Chapter 3. Decision-support Experiments within the Water Resource Management Sector

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KEY FINDINGS

Decision-support experiments that test the utility of SI information for use by water resource decision-makers have resulted in a growing set of successful applications. However, there is significant opportunity for expansion of applications of climate-related data and decision support tools, and for developing more regional and local tools that support management decisions within watersheds. Among the constraints that limit tool use are:

- the range and complexity of water resources decisions. This is compounded by the numerous organizations responsible for making these decisions, and the shared responsibility for implementing them.
- inflexible policies and organizational rules that inhibit innovation. Government agencies historically have been reluctant to change practices; in part because of value differences, risk aversion, fragmentation and sharing of authority. This conservatism impacts how decisions are made as well as whether to use newer, scientifically generated information, including SI forecasts and observational data.
- different spatial and temporal frames for decisions. Spatial scales for decision-making range from local, state, and national levels to international. Temporal scales range from hours to multiple decades impacting policy, operational planning, operational management, and near real-time operational decisions. Resource managers often make multi-dimensional decisions spanning various spatial and temporal frames.
- lack of appreciation of the magnitude of potential vulnerability to climate impacts. Communication of the risks differs among scientific, political, and mass media elites – each systematically selecting aspects of these issues that are most salient to their conception of risk, and thus, socially constructing and communicating its aspects most salient to a particular perspective.

Decision-support systems are not often well integrated into planning and management activities, making it difficult to realize the full benefits of these tools. Because use of many climate products requires special training or access to data that are not easily available, decision-support products may not equitably reach all audiences. Moreover, over-specialization and narrow disciplinary perspectives make it difficult for information providers, decision-makers, and the public to communicate with one another. Three lessons stem from this:

- Decision-makers need to understand the types of predictions that can be made, and the tradeoffs between longer-term predictions of information at the local or regional scale on the one hand, and potential decreases in accuracy on the other.

- Decision-makers and scientists need to work together in formulating research questions relevant to the spatial and temporal scale of problems the former manage.

- Scientists should aim to generate findings that are accessible and viewed as useful, accurate and trustworthy by stakeholders.

3.1 INTRODUCTION

> Over the past century, the U. S. has built a vast and complex infrastructure to provide clean water for drinking and for industry, dispose of wastes, facilitate transportation, generate electricity, irrigate crops, and reduce the risks of floods and droughts. . . . To the average citizen, the nation’s dams, aqueducts, reservoirs, treatment plants, and pipes are . . . taken for granted. Yet they help insulate us from wet and dry years and moderate other aspects of our naturally variable climate. Indeed they have permitted us to almost forget about our complex dependences on climate. We can no longer ignore these close connections. – From: Peter Gleick and Briane Adams, *Water: The Potential Consequences of Climate Variability and Change for the Water Resources of the United States* (2000), p. 1.

This chapter synthesizes and distills lessons for the water resources management sector from efforts to apply decision-support experiments and evaluations using *seasonal to* *inter-annual forecasts* and observational climate data. Its thesis is that, while there is a growing, theoretically-grounded body of knowledge on how and why resource decision-makers use information, there is little research on barriers to use of decision-support products in the water management sector. Much of what we know about these barriers comes from case studies on the application of seasonal to inter-annual forecast information and by efforts to span organizational boundaries dividing scientists and users. Research is needed on factors that can be generalized beyond these single cases in order to develop a strong, theoretically-grounded understanding of the processes that facilitate information dissemination, communication, use, and evaluation – and to predict effective methods of boundary spanning between decision-makers and information generators.

Decision support is a three-fold process that encompasses: (i) the generation of climate science products; (ii) the translation of those products into forms useful for decision-makers; and, (iii) the processes that facilitate the dissemination, communication, and use of climate science products, information, and tools (NRC, 2007). As shall be seen, because users include many private and small, as well as public and large users serving multiple jurisdictions and entities, effective decision support is difficult to achieve.

Section 3.2 describes the range of major decisions water users make, their decision support needs, and the role decision support systems can play in meeting them. We examine the attributes of water resource decisions, their spatial and temporal characteristics, and the implications of complexity, political fragmentation, and shared responsibility on forecast use. We also discuss impediments to forecast information use by decision-makers, including mistrust, uncertainty, and lack of agency coordination, and discuss four cases – whose problem foci range from severe drought to flooding – where efforts to address these impediments are being undertaken with mixed results.

Section 3.3 examines challenges in fostering closer collaboration between scientists and decision-makers in order to communicate, translate, and operationalize climate forecasts and hydrology information into integrated water management decisions. We review what the social and decision sciences have learned about barriers in interpreting, deciphering, and explaining climate forecasts and other meteorological and hydrological models and forecasts to decision-makers, including issues of relevance, accessibility, organizational constraints on decision-makers, and compatibility with users' values and interests. Case studies reveal how these issues manifest themselves in decision-support applications. Chapter 4 – which is a continuation of these themes in the context of how to surmount these problems – examines how impediments to effectively implementing decision-support systems can be overcome in order to make them more useful, useable, and responsive to decision-maker needs.

3.2 WHAT DECISIONS DO WATER USERS MAKE, WHAT ARE THEIR DECISION-SUPPORT NEEDS, AND WHAT ROLES CAN DECISION-SUPPORT SYSTEMS PLAY IN MEETING THESE NEEDS?

This section reviews the range and attributes of water resource decisions, including complexity, political fragmentation, shared decision-making, and varying spatial scale.

We also discuss the needs of water resource managers for climate variability forecast information, and the multi-temporal and multi-spatial dimensions of these needs. Finally, we examine how climatic variability affects water supply and quality. Embedded in this examination is discussion of the risks, hazards, and vulnerability of water resources (and human activities dependent on them) from climatic variability.

3.2.1 Range and Attributes of Water Resource Decisions

As discussed in Chapter 1, and as illustrated in Table 1.1, decisions regarding water resources in the U.S. are many and varied, and involve public and private sector decision-makers. Spatial scales for decision-making range from local, state, and national levels to international political jurisdictions – the latter with some say in the way U.S. water resources are managed (Hutson *et al*., 2004; Sarewitz and Pielke, 2006; Gunaji, 1993; Wagner, 1995. These characteristics dictate that information must be tailored to the particular roles, responsibilities, and concerns of different decision-makers to be useful. Chapter 1 also suggests that the way water issues are framed – a process determined partly by organizational commitments and perceptions, and in part by changing demands imposed by external events and actors – determines how information must be tailored to optimally impact various decision-making constituencies – and how it will likely be used once tailored. Here we focus on the implications of this multiple-actor, multi-jurisdictional environment for delivery of climate variability information.

3.2.1.1 Institutional Complexity, Political Fragmentation, and Shared Decision-Making: Impacts on Information Use

The range and complexity of water resource decisions, the numerous organizations responsible for making these decisions, and the shared responsibility for implementing them affect how water resource decision-makers use climate variability information in five ways: (1) a tendency toward institutional conservatism by water agencies, (2) a decision-making climate that discourages innovation, (3) a lack of national-scale coordination of decisions, (4) difficulties in providing support for decisions at varying spatial and temporal scales due to vast variability in "target audiences" for products, and (5) growing recognition that rational choice models that attempt to explain information use as a function of decision-maker needs for "efficiency" are overly simplistic. These are discussed in turn.

First, institutions that make water resource decisions, particularly government agencies, operate in domains where they are beholden to powerful constituencies. These constituencies have historically wanted public works projects for flood control, hydropower, water supply, navigation, and irrigation. They also have worked hard to maximize their benefits within current institutional structures, and are often reluctant to change practices that appear antiquated or inefficient to observers.

The success of these constituencies in leveraging federal resources for river and harbor improvements, dams, and water delivery systems is in part due to mobilizing regional development interests. Such interests commonly resist change and place a premium on engineering predictability and reliability (D. Feldman, 1995; D. Feldman, 2007; Ingram and Fraser, 2006; Merritt, 1979: 48; Holmes, 1979). This conservatism not only affects how these agencies and organizations make decisions, it also impacts how they employ, or do not employ, scientifically generated information, including that related to seasonal and inter-annual climate variability. Information that conflicts with their mandates, traditions, or roles may not be warmly received, as surveys of water resource managers has shown (*e.g.*, O'Connor *et al.*, 1999 and 2005; Yarnal *et al.*, 2006; Dow *et al.*, 2007)

Second, the decision-making culture of U.S. water resources management has traditionally *not* embraced innovation. It has long been the case that value differences, risk aversion, fragmentation, and sharing of authority has produced a decision-making climate in which innovation is discouraged. When innovations have occurred, they have usually resulted from, or been encouraged through, outside influences on the decision-making process, including extreme climate events or mandates from higher-level government entities (Hartig *et al.*, 1992; Landre and Knuth, 1993; Cortner and Moote, 1994; Water in the West, 1998; May *et al.*, 1996).

Third, throughout the history of U.S. water resources management there have been various efforts to seek greater synchronization of decisions at the national level, in part, to better respond to environmental protection, economic development, water supply, and other goals. These efforts hold many lessons for understanding the role of climate change information and its use by decision-makers, as well how to bring about communication between decision-makers and climate information producers. While there has been significant investment of federal resources to provide for water infrastructure improvements, there has been little national-scale coordination over decisions, or over the use of information employed in making them (Kundell, DeMeo, and Myszewski, 2001). The system does not encourage connectivity between the benefits of the federal investments and those who actually pay for them, which leaves little incentive for improvements in efficiency and does not reward innovation.

3.2.1.2 Implications of the federal role in water management

In partial recognition of the need to coordinate across state boundaries to manage interstate rivers, in the 1960s groups of Northeastern states formed the Delaware River Basin Commission (DRBC) and the Susquehanna River Basin Commission (SRBC) to pave the way for conflict resolution. These early federal interstate commissions functioned as boundary organizations that mediated communication between supply and demand functions for water and climate information (Sarewitz and Pielke, 2007). They relied on frequent, intensive, face-to-face negotiations; coordination among politically-neutral technical staffs; sharing of study findings among partners; willingness to sacrifice institutional independence when necessary; and commission authority to implement decisions so as to transcend short-term pressures to act expediently (Cairo, 1997; Weston, 1995)[1].

An ambitious effort to coordinate federal water policy occurred in 1965 when Congress established the Water Resources Council (WRC), under the Water Resources Planning

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[1] Compact entities were empowered to allocate interstate waters (including groundwater and inter-basin diversions), regulate water quality, and manage interstate bridges and ports. DRBC includes numerous federal partners such as the Interior Department and Corps of Engineers officials (DRBC, 1998; DRBC, 1960; Weston, 1999; Weston, 1995; Cairo, 1997). One of the forces giving rise to DRBC was periodic *drought* that helped exacerbate conflict between New York City and other political entities in the basin. This led to DRBC's empowerment, as the nation's first federal interstate water commission, in all matters relating to the water resources of its basin, ranging from flooding to fisheries to water quality.

Act, to coordinate federal programs. Due to objections to federal intervention in water rights issues by some states, and the absence of vocal defenders for the WRC, Congress de-funded WRC in 1981 (Feldman, 1995). Its demise points out the continued frustration in creating a national framework to coordinate water management, especially for optimal management in the context of climate variability. Since termination of the WRC, coordination of federal programs, when it has occurred, has come variously from the Office of Management and Budget, White House Council on Environmental Quality, and *ad hoc* bodies (*e.g.*, Task Force on Floodplain Management)[2].

Fourth, the physical and economic challenge in providing decision support due to the range of "target audiences" (*e.g.*, Naim, 2003) and the controversial role of the federal government in such arenas is illustrated by efforts to improve the use of seasonal to inter-annual climate change information for managing water resources along the U.S.-Mexico border, as well as the U.S.-Canadian border. International cross-boundary water issues in North America bring multiple additional layers of complexity, in part because the federal governments of Canada, Mexico and the U.S. often are ill equipped to respond to local water and wastewater issues. Bringing the U.S. State Department into discussions over management of treatment plants, for example, may not be an effective way to resolve technical water treatment or supply problems.

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[2] Today the need for policy coordination, according to one source, "stems from the . . . environmental and social crises affecting the nation's rivers" (Water In the West, 1998: xxvii). In nearly every basin in the West, federal agencies are responding to tribal water rights, growing urban demands, endangered species listings, and Clean Water Act lawsuits. Climate change is expected to exacerbate these problems.

