication of uncertainty—as our discussion has shown—can be significantly improved.

Another source of public pressure is social movements for change—hardly unknown in water policy (*e.g.*, Donahue and Johnston, 1998). Can public pressures through such movements actually change the way decision makers look at available sources of information? Given the anecdotal evidence, much more research is warranted. One of the most compelling recent accounts of how public pressures can change such perceptions is that by the historian Norris Hundley on the gradual evolution on the part of city leaders in Los Angeles, California, as well as members of the public, water agencies, and state and federal officials—toward diversion of water from the Owens Valley.

After decades of efforts and pressures from interested parties to, at first prevent and then later, roll back, the amount of water taken from the Owens River, the city of Los Angeles sought an out-of-court settlement over diversion; in so doing, they were able to study the reports of environmental degradation caused by the volumes of water transferred, and question whether to compensate the Valley for associated damages (Hundley, 2001). While Hundley's chronicling of resistance has a familiar ring to students of water policy, remarkably little research has been done to draw lessons using the grounded theory approach discussed earlier—about the impacts of such social movements.

While uncertainty is an inevitable factor in regards to climate variability and weather information, the communication of uncertainty—as our discussion has shown—can be significantly improved. Better understanding of innovative ways to communicate uncertainty to users should draw on additional literatures from the engineering, behavioral and social, and natural science communities (*e.g.*, NRC 2005; NRC 2006). Research efforts are needed by various professional communities involved in the generation and dissemination of climate information to better establish how to define and communicate climate variability risks clearly and coherently and in ways that are meaningful to water managers. Additional research is needed to determine the most effective communication, dissemination and evaluation tools to deliver information on potential impacts of climate variability, especially with regards to such factors as further reducing uncertainties associated with future sea-level rise, more reliable predictions of changes in frequency and intensity of tropical and extra-tropical storms, and how saltwater intrusion will impact freshwater resources, and the frequency of drought. Much can be learned from the growing experience of RISAs and other decision-support partnerships and networks.



Research on lessons from other resource management sectors on decision-support use and decision maker/researcher collaboration would be useful. While water issues are ubiquitous and connect to many other resource areas, a great deal of research has been done on the impediments to, and opportunities for, collaboration in other resource areas such as energy, forests, coastal zone and hydropower. This research suggests that there is much that water managers and those who generate SI information on climate variability could learn from this literature. Among the questions that need further investigation are issues surrounding the following subject areas: (1) innovation (Are there resource areas in which tool development and use is proceeding at a faster pace than in water management?); (2) organizational culture and leadership (Are some organizations and agencies more resistant to change, more hierarchical in their decision making, more formalized in their decisional protocols than is the case in water management?); and (3) collaborative style (Are some organizations in certain resource areas or science endeavors better at collaborating with stakeholder groups in the generation of information tools, or other activities? [*e.g.*, Kaufman, 1967; Bromberg, 2000]). Much can also be learned about public expectations and the expectations of user groups from their collaborations with such agencies that could be valuable to the water sector.