In the last decade, climate-related issues that have arisen between Mexico and the U.S. regarding water revolve around disagreements among decision-makers on how to define extraordinary drought and how to allocate shortages – and over how to cooperatively prepare for climate extremes. These issues have led to renewed efforts to better consider the need for predictive information and ways to use it to equitably distribute water under drought conditions. Continuous monitoring of meteorological data, consumptive water uses, calculation of drought severity, and detection of longer-term climate trends could, under the conditions of these agreements, prompt improved management of the cross boundary systems (Gunaji, 1995; Mumme, 2003; Mumme, 1995; Higgins, Chen and Douglas, 1999). The 1906 Rio Grande Convention and 1944 Treaty between the U.S. and Mexico – the latter established the *International Boundary Water Commission* – contain specific clauses related to “extraordinary droughts.” These clauses prescribe that the U.S. government appraise Mexico of the onset of drought conditions as they develop, and adjust water deliveries to both U.S. and Mexican customers accordingly (Gunaji, 1995). However, there is some reluctance to engage in conversations that could result in permanent reduced water allocations or reallocations of existing water rights.

For the U.S. and Canada, a legal regime similar to that between the U.S. and Mexico has existed since the early 1900s. The anchor of this regime is the 1909 Boundary Waters Treaty that established an *International Joint Commission* with jurisdiction over threats to water quality, anticipated diversions, and protection of instream flow and water supply inflow to the Great Lakes – the latter being a region in which climate change-related concerns have grown in recent years due, especially, to questions arising over calls to treat its water resources as a marketable commodity, as well as concerns over what criteria to use to resolve disputes over these and other questions (Wagner, 1995; International Joint Commission, 2000).

3.2.1.3 Institutions and decision-making

Fifth, there is growing recognition of the limits of so-called *rational choice models* of information use, which assume that decision-makers deliberately focus on optimizing organizational performance when they use climate variability or other water resource information. This recognition is shaping our understanding of the impacts of institutional complexity on use of climate information. An implicit assumption in much of the research on probabilistic forecasting of seasonal and inter-annual variation in climate is that decision makers on all levels will value and use improved climate predictions, monitoring data, and forecast tools that can predict changes to conditions affecting water resources (*e.g.*, Nelson and Winter, 1960). *Rational choice* models of decision-making are predicated on the assumption that decision makers seek to make optimal decisions (and perceive that they have the flexibility and resources to implement them).

A widely-cited study of four water management agencies in three locations – the Columbia River system in the Pacific Northwest, Metropolitan Water District of Southern California, and Potomac River Basin and Chesapeake Bay in the greater Washington, D.C. area - examined the various ways water agencies at different spatial scales use probabilistic climate forecast information. The study found that not only the multiple geographic scales at which these agencies operate – but the complexity of their decision-making systems – dramatically influences how, and to what extent, they use probabilistic climate forecast information. An important lesson is that the complexity of these systems' sources of supply and infrastructure, and the stakeholders they serve are important influences on their capacity to use climate information. Decision-systems may rely on multiple sources of data, support the operation of various infrastructure components, straddle political (and hydrological) boundaries, and serve stakeholders with vastly different management objectives (Rayner, Lach, and Ingram, 2005). Thus, science is only one of an array of potential elements influencing decisions.

The cumulative result of these factors is that water system managers and operations personnel charged with making day-to-day decisions tend toward an overall institutional conservatism when it comes to using complex meteorological information for short-to medium term decisions. Resistance to using new sources of information is affected by the complexity of the institutional setting within which managers work, dependency on craft skills and local knowledge, and a hierarchy of values and processes designed to ensure their political invisibility. Their goal is to smooth out fluctuations in operations and keep operational issues out of the public view (Rayner, Lach, and Ingram, 2005).

In sum, the use of climate change information by decision makers is constrained by a politically fragmented environment, a regional economic development tradition that has inhibited – at least until recently – the use of innovative information (*e.g.*, conservation, integrated resource planning), and multiple spatial and temporal frames for decisions. All this makes the target audience for climate information products vast and complex.

The interplay of these factors, particularly the specific needs of target audiences and the inherently conservative nature of water management, is shown in the case of how Georgia has come to use drought information to improve long-term water supply planning. As shall be seen later (section 3.3.1), while the good news in this case is that information is beginning to be used by policymakers, the downside is that *some* information use is being inhibited by institutional impediments – namely, inter-state political conflicts over water.

Box 3.1: Georgia Drought

Background

Two apparent physical causes of the 2007-08 Southeast drought include a lack of tropical storms and hurricanes, which usually can be counted on to replenish declining reservoirs and soil moisture, and the development of a La Niña episode in the tropical Pacific, which continues to steer storms to the north of the region (see Figure 3.1). Drought risk is frequently modeled as a function of hazard (*e.g.*, lack of precipitation) and vulnerability (*i.e.*, susceptibility of society to the hazard) using a multiplicative formula, risk = hazard *vulnerability (Hayes *et al.*, 2004). In 2007, Atlanta, Georgia received only 62% of its average annual precipitation, the second driest calendar year on record; moreover, streamflows were among the lowest recorded levels on several streams. By June 2007, the National Climatic Data Center reported that December-May precipitation totals for the Southeast were at new lows. Spring wildfires spread throughout southeastern Georgia which also recorded its worst pasture conditions in 12 years. Georgia's Governor Purdue extended a state of emergency through June 30; however, the state's worst drought classification, accompanied by a ban on outdoor water use, was not declared until late September.

While progressive state drought plans, such as Georgia's (which was adopted in March, 2003), emphasize drought preparedness and mitigation of impacts through mandatory restrictions in some water use sectors, they do not commonly factor in the effect of population growth on water supplies. Moreover, conservation measures in a single state cannot address water allocation factors affecting large, multi-state watersheds, such as the Apalachicola- Chattahoochee-Flint (ACF), which encompasses parts of Georgia, Alabama, and Florida.

Institutional barriers and problems

The source of water woes in this Southeastern watershed dates back to a 1987 decision by the Army Corps of Engineers to reallocate 20% of power generation flow on the Chattahoochee River to municipal supply for Atlanta, which sits near the headwaters of the river. Alabama and Florida soon demanded an assessment of the environmental and economic effects of that decision, which set off a series of on-again, off-again disputes and negotiations between the three states, known as the "Tri- State Water Wars," that have not been resolved (as of January, 2008). At the heart of the disputes is a classic upstream-downstream water use and water rights dispute, pitting municipal water use for the rapidly expanding Atlanta metropolitan region against navigation, agriculture, fishing, and environmental uses downstream in Alabama and Georgia. The situation is further complicated by water quality concerns, as downstream users suffer degraded water quality, due to polluted urban runoff and agricultural waste, pesticide, and fertilizer leaching. Despite the efforts of the three states and Congress to create water compacts, by engaging in joint water planning and developing and sharing common data bases, the compacts have never been implemented as a result of disagreements over what constitutes equitable water allocation formulae (Feldman, 2007).

Political and sectoral disputes continue to exacerbate lack of coordination on water-use priorities, and there is a continuing need to include climate forecast information into these activities, as underscored by continuing drought in the Southeast. The result is that water management decision-making is constrained, and there are few opportunities to insert effective decision support tools, aside from the kinds of multi-stakeholder shared-vision modeling processes developed by the Army Corps of Engineers Institute for Water Resources.

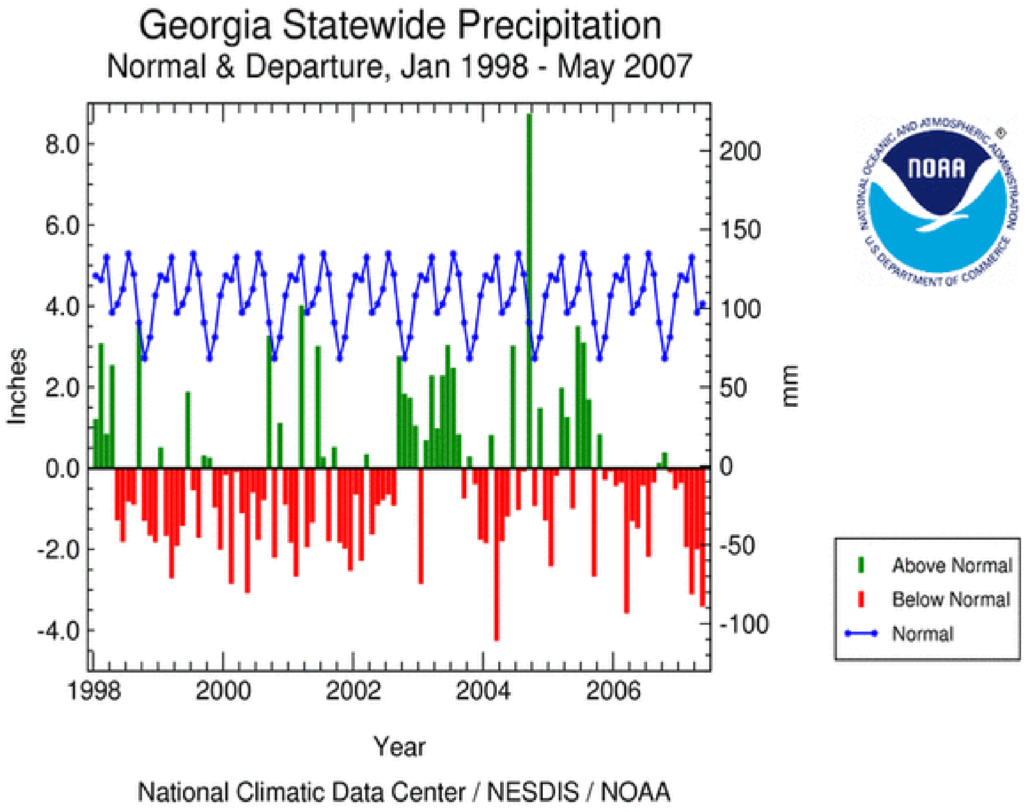

Figure Box 3.1 Georgia statewide precipitation: 1998-2007

(end box)

Spatial scale of decisions

In addition to the challenges created by institutional complexity, the spatial scale of decisions made by water management organizations ranges from small community water systems to large, multi-purpose metropolitan water service and regional water delivery systems (Rayner, Lach, and Ingram, 2005). Differences in spatial scale of management also affect information needed – an issue discussed in chapter 4 when we analyze Regional Integrated Science Assessment (RISA) experiences. These problems of diverse spatial scale are further compounded by the fact that most water agencies do not conform to hydrological units. While some entities manage water resources in ways that conform to hydrological constraints (*i.e.*, watershed, river basin, aquifer or other drainage basin – Kenney and Lord, 1994; Cairo, 1997), basin-scale management is not the most common U.S. management approach. Because most hydrologic tools focus on watershed boundaries, there is a disconnect between the available data and the decision context.

Decision-makers often *share* authority for decisions across local, state, and national jurisdictions. In fact, the label "decision maker" embraces a vast assortment of elected and appointed local, state, and national agency officials, as well as public and private sector managers with policy-making responsibilities in various water management areas (Sarewitz and Pielke, 2007). Because most officials have different management objectives while sharing authority for decisions, it is likely that their specific seasonal to inter-annual climate variability information needs will vary not only according to spatial scale, but also according to institutional responsibilities and agency or organization goals. Identifying who the decision makers are is equally challenging. The Colorado River basin illustrates the typical array of decision-makers on major U.S. streams. A recent study in Arizona identified an array of potential decision makers affected by water shortages during drought, including conservation groups, irrigation districts, power providers, municipal water contractors, state water agencies, several federal agencies, two regional water project operators (the Central Arizona and Salt River projects), tribal representatives, land use jurisdictions, and individual communities (Garrick, Jacobs, Garfin, 2006). This layering of agencies with water management authority is also found at the national level.

There is no universally agreed-upon classification system for defining *water users*. Taking as one point of departure the notion that water users occupy various "sectors" (*i.e.*, activity areas distinguished by particular water uses), the U.S. Geological Survey monitors and assesses water use for eight user categories: public supply, domestic use, irrigation, livestock, aquaculture, industrial, mining, and thermo-electric power. These user categories share freshwater supplies withdrawn from streams and/or aquifers and, occasionally, from saline water sources as well (Hutson *et al*., 2004). However, the definitions of these classes of users vary from state to state.

One limitation in this user-driven classification scheme in regards to identifying information needs for seasonal to inter-annual climate forecasts is that it inadvertently excludes in-stream water users – those who do not remove water from streams or aquifers. Instream uses are extremely important, as they affect aquatic ecosystem health, recreation, navigation, and public health (Gillilan and Brown, 1997; Trush and McBain, 2000; Rosenberg *et al*., 2000; Annear *et al*., 2002). Moreover, instream uses and wetland habitats have been found to be among the most vulnerable to impacts of climate variability and change (USGCRP, 2001)[3].

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[3] In general, federal law protects instream uses only when an endangered species is affected. Protection at the state level varies, but extinction of aquatic species suggests the relatively low priority given to

Finally, decision-makers' information needs are also influenced by the time frame for decisions – and to a greater degree than scientists. For example, while NOAA researchers commonly distinguish between weather prediction information, produced on an hours-to-weeks time frame, and climate predictions, which may be on a seasonal to inter-annual time frame, many managers make decisions based on annual operating requirements or on shorter time frames that may not match the products currently produced.

Two important points stem from this. First, as longer-term predictions gain skill, use of longer-term climate information is likely to expand, particularly in areas with economic applications. Second, short-term decisions may have long-term consequences. Thus, identifying the information needed to make better decisions in all time frames is important – especially since it can be difficult to get political support for research that focuses on long-term, incremental increases in knowledge that are the key to significant policy changes (Kirby, 2000). This poses a challenge for decision-makers concerned about adaptation to global change.

Multi-decadal climate-hydrology forecasts and demand forecasts (including population and economic sector forecasts and forecasts of water and energy demand) are key inputs for policy decisions. Changes in climate that affect these hydrology and water demand forecasts are particularly important for policy decisions, as they may alter the anticipated

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protecting flow and habitat. Organizations with interests in the management of instream flows are diverse, ranging from federal land management agencies to state natural resource agencies and private conservation groups, and their climate information needs widely vary (Pringle, 2000; Restoring the Waters, 2000).

streams of benefits and impacts of a proposal. Information provided to the policy planning process is best provided in the form of tradeoffs assessing the relative implications, hazards, risks, and vulnerabilities associated with each policy option[4].

3.2.2 Decision-support Needs of Water Managers for Climate Information

As we have noted, the decision-support needs of water resource decision-makers for information on climate variability depend upon the temporal and spatial scale of the decisions that they make. The complexity of the decision process is graphically illustrated in Figure 3.2 (Georgakakos, 2006a; HRC-GWRI, 2006). This figure includes *four* temporal scales ranging from multiple decades to hours. The *first* decision level includes *policy decisions* pertaining to multi-decadal time scales and involving infrastructure changes (*e.g.*, storage projects, levee systems, energy generation facilities, waste water treatment facilities, inter-basin transfer works, sewer/drainage systems, well fields, and monitoring networks), as well as water sharing compacts, land use planning, environmental sustainability requirements and targets, regulations, and other legal and institutional requirements. Policy decisions may also encompass many political entities. Decisions pertaining to trans-boundary water resources are particularly challenging, as noted in section 3.2.1.1, because they aim to reconcile benefits and impacts measured and interpreted by different standards, generated and accrued by stakeholders of different

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[4] Ideally, the purpose of the participatory planning processes is to formulate policies benefiting stakeholders. The process is highly interactive and iterative with stakeholder groups formulating policy options for assessment by the decision support systems and experts, in turn, interpreting the assessment results for the stakeholders who evaluate and refine them. It is acknowledged, however, that water resource decisions are often contentious, and stakeholder decision processes may fail to reach consensus.

nations, and regulated under different legal and institutional regimes (Naim, 2003; Mumme, 2003; Mumme, 1995; Higgins, Chen and Douglas, 1999).

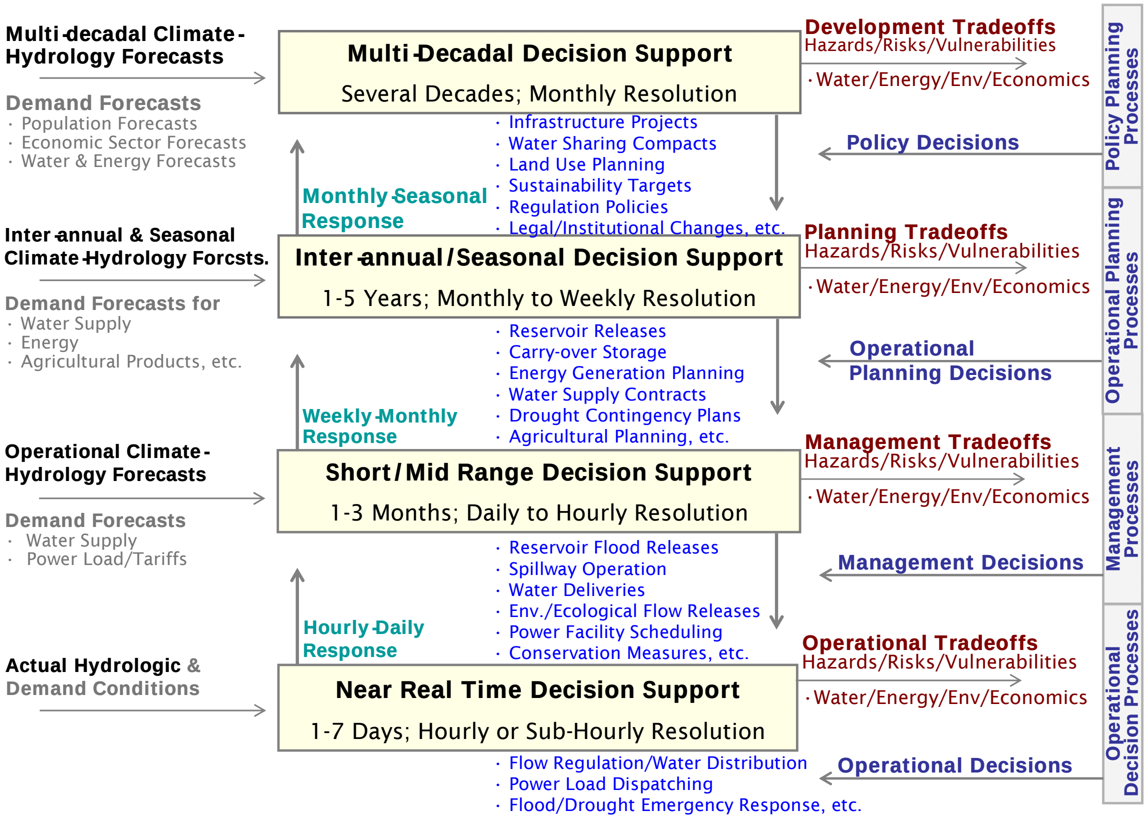

Figure 3.2 Water Resources Decisions: Range and Attributes

The second decision level involves *operational planning decisions pertaining to inter-annual and seasonal time scales.* These and other lower level decisions are made within the context set by the policy decisions and pertain to inter-annual and seasonal reservoir releases, carry-over storage, hydro-thermal energy generation plans, agreements on tentative or final water supply and energy contracts, implementation of drought contingency plans, and agricultural planning decisions, among others. The relevant spatial scales for operational planning decisions may be as large as those of the policy decisions, but are usually associated with individual river basins as opposed to political jurisdictions. Inter-annual and seasonal hydro-climatic and demand forecasts (for water supply, energy, and agricultural products) are critical inputs for this decision level.

The third decision level pertains to *operational management decisions associated with short and mid range time scales of 1-3 months.* Typical decisions include reservoir releases during flood season, spillway operations, water deliveries to urban, industrial, or agricultural areas, releases to meet environmental and ecological flow requirements, power facility operation, and drought conservation measures. The benefits and impacts of these decisions are associated with daily and hourly system response (high resolution). This decision level requires operational hydro-climatic forecasts and forecasts of water and power demand and pricing. The decision process is similar to those of the upper decision layers, although, as a practical matter, general stakeholder participation is usually limited, with decisions taken by the responsible operational authorities. This is an issue relevant to several cases discussed in chapter 4.

The final decision level pertains to *near real time operations* associated with hydrologic and demand conditions. Typical decisions include regulation of flow control structures, water distribution to cities, industries, and farms, operation of power generation units, and implementation of flood and drought emergency response measures. Data from real time monitoring systems are important inputs for daily to weekly operational decisions. Because such decisions are made frequently, stakeholder participation may be impractical, and decisions may be limited to government agencies or public sector utilities according to established operational principles and guidelines.

While the above illustration addresses water resources complexity (*i.e.*, multiple temporal and spatial scales, multiple water uses, multiple decision makers), it cannot be functionally effective (*i.e.*, create the highest possible value) unless it exhibits consistency and adaptiveness. *Consistency* across the decision levels can be achieved by ensuring that (*1*) lower level forecasts, decision support systems, and stakeholder processes operate within the limits established by upper levels (as represented by the downward pointing feedback links in Figure 1, and (*2*) upper decision levels capture the benefits and impacts associated with the high resolution system response (as represented by the upward pointing feedback links in Figure 3.2). *Adaptiveness*, as a number of studies indicate, requires that decisions are continually re-visited as system conditions change and new information becomes available, or as institutional frameworks for decision-making are amended (Holling, 1978; Walters, 1986; Lee, 1993).

3.2.3 How Does Climate Variability Affect Water Management?

Water availability is essential for human health, economic activity, ecosystem function, and geophysical processes. Climate variability can have dramatic seasonal and inter-annual effects on precipitation, drought, snow-pack, runoff, seasonal vegetation, water quality, groundwater, and other variables. Much recent research on climate variability impacts on water resources is linked to studies of long-term climate change, necessitating some discussion of the latter. In fact there is a relative paucity of information on the potential influence of climate change on the underlying patterns of climate variability (*e.g.*, CCSP, 2007). At the close of this section, we explore one case – that of drought in the Colorado River basin – exemplifying several dimensions of this problem, including adaptive capacity, risk perception, and communication of hazard.

According to the Intergovernmental Panel on Climate Change, while total annual precipitation is increasing in the northern latitudes, and average precipitation over the continental U.S. has increased, the southwestern U.S. (and other semi-tropical areas worldwide) appear to be tending towards reduced precipitation, which in the context of higher temperatures, results in lower soil moisture and a substantial effect on runoff in rivers (IPCC, 2007b). The observed trends are expected to worsen due to continued warming over the next century. Observed impacts on water resources from changes that are thought to have already occurred include increased surface temperatures and evaporation rates, increased global precipitation, an increased proportion of precipitation received as rain rather than snow, reduced snowpack, earlier and shorter runoff seasons, increased water temperatures and decreased water quality (IPCC, 2007a, b).

Additional effects on water resources result from sea level rise of approximately 10-20 cm since the 1890s (IPCC, 2007a)[5], an unprecedented rate of mountain glacier melting, seasonal vegetation emerging earlier in the spring and a longer period of photosynthesis, and decreasing snow and ice cover with earlier melting. Climate change is also likely to produce increases in intensity of extreme precipitation events (*e.g.*, floods, droughts, heat waves, violent storms) that could "exhaust the social buffers that underpin" various

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[5] According to the IPCC 2007 Fourth Assessment Report, sea level has risen an average of 1.8 mm per year over the period 1961-2003 (IPCC, 2007: 5).

economic systems such as farming; foster dynamic and interdependent consequences upon other resource systems (*e.g.*, fisheries, forests); and generate "synergistic" outcomes due to simultaneous multiple human impacts on environmental systems (*i.e.*, an agricultural region may be simultaneously stressed by degraded soil and changes in precipitation caused by climate change) (Homer-Dixon, 1999).

Studies have concluded that changes to runoff and stream flow would have considerable regional-scale consequences for economies as well as ecosystems, while effects on the latter are likely to be more severe (Milly *et al*., 2005). If elevated aridity in the western U.S is a natural response to climate warming, then any trend toward warmer temperatures in the future could lead to serious long-term increase in droughts - highlighting both the extreme vulnerability of the semi-arid west to anticipated precipitation deficits caused by global warming, and the need to better understand long term drought variability and its causes (Cook *et al*., 2004).

The impacts of climate variability are largely regional, making the spatial and temporal scale of information needs of decision-makers likewise regional. This is why we focus (section 3.2.3.1) on specific regional hazards, risks, and vulnerabilities of climate variability on water resources). TOGA and RISA studies focus on the regional scale consequences of changes to runoff and stream flow on economies as well as ecosystems (Milly *et al*., 2005).

3.2.3.1 Hazards, risks, and vulnerabilities of climate variability

A major purpose of decision-support tools is to reduce the risks, hazards, and vulnerabilities to water resources from seasonal to inter-annual climate variation, as well as to related resource systems, by generating climate science products and *translating* these products into forms useful to water resource managers (NRC, 2008). In general, what water managers need help in translating is *how* changes resulting from weather and seasonal to inter-annual climate variation can affect the functioning of the systems they manage. Numerous activities are subject to risk, hazard, and vulnerability, including fires, navigation, flooding, preservation of threatened or endangered species, and urban supplies. At the end of this section, we focus on three less visible but nonetheless important challenges: water quality, groundwater depletion, and energy production.

Despite their importance, hazard, risk, and vulnerability can be confusing concepts. A *hazard* is an event that is potentially damaging to people or to things they value. Floods and droughts are two common examples of hazards that affect water resources. *Risk* indicates the probability of a particular hazardous event occurring. Hence, while the hazard of drought is a concern to all water managers, drought risk varies considerably with physical geography, management context, infrastructure type and condition, and many other factors so that some water resource systems are more at-risk than others (Stoltman *et al*., 2004; Stern and Fineberg, 1996; Wilhite, 2004).

A related concept—vulnerability—is more complex and can cause further confusion[6]. Although experts dispute precisely what the term means, most agree that vulnerability considers the likelihood of harm to people or things they value and it entails a physical as

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[6] Much of this discussion on vulnerability is modified from Yarnal (in press). See also Polsky *et al*., and Dow *et al*., (in press) for definitions of vulnerability, especially in relation to water resource management.

well as social dimension (*e.g.*, Cutter 1996; Schröter *et al.*, 2005; Handmer, 2004). Physical vulnerability has to do with exposure to harmful events, while social vulnerability entails the factors affecting a system's sensitivity and capacity to respond to exposure. Moreover, experts accept some descriptions of vulnerability more readily than others. One commonly accepted description considers vulnerability to be a function of exposure, sensitivity, and adaptive capacity (Schneider and Sarukhan, 2001). Exposure is the degree to which people and the places or things they value, such as their water supply, are likely to be impacted by a hazardous event, such as a flood. The "things they value" include not only economic value and wealth but also cultural, spiritual, and personal values. This concept also refers to physical infrastructure (*e.g.*, water pipelines and dams) and social infrastructure (*e.g.*, water management associations and the Army Corps of Engineers). Valued components include intrinsic values like water quality and other outcomes of water supply availability such as economic vitality.

Sensitivity is the degree to which people and the things they value can be harmed by exposure. Some water resource systems, for example, are more sensitive than others when exposed to the same hazardous event. All other factors being equal, a water system with old infrastructure will be more sensitive to a flood or drought than one with new state-of-the-art infrastructure; in a century, the newer infrastructure will be considerably more sensitive to a hazardous event than it is today because of aging.

Adaptive capacity is the least explored and most controversial aspect of vulnerability. The understanding of adaptive capacity favored by the climate change research community is the degree to which people can mitigate the potential for harm—that is, reduce vulnerability—by taking action to reduce exposure or sensitivity, both before and after the hazardous event. The physical, social, economic, spiritual, and other resources they possess, including such resources as educational level and access to technology, determine the capacity to adapt. For instance, all things being equal, a community water system that has trained managers and operators with and up-to-date computer technology will be less vulnerable than a neighboring system with untrained volunteer operators and limited access to computer technology[7].

Some people or things they value can be highly vulnerable to low-impact events because of high sensitivity or low adaptive capacity. Others may be less vulnerable to high-impact events because of low sensitivity or high adaptive capacity. A hazardous event can result in a patchwork pattern of harm due to variation in vulnerability over short distances (Rygel *et al.*, 2006). Such variation means that preparing for or recovering from flood or drought may require different preparation and recovery efforts from system to system.

3.2.3.2 Perceptions of risk and vulnerability – Issue frames and risk communication

Much of the research on vulnerability of water resources to climate variability has focused on *physical vulnerability, i.e.*, the exposure of water resources and water resource systems to harmful events. Cutter *et al.*, (2002) and many others have noted, however,

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[7] A slightly different view of adaptive capacity favored by the hazards and disaster research community is that it consists of two subcomponents: coping capacity and resilience. The former is the ability of people and systems to endure the harm; the latter is the ability to bounce back after exposure to harmful events. In both cases, water resource systems can take measures to increase their ability to cope and recover, again depending on the physical, social, economic, spiritual, and other resources they possess or have access to.

that *social vulnerability*—the social factors that affect a system's sensitivity to exposure, and that influence its capacity to respond and adapt in order to lessen its exposure or sensitivity—can often be more important than physical vulnerability. Understanding the social dimensions of vulnerability and related risks is therefore crucial to determining how climate variation and change will affect water resources.

The perception of risk is perhaps the most-studied of the social factors relating to climate information and the management of water resources. At least three barriers stemming from their risk perceptions prevent managers from incorporating weather and climate information in their planning; each barrier has important implications for communicating climate information to resource managers and other stakeholders (Yarnal *et al.*, 2005). A fourth barrier relates to the underlying public perceptions of the severity of climate variability and change – and thus, implicit public support for policies and other actions that might impel managers to incorporate climate variability into decisions.

The first conceptual problem is that managers who find climate forecasts and projections to be reliable appear in some cases no more likely to use them than managers who find them to be unreliable (O'Connor *et al.*, 1999 and 2005)[8]. Managers most likely to use weather and climate information may have experienced weather and climate problems in the recent past – their heightened feelings of vulnerability are the result of negative

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[8] Based on findings from two surveys of community water system managers (N>400 in both studies) in Pennsylvania's Susquehanna River Basin. The second survey compared Pennsylvania community water system managers to their counterparts in South Carolina (N>250) and found that managers who find climate forecasts and projections to be reliable are no more likely to use them than are those who find them to be unreliable. Thus, unless managers feel vulnerable (vulnerability being a function of whether they have had adverse experience with weather or climate), they are statistically less likely to use climate forecasts.

experiences with weather or climate. 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 U.S. that we have studied[9]. Purveyors of weather and climate information may need to convince potential users that, despite the absence of recent adverse events, their water resources have suffered historically from—and therefore are vulnerable to—weather and climate.

The second barrier is that managers' perceptions about the usefulness of climate information varies not only with their exposure to adverse events, but also with the financial, regulatory, and management contexts of their decisions (Yarnal *et al.*, 2006; Dow *et al.*, 2007). The implication of this finding is that assessments of weather and climate vulnerability and of climate information needs must consider the institutional contexts of the resource systems and their managers. Achieving a better understanding of these contexts and of the informational needs of resource managers requires working with them directly.

The third barrier is that managers expect more difficulties to come from associated financial and water quality impacts of climate challenges associated with floods and droughts than from their ability to find water and supply it to their customers (Yarnal *et al.*, 2006; Dow *et al.*, 2007). Combined with the second barrier, the implication is that managers view weather and climate forecasts as more salient when put into the context of

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[9] Additional research on water system manager perceptions is needed, in regions with varying hydro-meteorological conditions, to discern if this finding holds true in other regions.

system operations and management needs. Presenting managers with a climate forecast for the United States showing the regional probability of below-normal precipitation for the coming season may not generate much interest; presenting those managers with a Palmer Drought Severity Index tailored to their state that suggests a possible drought watch, warning, or emergency will grab their attention (Carbone and Dow, 2005). The Southwest drought case discussed at the end of this section exemplifies how this salience worked to prod decision-makers to partner closely with water managers, and how the latter embraced climate knowledge in improving forecasts and demand estimates.

The fourth barrier is the way climate variability and change are framed as public policy issues, and how their risks are publically communicated. Regardless of the “actual” (if indeterminate) risks from climate change and variability, communication of the risks differs among scientific, political, and mass media elites – each systematically selecting aspects of these issues that are most relevant to their conception of risk, and thus, socially constructing and communicating its aspects most salient to a particular perspective. Thus, climate variability can be viewed as: a phenomenon characterized by probabilistic and consequential uncertainty (science); an issue that imposes fiduciary or legal responsibility on government (politics); or, a sequence of events that may lead to catastrophe unless immediate action is taken (Weingart *et al*., 2000).

Related to this is considerable research which suggests that when risk information – such as that characteristic of climate change or variability modeling and forecasting – is generated by select groups of experts who work in isolation from the public (or from decision-makers) – the risks presented may sometimes be viewed as untrustworthy or as not fully warranting a reposing of credibility. This research also suggests that building trust requires the use of public forums designed to facilitate open risk communication that is clear, succinct, and jargon-free, and that affords groups ample opportunity for questions, discussion, feedback, and reaction (*e.g.*, Freudenburg and Rursch, 1994; Papadakis, 1996; Jasanoff, 1987; Covello, Donovan and Slavick, 1990; NRC, 1989).

Research on these barriers also shows that personal experience has a powerful influence on perceptions of risk and vulnerability. They suggest that socioeconomic context is important in shaping perceptions, and, thus, the perceptions they produce are very specific. They also show that climate information providers must present their information in ways salient to potential users, necessitating customizing information for specific user groups. Finally, they suggest ways that perceptions can be changed.

Research on the influence of climate science on water management in western Australia (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. In this instance, affected western Australian states formed a partnership between state agencies representing economic interests affected by drought, national research institutions engaged in meteorology and hydrology modeling, and water managers. This partnership succeeded in influencing decision-making by: being sensitive to the needs of water managers for advice that was seen as "independent," in order to assure the public that water use restrictions were actually warranted; providing timely products and services to water users in an accessible way; and, directly involving water managers in the process of generating forecast information. The Georgia drought case (section 3.2.1) also illustrates the need to be sensitive and responsive to decision-maker needs. As in Australia, ensuring scientific "independence" facilitated the efforts of managers to consider climate science in their decisions, and helped ensure that climate forecast information was "localized" through presentation at public meetings and other fora so that residents could apply it to local decisions (Power *et al*., 2005). In sum, to overcome barriers to effective climate information communication, information must be specific to the sectoral context of managers and enhance their ability to realize management objectives threatened by weather and climate.

We now examine three particularly vulnerable areas to climate variability: water quality, groundwater depletion, and energy production. Following this discussion, we feature a case study on *drought responses in the Southwest U.S.* which is instructive about the role that perceived vulnerability has played in adaptive responses.

Water Quality: Assessing the vulnerability of water *quality* to climate variability and change is a particularly challenging task, not only because quality is a function – partly – of water quantity, but because of the myriad physical, chemical and biological transformations that non-persistent pollutants undergo in watersheds and water bodies. One of the most comprehensive literature reviews of the many ways in which water quality can be impacted by climate variability and change was undertaken by Murdoch *et al*. (2000). A synopsis of their major findings is depicted in Table 3.1.

Table 3.1 Water Quality, Climate Variability, and Climate Change*

Impacts associated with increases in temperature alone

- Decreased oxygen-holding capacity due to higher surface-water temperatures
- In arctic regions, the melting of ice and permafrost resulting in increased erosion, runoff, and *cooler* stream temperatures.
- Changes in the seasonal timing and degree of stratification of temperate lakes.
- Increased biomass productivity leading to increased rates of nutrient cycling, eutrophication and anoxia.
- Increased rates of chemical transformation and bioaccumulation of toxins.
- Changes in the rates of terrestrial nutrient cycling and the delivery of nutrients to surface waters.

Impacts associated with drought and decreases in streamflow

- Increased concentration of pollutants in streams, but decreased total export of those pollutants to the receiving water body.
- Decreases in the concentration of pollutants that are derived from the flushing of shallow soils and by erosion.
- Increases in the concentration of pollutants that are derived from deeper flow paths and from point sources.
- Decreased stratification and increased mixing in estuaries and other coastal waters, leading to decreased anoxia of bottom waters and decreased nutrient availability (and eutrophication).
- Movement of the freshwater-saltwater boundary up coastal river and intrusion of saltwater into coastal aquifers—impacts which would be exacerbated by sea-level rise.

Impacts associated with flooding and increases in streamflow

- In general, mitigation of the impacts associated with drought and decreases in streamflow
- Increases in the spatial extent of source areas for storm flow, leading to the increased flushing of pollutants from both point and non-point sources of pollution.
- Increased rates of erosion
- Increased rates of leaching of pollutants to groundwater
- Greater dilution of pollutants being countervailed by decreased rates of chemical and biological transformations owing to shorter residence times in soils, groundwater and surface waters.

* From Murdoch, *et. al.*, 2003

One conclusion to be drawn from Table 3.1 is that climate variability and change can have both negative and positive impacts on water quality. In general, warmer surface-water temperatures and lower flows tend to have a negative impact through decreases in dissolved oxygen (DO). In contrast, decreased flows to receiving water bodies—especially estuaries and coastal waters—can improve water quality, while increased flows can degrade water quality of the receiving water bodies, particularly if they carry increased total loads of nutrients and sediments. In healthy watersheds that are relatively unimpacted by disturbances to the natural vegetation cover, increased stream flow may increase water quality in the given stream by increasing dilution and DO.

Increased runoff and flooding in urbanized areas can lead to increased loads of nonpoint-source pollutants (Kirshen *et al.*, 2008) such as pesticides and fertilizer from landscaped areas, and point-source pollutants, from the overflow of combined sewer systems (Furlow 2006). In addition to increasing pesticide and nutrient loads (Chang *et al.*, 2001), increase in runoff from agricultural lands can lead to greater sediment loads from erosion and pathogens from animal waste (Dorner *et al.*, 2006). Loads of non-point pollution may be especially large during flooding if the latter occurs after a prolonged dry period in which pollutants have accumulated in the watershed.

The natural vegetation cover that is integral to a healthy watershed can be disturbed not only by land-use but by the stresses of climate extremes directly (*e.g.*, die off during drought and blow down of trees during tropical storms and hurricanes) and climate-sensitive disturbances indirectly (*e.g.*, pest infestations and wildfire). Climate change and variability can also lead to both adaptive human changes in land use and land cover that can impact water quality (*e.g.* for example changes in cropping patterns and fertilizer use), as well as to mitigative ones (*e.g.*, increased production of bio-fuels.) Hence there is a tight and complex coupling between land use changes and the potential impacts of climate variability and change on water quality.

Water quality can also be indirectly impacted by climate variability and change through changes in water-use. Withdrawals from streams and reservoirs may increase during a drought thereby degrading stream water quality through lower in-stream flows, polluted return flows, or both. Under the water rights system of the western United States, junior agricultural users may be cut off during drought thereby actually reducing return flows from agricultural lands, further lowering in-stream flows.

Perhaps the most common water-quality-related, climate-sensitive decisions undertaken by water-resource managers in the U.S. are in relation to the regulation of dams and reservoirs. Very often, reservoir releases are made to meet low flow requirements or maintain stream temperatures in downstream river reaches. Releases can also be made to improve water quality in downstream reservoirs, lakes and estuaries. Any operating decisions based on water quality usually occur in the context of the purpose(s) for which the dam and reservoir were constructed—typically some combination of hydropower, flood control, recreation, and storage for municipal supply and irrigation. Thus decision support systems for reservoir operation that include water quality usually do so in a multi-objective framework (*e.g.*, Westphal *et al.*, 2003).

Municipal water providers would also be expected to respond to water quality degradation forecasts. Some decisions they might undertake include stockpiling treatment chemicals, enhanced treatment levels, *ad hoc* sediment control, preparing to issue water quality alerts, increasing water quality monitoring, and securing alternative supplies (see Denver and New York City case studies in Miller and Yates (2005) for specific examples of climate-sensitive water-quality decision-making by water utilities). Managers of coastal resources such as fisheries and beaches also respond to water-quality forecasts.

Decision-making with regards to point sources will necessarily occur within the context of the permitting process under the National Pollution Discharge Elimination System and the in-stream water quality standards mandated by the Clean Water Act (Jacoby, 1990). Regulation of non-point sources falls entirely to the states and is therefore highly variable across the nation, but is in general done to a lesser degree than the regulation of point sources. Examples of actions—either voluntary or mandatory—that could be taken in response to a seasonal forecast of increased likelihood of flooding include: decreased fertilizer and pesticide application by farmers, measures for greater impoundment of runoff from feedlots, and protection of treatment ponds of all kinds from overflow.

Groundwater Depletion: The vulnerability of groundwater resources to climate variability and change is very much dependent on the hydrogeologic characteristics of the given aquifer. In general, the larger and deeper the aquifer, the less inter-annual climate variability will impact groundwater supplies. On the other hand, shallow aquifers that are hydraulically connected to surface waters tend to have shorter residence times and therefore respond more rapidly to climate variability. The vulnerability of such aquifers should be evaluated within the context of their *conjunctive use* with the surface waters.

Seasonal and inter-annual variability in water-table depths are a function of natural climate variability as well as variations in human exploitation of the resource. During periods of drought, water tables in unconfined aquifers may drop because of both reduced recharge and increased rates of pumping. Reduced hydraulic head at well intakes then decreases the potential yield of the given well or well field and increases the energy required for pumping. In extreme cases the water table may drop below the well intake, resulting in complete drying of the well. Municipal supply and irrigation wells tend to be developed in larger aquifers and at depths greater than wells supplying individual domestic users. Therefore, they are in general less vulnerable to interannual climate variability. In addition to the reduction in the yield of water-supply wells, drops in water table depths during droughts may result in the drying of springs and worsening of low flow conditions in streams. Greater withdrawals may result because of the shifting of usage from depleted surface waters, as well as because of an overall increase in demand due to lower precipitation and greater evapotranspirative demand from the land surface and water bodies. Morehouse *et al.* (2002) find this to be the case in southern Arizona. To the extent that climate change reduces surface water availability in the Southwest U.S. it can be anticipated that pressure on groundwater supplies will increase as a result.

When long-term average pumping rates exceed recharge rates the aquifer is said to be in *overdraft*. Zekster *et al*. (2005) identify four major impacts associated with groundwater extraction and overdraft: (1) reduction of stream flow and lake levels, (2) reduction or elimination of vegetation, (3) land subsidence, and (4) seawater intrusion. Additional impacts include changes in water quality due to pumping from different levels in aquifers and increased pumping costs. The karst Edwards Aquifer in south-central Texas, which supplies over 2 million people in the San Antonio metropolitan area, is identified by

Loáiciga (2003) as particularly vulnerable to climate change and variability because it is subject to highly variable rates of recharge and has undergone a steady increase in pumping rates over the last century. While groundwater overdraft is most common in the arid and semi-arid western U.S. (Roy *et al.*, 2005; Hurd *et al.*, 1999), it is not uncommon in the more humid East. Lyon *et al.* (2005) study the causes of the three drought emergencies that have been declared in Rockland County, New York since 1995. 78% of the county's public water supply is from small regional aquifers. Rather than increased frequency or intensity of meteorological or hydrologic drought, the authors attribute drought emergencies to development and population growth overtaxing local supplies and to failure of aging water-supply infrastructure. The former is an example of *demand-driven* drought. The Ipswich River Basin in northeast Massachusetts is another example in the east where population growth is taxing groundwater resources. Because of reliance on ground water and in-stream flows for municipal and industrial supply, summer low flows in the Ipswich frequently reach critical levels (Zarriello and Ries, 2000).

A few researchers have studied the potential application of seasonal-to-interannual climate forecasting to forecasting of groundwater recharge and its implications for water management. For example, using U.S. Geological Survey recharge estimates for the Edwards Aquifer from 1970-1996, Chen *et al.* (2005) find that recharge rates during La Niña years average about twice those during El Niño years. Using a stochastic dynamic programming model, they show that optimal water use and allocation decision-making based on ENSO forecasts could result in benefits of $1.1 to $3.5 million per year, mainly to agricultural users as a result of cropping decisions.

Hanson and Dettinger (2005) evaluate the seasonal-to-interannual predictability of groundwater levels in the Santa Clara-Calleguas Basin in coastal Southern California using a regional groundwater model (RGWM) as driven by a general circulation model (GCM). In agreement with other studies, they find a strong association between groundwater levels and the Pacific Decadal Oscillation (PDO) and ENSO. Their results lead them to conclude that coupled GCM-RGWM modeling is useful for planning and management purposes, particularly with regard to conjunctive use of surface and ground water and the prevention of saltwater intrusion. They also suggest that GCM forecast skill may at times be strong enough to predict groundwater levels. Forecasts of greater surface water availability may allow utilities to reduce reliance on over-utilized and expense groundwater resources. Bales *et al.* (2004) note that a forecast for heavy winter snowpack during the 1997/1998 El Niño led the Salt River Project in Arizona to reducing groundwater pumping in the fall and winter in favor of greater releases from reservoirs, thereby saving about $1 million.

Water Supply and Energy Production: Adequate water supplies are an essential part of energy production, from energy resource extraction (mining) to electric-power generation (DOE, 2006). Water withdrawals for cooling and scrubbing in thermoelectric generation now exceed those for agriculture in the U.S. (Hutson *et al.*, 2004), and this difference becomes much greater when hydropower uses are considered. Emerging energy sources, such as biofuels, synfuels, and hydrogen, will add to future water demands. Another new energy-related stress on water resource systems will be the integration of hydropower with other intermittent renewables, such as wind and solar, at the power system level. Hydropower is a very flexible, low-cost generating source that can be used to balance periods when other renewables are not available (*e.g.*, times of calm winds) and thus maintain electricity transmission reliability. As more non-hydro renewables are added to transmission grids, calls for fluctuating hydropower operation may become more frequent and economically valuable, and may compete with other water demands. If electricity demand increases by 50% in the next 25 years, as predicted by the Energy Information Administration, then energy-related water uses can also be expected to expand greatly – an ominous trend, especially where available water resources are already over allocated.

The Climate Change Science Program's Synthesis and Analysis Product 4.5 examined how climate change will affect the energy sector (CCSP, 2007). Some of the most direct effects of climate change on the energy sector will occur via water cycle processes (CCSP, 2007). For instance, changes in precipitation could affect prospects for hydropower, either positively or negatively at different times and locations. Increases in storm intensity could threaten further disruptions of the type experienced in 2005 with Hurricane Katrina. Also, average warming can be expected to increase energy needs for cooling and reduce those for warming. Concerns about climate change impacts could change perceptions and valuations of energy technology alternatives. Any or all of these types of effects could have very real meaning for energy policies, decisions, and institutions in the U.S., affecting discussions of courses of action and appropriate strategies for risk management and energy's water demands will change accordingly.

The energy-related decisions in water management are especially complex, because they usually involve both water quality and quantity aspects, and they often occur in the context of multiple-use river basins. The Tennessee Valley is a good example of these complexities. The Tennessee Valley Authority (TVA) operates an integrated power system of nuclear, coal, and hydropower projects along the full length of the Tennessee River. TVA's river operations include upstream storage reservoirs and mainstem locks and dams, most of which include hydropower facilities. Cold water is a valuable resource that is actively stored in the headwater reservoirs and routed through the river system to maximize cooling efficiencies of the downstream thermoelectric plants. Reservoir releases are continuously optimized to produce least-cost power throughout the river basin, with decision variables of both water quantity and quality.

Case Study: Southwest drought – climate variability, vulnerability, and water management

Introduction

Climate variability affects water supply and management in the Southwest through drought, snowpack runoff, groundwater recharge rates, floods, and temperature-driven water demand. The region sits at a climatic crossroads, at the southern edge of reliable winter storm tracks and at the northern edge of summer North American monsoon penetration (Sheppard *et al.*, 2002). This accident of geography, in addition to its continental location, drives the region's characteristic aridity. Regional geography also sets the region up for extreme vulnerability to subtle changes in atmospheric circulation and the impacts of temperature trends on snowmelt, evaporation, moisture stress on ecosystems, and urban water demands. The instrumental climate record provides ample evidence of persistent regional drought during the 1950s (Sheppard *et al.*, 2002; Goodrich and Ellis, 2006), and its influence on Colorado River runoff (USGS, 2004); in addition the impact of the 1950s drought on regional ecosystems is well documented (Allen and

Breshears, 1998; Swetnam and Betancourt, 1998). Moreover, it has been well known for close to a decade that interannual and multi-decade climate variations, forced by persistent patterns of ocean-atmosphere interaction, lead to sustained wet periods and severe sustained drought (Andrade and Sellers, 1988; D'Arrigo and Jacoby, 1991; Cayan and Webb, 1992; Meko *et al.*, 1995; Mantua *et al.*, 1997; Dettinger *et al.*, 1998).

Sources of vulnerability

Despite this wealth of information, interest in the effects of climate variability on southwestern water supplies has been limited by dependence on seemingly unlimited groundwater resources, which are largely buffered from inter-annual climate fluctuations. Evidence of extensive groundwater depletion in Arizona and New Mexico, from a combination of rapid urban expansion and sustained pumping for irrigated agriculture, has forced changes in water policy, resulting in a greater reliance on renewable surface water supplies (Holway, 2007; Anderson and Woosley, Jr., 2005; Jacobs and Holway, 2004). The distance between southwest urban water users and the sparsely-populated mountain sources of their surface water in Wyoming, Utah, and Colorado, reinforces a lack of interest in the impacts of climate variations on water supplies (Rango, 2006; Redmond, 2003). Until Southwest surface water supplies were substantially affected by sustained drought, beginning in the late 1990s, water management interest in climate variability seemed to be focused on the increased potential for flood damage during El Niño episodes (Rhodes *et al.*, 1984; Pagano *et al.*, 2001).

Observed vulnerability of Colorado River and Rio Grande water supplies to recent sustained drought, has generated profound interest in the effects of climate variability on water supplies and management (*e.g.*, Sonnett *et al.*, 2006). In addition, extensive drought-driven stand-replacing fires in Arizona and New Mexico watersheds have brought to light indirect impacts of climate variability on water quality and erosion (Neary *et al.*, 2005; Garcia *et al.*, 2005; Moody and Martin, 2001). Prompted by these recent dry spells and their impacts, New Mexico and Arizona developed their first drought plans (NMDTF, 2006; GDTF, 2004); in fact, repeated drought episodes, combined with lack of effective response, compelled New Mexico to twice revise its drought plan (NMDTF, 2006; note, these workshops are discussed in chapter 4 in case study H). Colorado River Basin water managers have commissioned tree-ring reconstructions of streamflow, in order to revise estimates of record droughts, and to improve streamflow forecast performance (Woodhouse and Lukas, 2006; Hirschboeck and Meko, 2005). These reconstructions and others (Woodhouse *et al.*, 2006; Meko *et al.*, 2007) reinforce concerns over surface water supply vulnerability, and the effects of climate variability and trends (*e.g.*, Cayan *et al.*, 2001; Stewart *et al.*, 2005) on streamflow.

Decision-support tools

Diagnostic studies of the associations between El Niño-Southern Oscillation (ENSO) teleconnections, multi-decade variations in the Pacific Ocean-atmosphere system, and Southwest climate demonstrate the potential predictability of seasonal climate and hydrology in the Southwest (Cayan *et al.*, 1999; Gutzler, *et al.*, 2002; Hartmann *et al.*, 2002; Hawkins *et al.*, 2002; Clark *et al.*, 2003; Brown and Comrie, 2004; Pool, 2005). ENSO teleconnections currently provide an additional source of information for ensemble streamflow predictions by the National Weather Service Colorado Basin River Forecast Center (Brandon *et al.*, 2005). The operational use of ENSO teleconnections as a primary driver in Rio Grande and Colorado River streamflow forecasting, however, is hampered by high variability (Dewalle *et al.*, 2003), and poor skill in the headwaters of these rivers (Udall and Hoerling, 2005; FET, 2008).

Future prospects

Current prospects for forecasting beyond ENSO time-scales, using multi-decade “regime shifts” (Mantua, 2004) and other information (McCabe *et al.*, 2004) are limited by lack of spatial resolution, the need for better understanding of land-atmosphere feedbacks, and global atmosphere-ocean interactions (Dole, 2003; Garfin *et al.*, 2007). Nevertheless, Colorado River and Rio Grande water managers, as well as managers of state departments of water resources have embraced the use of climate knowledge in improving forecasts, preparing for infrastructure enhancements, and estimating demand (Fulp, 2003; Shamir *et al.*, 2007). Partnerships among water managers, forecasters, and researchers hold the most promise for reducing water supply vulnerabilities and other water management risks through the incorporation of climate knowledge (Wallentine and Matthews, 2003).

3.2.4 Institutional Factors that Inhibit Information Use in Decision-Support Systems

In section 3.1, decision-support was defined as a process that generates climate science products *and* translates them into forms useful for decision-makers through dissemination and communication. This process, when successful, leads to institutional *transformation* (NRC, 2008). Five factors are cited as impediments to optimal use of decision-support systems' information: (1) lack of integration of systems with expert networks; (2) lack of institutional coordination; (3) insufficient stakeholder engagement in product development; (4) insufficient cross-disciplinary interaction; and, (5) expectations that the expected "payoff" from forecast use may be low. The *Red River flooding and flood management case* following this discussion exemplifies some of these problems, and promising efforts being expended in overcoming them.

Some researchers (Georgakakos *et al.*, 2005) note that because water management decisions are subject to gradual as well as rapid changes in data, information, technology, natural systems, uses, societal preferences, and stakeholder needs, effective decision-support processes regarding climate variability information must be adaptive and include self-assessment and improvement mechanisms in order to be kept current (Fig.3.3).

These assessment and improvement mechanisms, which produce transformation, are denoted by the upward-pointing feedback links shown in Figure 3.3, and begin with monitoring and evaluating the impacts of previous decisions. These evaluations ideally identify the need for improvements in the effectiveness of policy outcomes and/or legal and institutional frameworks. They also embrace assessments of the quality and completeness of the data and information generated by decision support systems and the validity and sufficiency of current knowledge. Using this framework as a point of departure makes discussing our five barriers to information use easier to comprehend.

First, the lack of integrated decision support systems and expert networks to support planning and management decisions means that decision-support experts and relevant climate information are often not available to decision-makers who would otherwise use this information. This lack of integration is due to several factors, including resources (*e.g.*, large agencies can better afford to support modeling efforts, consultants, and large-scale data management efforts than can smaller, less-well funded ones), organizational design (expert networks and support systems may not be well-integrated administratively from the vantage point of connecting information with users' "decision routines"), and opportunities for interaction between expert system designers and managers (the strength of communication networks to permit decisions and the information used for them to be challenged, adapted, or modified – and event to frame scientific questions). This challenge embraces users and producers of climate information, as well as the boundary organizations that can serve to translate information (Hartmann, 2001; National Research Council, 1996; Sarewitz and Pielke, 2007; NRC, 2008).

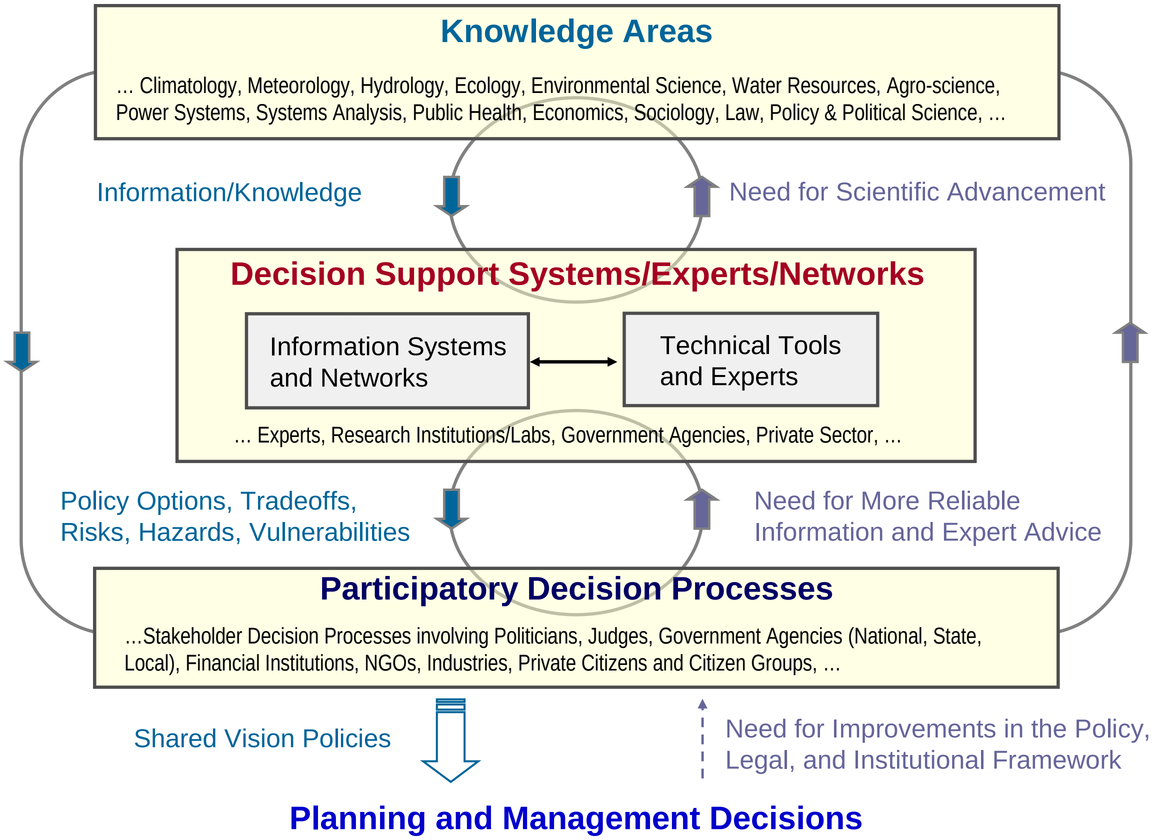

Figure 3.3 Water Resources Decision Processes

Second, the lack of coordination of institutions responsible for water resources management means that information generated by decision support networks must be communicated to various audiences in ways relevant to their roles and responsibilities (see section 3.2.1). Figure 3.3 – and discussion of the factors that led to development of better decision-support for flood hazard alleviation on the *Red River of the North* – reveal how extreme environmental conditions compounds the challenge in conveying information to different audiences given the dislocation and conflict that may arise.

Third, limited stakeholder participation and political influence in decision making processes – a problem discussed in chapter 1 in the context of the typically low public interest in water policy given the traditional, technical framing of water issues in American society – means that decision support products may not equitably penetrate to all relevant audiences. It also means that because water issues typically have low visibility for most of the public, the economic and environmental dislocations caused by climate variability events (*e.g.*, drought, floods), or even climate change, may exacerbate these inequities and draw sudden, sharp attention to the problems resulting from failure to properly integrate decision-support models and forecast tools, since disasters often strike disadvantaged populations disproportionately (*e.g.*, Hurricane Katrina on 2005) (Hartmann, *et al.*, 2002; Carbone and Dow, 2005; Subcommittee on Disaster Reduction, 2005; Leatherman and White, 2005).

Fourth, the lack of adequate cross-disciplinary interaction between science, engineering, public policy-making, and other knowledge and expertise sectors – across agencies, academic institutions, and private sector organizations – exacerbates these problems by making it difficult for decision support information providers to communicate with one another. It also exacerbates the problem of information overload by inhibiting use of incremental additional the sources and benefits of which are unclear to the user. In short, certain current decision support services are often narrowly focused, developed by over-specialized professionals working in a "stovepipe" system of communication within their organizations. While lack of integration can undermine the effectiveness of decision support tools and impede optimal decisions, it may create *opportunities* for design, development and use of effective decision support services.

Case Study: Red River of the North – Flooding and Water Management

Overview

This case study of climate variability information use focuses on flooding. Model outputs to better encompass seasonal precipitation, snowmelt and other factors, are increasingly being incorporated into operations decisions. Lessons include how to translate complex data into useable warning and alert systems for decision-making and, are deterministic forecasts an effective mechanism for communicating information for use water resource planning and management?

Background and Context

Flooding on the Red River of the North in April 1997 resulted in losses estimated to be four billion dollars. The Red River crested about 5 feet higher than the maximum flood height of 49 feet predicted by the NOAA National Weather Service North Central River Forecast Center (NCRFC) and the public outcry was that the NWS had failed to render a correct forecast (Pielke, 1999). With snowmelt as the dominant contributor to spring flooding, in February 1997, the NCRFC had issued an outlook assuming average temperatures and no additional precipitation for the next few months of 47.5 feet and a second outlook assuming average temperature and precipitation of 49 feet. In early April 1997, there was a record snowfall in the region, which neither outlook scenario anticipated. On April 14, 1997, a crest forecast of 50 feet was issued for East Grand Forks to occur in the April 19-22 time period; the river actually crested at 54 feet on April 19, breaching levees. A critical issue identified in the NOAA Office of Hydrology 1999 report is that the previous record flood stage height was 48.8 feet and NWS outlooks were based on extrapolations of the rating curves and there was no way to know that experimental rating curves being developed by the Army Corps of Engineers would have been more accurate.

Although the NWS outlooks contained a disclaimer that there was a 50 percent chance of the forecast stage height being equaled or exceeded, they provided no measure of uncertainty, and were interpreted as either an exact or maximum estimate of expected river crest height. The communication and interpretation of these rather precise flood outlooks, with no updates prior to mid-April, led local officials to assume they were prepared to deal with worse-case flood scenarios.

In fall 2006, the NRC released a report entitled "Completing the Forecast: Characterizing and Communicating Uncertainty for Better Decisions Using Weather and Climate Forecasts," noting that all predictions are inherently uncertain, and that effective communication of uncertainty information in weather, seasonal climate, and hydrological forecasts benefits users' decisions (*e.g.*, AMS, 2002; NRC, 2003b). The chaotic character of the atmosphere, coupled with inevitable inadequacies in observations and computer models, results in forecasts that always contain uncertainties. These uncertainties generally increase with forecast lead time and vary with weather situation and location. Uncertainty is thus a fundamental characteristic of weather, seasonal climate, and hydrological prediction, and no forecast is complete without a description of its uncertainty. Nonetheless, for decades, users of weather, seasonal climate, and hydrological (collectively called "hydrometeorological") forecasts have not provided complete information about the certainty or likelihood of a particular event.

Users became comfortable with single-valued forecasts and applied their own experience in determining how much confidence to place in the forecast. The evolution of the media as the primary vehicle for conveying weather information in the United States compounded this trend. The inclusion of uncertainty information in a forecast was viewed by some as a weakness or disadvantage instead of supporting a more scientifically sound and useful product.

Most forecast products from the weather and climate enterprise including those from the National Oceanic and Atmospheric Administration's (NOAA's) National Weather Service (NWS), continue this deterministic legacy. Decisions by users at all levels, but perhaps most critically those associated directly with protection of life and property, are being made without the benefit of knowing the uncertainties of the forecasts upon which they rely.

The complex hydraulic characteristics of the Red River of the North at Grand Forks and East Grand Forks were difficult to model with the NWS forecast methods in place during the April 1997 flood. This was the primary reason for the forecast error at that location.

Lessons learned

As the NWS RFC move to develop probabilistic forecasts, making sure that these climate variability forecasts are of use to decision makers will be critical. In this regard, a number of useful lessons emanate from this case, including: incorporating the latest rating curves for flooding to reflect recent data, conducting inter-agency review of available data that might be applicable to future flooding, moving toward real-time forecasting to the extent that dynamic routing procedures permit, warning decision-makers when a forecast exceeds the top of the rating curve – so that appropriate risk responses can be better contemplated, modeling the impact of temporary meltwater storage on flood hazard, supporting aerial snow cover surveys, incorporating user feedback to improve communication of forecast information, and conducting post-flooding technical assessment workshops among relevant agencies to assess how , and how effectively climate forecast information was used.

3.2.5 Reliability and Trustworthiness as Problems in Collaboration

The collaborative process for decision-support must be believable and trustworthy, with benefits to all engaged in it. One of the challenges in ensuring that information is perceived by decision-makers as trustworthy is that trust is the result of an interactive process of long-term, sustained effort by scientists to respond to, work with, and be sensitive to the needs of decision-makers and users, and of decision-makers becoming sensitive to – and informed about – the process of research. In part, trust is also a matter of the perceived credibility of the outcomes generated by decision-support systems.

The *Red River Flood warning case* (section 3.2.4) provides an excellent example of this problem – users are becoming comfortable with single-valued forecasts and applied their own experience in determining how much confidence to place in them. Coupled with the dependence on media as the tool for conveying weather information, the inclusion of uncertainty information in a forecast was viewed by some as a weakness, or disadvantage, in providing adequate warning of impending flood conditions, instead of an advantage in ensuring a more sound and useful forecast product.

Two other case vignettes featured below – *the Yakima and Upper Colorado River basins* – reveal the inverse dimensions of this problem. In effect, what happens if forecast information proves to be incorrect in its predictions, because predictions turned out to be technically-flawed, overly (or not sufficiently) conservative in their estimate of hazards, contradictory in the face of other information, or simply insufficiently sensitive to the audiences to whom forecasts were addressed?

As these cases suggest, given the different expectations and roles of scientists and decision-makers, what constitutes credible information to a scientist involved in climate prediction or evaluation may differ from what is considered credible information by a decision-maker. To a decision-maker forecast credibility is often unfortunately perceived as hinging upon its *certainty*. The more certain and exact a forecast, in other words, the more trusted it will be by decision-makers, and the more trustworthy the developers of that information will be perceived. As shown below, improvements in forecast interpretation and translation, communication and institutional capacity to adjust to changing information and its consequences, are essential to addressing this problem. A basic characteristic of much forecast information is that even the best forecasts rarely approach close to absolute certainty of prediction – we discuss this issue in section 3.3.2.

Case Study: Credibility and the Use of Climate Forecasts: Yakima River Basin/El Nino and Colorado Basin Case Studies

Yakima Case – Background

Establishing credibility is essential to fostering the use of climate forecasts in water management decisions. Although daily weather forecasts, relied upon by millions of people, can be extremely accurate the majority of the time, the most memorable forecasts are ones that miss the mark. This is especially true where operational risk tolerance is low, and the consequences are costly, such as the case of the Yakima River basin in 1977 (Glantz, 1982). At risk in this well documented case were the livelihoods of hundreds in a heavily irrigated agricultural region in the lee of Washington's Cascade Mountains.

The Problem – Relating Forecast to Allocation Decisions

Low snowpack in the late winter of 1977 prompted the U.S. Bureau of Reclamation to issue a forecast for summer runoff below the threshold established in a legal precedent (U.S. District Court, 1945), with the consequence that junior water rights holders would receive irrigation allocations as low as 6% of normal. In fact, the forecast issued by Reclamation was exceedingly conservative, well below runoff estimates by the National Weather Service and Soil Conservation Service. As noted by Glantz (1982), such low allocations "were noted by all observers as insufficient to protect perennial plants and trees from drought-related destruction. The loss of perennial plants and trees could mean a loss of production for up to eight years...[with] replacement costs…on the order of $7-$8000 per acre." Orchardists and others were forced to pursue expensive tactics to protect their investments, including well digging and deepening, leasing water rights, and transplanting crops. As it turned out, Reclamation's forecast suffered from technical deficiencies: calculations failed to include return flows and treated some reservoir storage as flow. In addition, changes in operations that differed from Reclamation policy within memory of Yakima basin farmers, and poor communications, left water users and the public frustrated and uninformed. The aftermath of the forecast, actions taken by agriculturalists, and subsequent investigations, resulted in animosity between senior and junior water rights holders, a loss of confidence in Reclamation, and lawsuits against the agency (Allen Orchards *et al.*, 1980).

Lessons

Glantz surmises that greater transparency in forecast methods, including issuing forecast confidence limits, better communication between agencies and the public, and consideration of the consequences of potential actions taken by users in the event of an erroneous forecast, would have improved the value of the forecast and the actions taken by Reclamation. Twenty years later, NOAA made a similar error when issuing a *perfectly confident* forecast of intensifying drought conditions for the Midwestern U.S. in 2000 (Changnon, 2002). Based on the forecasts, state water officials took actions they felt were needed anyway, and were not harmed by the lack of predictive skill and over-confidence in the forecast; however, agricultural producers may have sustained losses on the order of $1 billion, depending on the extent to which they employed particular pricing strategies. The upshot of this case of a failed forecast, once again, was increased skepticism in long-term climate forecasts and government institutions (Changnon, 2002).

El Nino and the Lower Colorado River basin

Background

Incorporating probabilistic climate forecast information into water management actions is more difficult than most climate researchers expect. Pagano *et al.* (2001; 2002) documented Arizona water and emergency management use of climate forecasts during the 1997-98 El Niño. Studies determined that issues in interpretation of the NOAA Climate Prediction Center's three category probabilistic forecasts presented a major barrier to forecast use (Pagano *et al.*, 2002). Despite the fact that the climate forecasts expressed a 50% probability of seasonal precipitation totals being in the wettest one-third of the 1961-90 distribution of precipitation, agencies prepared for an array of outcomes ranging from "business as usual," to 100% above normal precipitation. Some stakeholders, such as the U.S. Bureau of Reclamation, took action, by reducing reservoir levels, in order to avoid potential structural damage. The 1982-83 El Niño events threatened to undermine Glen Canyon dam (Rhodes *et al.*, 1984), and the memory of nearly losing the dam was still fresh in the Bureau's institutional memory.

Problem: Conflicting predictions

Another noteworthy barrier to forecast use was noted in the 1997-98 ENSO event, when ENSO-based climate forecasts contradicted historical regression-based water supply outlooks, and it became difficult for stakeholders to reconcile differences between the forecasts. One stakeholder noted "the man with two watches never knows what time it is" (Pagano *et al.*, 2001). Salt River Project (SRP), the major surface water manager in the Phoenix metropolitan area, relied upon in-house research and a history of tracking ENSO in their decision to shift from groundwater to surface water supplies in anticipation of the 1997-98 El Nino. However, SRP chose to [correctly] ignore forecasts for an East Pacific hurricane to track across their region of interest, based on a greater perceived margin of error in such forecasts (Pagano *et al.*, 2001). These examples resonate, in part, with the Yakima, 1977, case study, because they demonstrate decision-makers' ability to substitute their own judgment after previously relying on information with a poor track record or insufficient interpretation of potential outcomes.

Lessons

The Arizona examples illustrate the need for capacity building to promote understanding of uncertainty in forecasts, and to avoid the outcome of "once burned, twice shy," identified by Adeel and Glantz (2001), especially where agencies or operations have little capacity to recover from poor decisions based on "blown" (*i.e.*, failed) forecasts.

3.2.5.1 Other Reliability and Trustworthiness Issues: The Need for High Resolution Data

Research on the information needs of water decision-makers has increasingly brought attention to the fact that use of climate-related decision support tools is partly a function of the extent to which they can be made relevant to site-specific conditions and specific managerial resource needs, such as flow needs of aquatic species; the ability to forecast the impact of climate variability on orographic precipitation; and, the ability to fill in gaps in hydrologic monitoring (Proceedings of the Western Governors Association, 2007). In effect, proper integration of climate information into a water resource management context means developing high-resolution outputs able to be conveyed at the watershed level. It also means predicting changes in climate forecasts through the season and year, and regularly updating predictions. Specificity of forecast information can be as important as reliability for decision-making at the basin and watershed level (Proceedings of the Western Governors Association, 2007). The Southwest drought case discussed in section 3.2.3 illustrates this importance of information specificity in the context of water managers’ responses, particularly within the Colorado River basin.

3.2.5.2 Uncertainty in the regulatory process

While uncertainty is an inevitable part of the water resource decision-makers’ working environment, one source of lack of trust revolves around multi-level, multi-actor governance (see section 3.2 1). Shared governance for water management, coupled with the risk-averse character of traditional public works-type water agencies in particular, leads to situations where – while parties may act together for purposes of shared governance, “they may not have common goals or respond to common incentives” (NRC, 2008). Moreover, governance processes that cross various agencies, jurisdictions, and stakeholder interests are rarely straightforward, linear, or predictable because different actors are asked to provide information or resources peripheral to their central functions. In the absence of clear lines of authority, trust among actors and open lines of communication are essential (NRC, 2008).

As shown in chapter 4 in the discussion of the *South Florida water management* case, one regulatory change introduced to guide water release decisions helped increase certainty and trust in the water allocation and management process. The South Florida water management district uses a Water Supply and Environment (WSE) schedule for Lake Okeechobee that employs seasonal and multi-seasonal climate outlooks as guidance for regulatory releases (Obeysekera, 2007). The WSE schedule, in turn, uses ENSO and Atlantic Multi-decadal Oscillation (AMO; Enfield *et al.*, 2001) to estimate net inflow. While uncertainty in regional hydrology remains and is attributable to natural climatic variation, long-term global climate change, changes in precipitation patterns associated with drainage and development, and rainfall-runoff relationships altered by infrastructure change, the overall decision-making process is effective (Obeysekera, 2007).

3.2.5.3 Data problems

Lack of information about geographical and temporal variability in climate processes is one of the primary barriers to adoption and use of specific products. An important dimension of this lack of information problem – relevant to discussions of reliability and trust – revolves around how decision-makers make decisions when they have poor, no, or little data. Decision research from the social and behavioral sciences suggests that when faced with such problems, individual decision makers typically omit or ignore key elements of good decision processes. This leads to decisions that are often ineffective in bringing about the results they intended (Slovic, Fischhoff, and Lichtenstein, 1977). Furthermore, decision-makers, such as water managers responsible for making flow or allocation decisions based on incomplete forecast data, may respond to complex tasks by employing professional judgment to simplify them in ways that seem adequate to the problem at hand – sometimes adopting "heuristic rules" that presume different levels of risk are acceptable based on their prior familiarity with a similar set of problems (Tversky and Kahneman, 1974; Payne *et al*., 1993).

Decision-makers and the public also may respond to probabilistic information or questions involving uncertainty with predictable biases that ignore or distort important information (Kahneman, Slovic, and Tversky, 1982) or exclude alternative scenarios and possible decisions (*e.g.*, Keeney, 1992; NRC, 2005). El Nino/Southern Oscillation (ENSO) forecasts illustrate some of these problems[10]. Operational ENSO-based forecasts have only been made since the late 1980s – while ENSO-related products that provide information about which forecasts are likely to be most reliable for what time periods, in which areas – have an even shorter history. Thus, decision-maker experience in their use has been limited. Essential knowledge for informed use of ENSO forecasts includes

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[10] El Ninos tend to bring higher than average winter precipitation to the U.S. Southwest and Southeast while producing below-average precipitation in the Pacific Northwest. By contrast, La Ninas produce drier than average winter conditions in the Southeast and Southwest while increasing precipitation received in the Pacific Northwest.

understanding of the temporal and geographical domain of ENSO impacts. Yet making a decision based *only* on this information may expose a manager unnecessarily to consequences from that decision.

3.2.5.4 Changing environmental, social and economic conditions

Over the past three decades, a combination of economic changes (*e.g.*, reductions in federal spending for large water projects), environmental conditions (*e.g.*, demands for more non-structural measures to address water problems, and heightened emphasis on environmental restoration practices), and public demands for greater participation in water resource management have led to new approaches to water management. In Chapter 4 we address two of these approaches – adaptive management and integrated resource management. These approaches emphasize 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 peer-reviewed science (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). As shall be seen, these approaches place added demands on water managers regarding use of climate variability information, including adding new criteria to decision processes such as: managing in-stream flows/low flows, climate variability impacts on runoff, water quality, fisheries, and water uses.

3.2.5.5 Public perception and politics may outweigh facts and professional judgment

Climate variability and its risks are viewed through perceptual frames that affect not only decision-makers and other policy elites, but members of the general public. Socialization and varying levels of education contribute to a social construction of risk information that may lead the public to view extreme climate variability as a sequence of events that may lead to catastrophe unless immediate action is taken (Weingart *et al*., 2000). Extreme events may heighten the influence of sensational reporting, impede reliance upon professional judgment, lead to sensationalized reporting, and a sudden rise in public attention that may even shut off political discussion of the issue (Weingert *et al*., 2000: 7).

3.2.5.6 Decision-makers may be vulnerable when they use information

Decision-makers can lose their jobs, livelihoods, stature, or reputation by relying on forecasts that are wrong. Likewise, similar consequences can come about from untoward outcomes of decisions based on *correct* forecasts. This fact tends to make decision-makers risk aversive, and sometimes politically over-sensitive when using information, as noted in section 4. As Jacobs (2005) notes in her review, much has been written on the reasons why decision-makers and scientists rarely develop the types of relationships and information flows necessary for full integration of scientific knowledge into the decision-making process (Kirby, 2000; Pagano *et al*., 2001; Pulwarty and Melis, 2001 Rayner, Lach and Ingram, 2005). The primary reasons are problems with relevance (are the scientists asking and answering the right questions?), accessibility of findings (are the data and the associated value-added analysis available to and understandable by the decision-makers?), acceptability (are the findings seen as accurate and trustworthy?)

conclusions being drawn from the data (is the analysis adequate?) and context (are the findings useful given the constraints in the decision process?)

Scientists have some authority to overcome some of these sources of uncertainty that result in distrust (*e.g.*, proper diagnosis of a problem, providing adequate data, regularly updating forecasts, and drawing correct forecast conclusions). Other constraints on uncertainty, however, may be largely out of their control. Sensitivity to these sources of uncertainty – and their influence upon decision-makers, is important.

The *Yakima case*, discussed earlier in the context of forecast credibility, further illustrates how decision-makers can become vulnerable by relying on information that turns out to be inaccurate, or a poor predictor of future climate variability events. It underscores the need for trust-building mechanisms to be built into forecast translation projects, such as issuing forecast confidence limits, communicating better with the public and agencies, and considering the consequences of potential actions taken by users in the event of an erroneous forecast. The next section discusses particular challenges related to translation.

3.3 WHAT ARE THE CHALLENGES IN FOSTERING COLLABORATION BETWEEN SCIENTISTS AND DECISION-MAKERS?

This section examines problems in translating climate forecasts and hydrology information into integrated water management decisions, forecast communication, and operationalizing decision-support systems. This discussion focuses on translation of scientific information into forms useful and useable by decision-makers.

3.3.1 General Problems in Fostering Collaboration

The social and decision sciences have learned a great deal about the obstacles, impediments, and challenges in translating scientific information, especially forecasts, for decision makers generally, and resource managers in particular. Simply "doing research" on a problem does not assure in any way that the research results can or will contribute to solving a societal problem; likewise "more research does not necessarily lead to better decisions" (*e.g.*, Cash *et al*., 2003; Jacobs *et al*., 2005; Sarewitz and Pielke, 2007; Rayner, Lach, and Ingram, 2005). Among the principal reasons information may not be used by decision makers are the following:

The information may be viewed as irrelevant to the user or inappropriate to the decision context: While scientists' worldviews are strongly influenced and affected by the boundaries of their own research and disciplines, decision-makers' worldviews are conditioned by the "decision space" (Jacobs *et al*., 2005). Decision space refers to the range of realistic options available to a given decision maker to resolve a particular problem. While a new scientifically derived tool or source of information may have obvious applications when viewed from a theoretical perspective, a decision maker may be constrained from using these tools and information by external factors.

External constraints such as laws and regulations may limit the range of options available to the decision-maker: Policies, procedures, and precedents relevant to a given decision – including decisional rules and protocols, expectations imposed by decision makers through training and by peer and supervisory expectations, sufficiency of resources (*e.g.*, time and money) within organizations to properly integrate information and tools into decision-making, and the practicality of implementing various options prescribed by tools and/or information given the key questions the decision-maker must manage on a daily basis – are all factors that limit decision-makers use of information. These factors can also limit the range of options available to decision-makers.

Political scientists who study administrative organizations cite three principal ways the rule-making culture of administrative organizations hinders information use, ranging from the nature of policy "attentiveness" in administrative organizations in which cues awareness of alternatives are often driven by demands of elected officials instead of newly available information (*e.g.*, Kingdon, 1995), to organizational goals and objectives which often frame or restrict the flow of information and "feedback." Another set of reasons revolves around the nature of indirect commands within organizations – that evolve through trial and error. Over time, these commands take the form, of rules and protocols which guide and prescribe appropriate and inappropriate ways of using information in bureaucracies (Stone, 1997; Torgerson, 2005).

The following case, relating to the translation of drought information in the Southeastern U.S., describes the influence of institutional constraints on information use. In this instance, the problem of drought is nested within a larger regional water dispute among three states. By describing the challenges in incorporating drought and water shortage information into basin wide water planning – this case also helps clarify a number of salient problems faced by water managers working with complex information in a contentious political or legal context. In short, information usefulness is determined in part by social and political context or "robustness." To be "socially robust," information must be valid outside, as well as inside the laboratory where it is developed; and, involve an extended group of experts, including lay 'experts' (Gibbons, 1999).

Case Study: The Southeast Drought: Another Perspective on Water Problems in the Southeastern U.S.

Introduction and context

As mentioned earlier, drought risk consists of a hazard component (*e.g.*, lack of precipitation, along with direct and indirect effects on runoff, lake levels and other relevant parameters) and a vulnerability component. Some aspects of vulnerability include the condition of physical infrastructure, economics, awareness and preparedness, institutional capability and flexibility, policy, demography, access to technology (Wilhite *et al.*, 2000). Thus, there are clearly non-climatic factors that can enhance or decrease the likelihood of drought impacts. Laws, institutions, policies, procedures, precedents and regulations, for instance, may limit the range of options available to the decision-maker, even if armed with a perfect forecast.

In the case of the ongoing drought in the southeastern United States, the most recent episode (beginning in 2006 and intensifying in 2007, see Figure 3.1), impacts to agriculture, fisheries, and municipal water supplies were likely exacerbated by a lack of action on water resources compacts between Georgia, Alabama, and Florida (Feldman, 2007). The hazard component was continuously monitored at the state, regional, and national level by a variety of institutions, including state climatologists, the Southeast Regional Climate Center, the Southeast Climate Consortium, the USGS, the National Weather Service, the U.S. Drought Monitor and others. In some cases, clear decision points were specified by state drought plans (Steinemann and Cavalcanti, 2006; Georgia DNR, 2003). (Florida lacks a state drought plan.) During spring 2007, as record precipitation deficits mounted, water supplies declined, and drought impacts, including record-setting wildland fires accumulated (Georgia Forestry Commission, 2007). Georgia decision-makers faced the option of relying on a forecast for above-average Atlantic hurricane frequency, or taking more cautious, but decisive, action to stanch potentially critical water shortages. Public officials allowed water compacts to expire, because they could not agree on water allocation formulae; hence, unresolved conflicts regarding the relative priorities of upstream and downstream water users, such as streamflows intended to preserve endangered species and enrich coastal estuaries, versus reservoir holdings intended to drought-proof urban water uses, impeded the effective application of climate information to mitigate potential impacts.

The Apalachicola-Chattahoochee-Flint River basin compact negotiations

The Apalachicola-Chattahoochee-Flint (ACF) River Basin Compact was formed to address the growing demands for water in the region's largest city, Atlanta, while at the same time balancing off-stream demands of other users against in-stream needs to support fisheries and minimum flows for water quality (Hull, 2000). While the basin is rapidly urbanizing, farming – and the rural communities that depend upon it – remain important parts of the region's economy. Conflicts between Georgia, Florida, and Alabama over water rights in the basin began in the late 1800s. Today, metro Atlanta currently draws more than 400 million gallons of water per day from the river and discharges into it more than 300 million gallons of wastewater each day.

Following protracted drought in the region in the 1990s, decision-makers in Alabama, Florida, and Georgia dedicated themselves to avoiding lengthy and expensive litigation that likely would have led to a decision that would have pleased no one. In 1990, the three states began an 18-month negotiation process that resulted, first, in a *Letter of Agreement* (April, 1991) to address short term issues in the basin and then, in January 1992, a *Memorandum of Agreement* that, among other things, stated that the three states were in accord on the need for a study of the water needs of the three states. The three states' governors also agreed to initiate a comprehensive study by the Corps of Engineers (Kundell and Tetens, 1998).

At the conclusion of the 1998 compact summit chaired by former Representative Gingrich, the three states agreed to: protect federal regulatory discretion and water rights; assure public participation in allocation decisions; consider environmental impacts in allocation and, develop specific allocation numbers – in effect, guaranteeing volumes "at the state lines." Water allocation formulas were to be developed and agreed upon by December 31, 1998. However, negotiators for the three states requested at least a one-year extension of this deadline in November of 1998, and several extensions and requests for extensions have subsequently been granted over the past dozen years – often at the 11th hour of stalemated negotiations.

Opportunities for a breakthrough came in 2003. Georgia's chief negotiator claimed that the formulas posted by Georgia and Florida, while different, were similar enough to allow the former to "accept Florida's numbers (and to work to resolve language differences in the terms and conditions of the formula." Alabama representatives concurred that the numbers were workable and that differences could be resolved. Nonetheless, within days of this tentative settlement, negotiations broke off once again (Georgia Environmental Protection Division, 2002a). In August 2003, Governors Riley, Bush, and Perdue from Alabama, Florida, and Georgia, respectively, actually signed a memorandum of understanding detailing the principles for allocating water for the ACF over the next 40 years; however, as of this writing, Georgia has lost an appeal in the Appellate Court of the District of Columbia to withdraw as much water as it had planned to do – lending further uncertainty to this dispute (Goodman, 2008).

Policy impasse

Three issues appear to be paramount in the failure to reach accord. First, various demands imposed on the river system may be incompatible, such as protecting in-stream flow while permitting varied off-stream uses. Second, many of the prominent user conflicts facing the three states are really up- versus down-stream disputes. For example, Atlanta is a major user of the Chattahoochee. However, it is also a "headwaters" metropolis. The same water used by Atlanta for water supply and wastewater discharge is used by "upstreamers" for recreation and to provide shoreline amenities such as high lake levels for homes (true especially along the shoreline of Lake Lanier) – and provides downstream water supply to other communities. Without adequate drawdown from Lanier, for example, water supplies may be inadequate to provide for all of Atlanta's needs. Likewise, water quality may be severely degraded because of the inability to adequately dilute pollution discharges from point and non-point sources around Atlanta. This is especially true *if* in-stream water volumes decline due to growing off-stream demands.

Finally, the compact negotiating process itself lacks robustness – technically, the compact does not actually take effect *until* an allocation formula can be agreed upon. Thus, instead of agreeing on an institutional framework that can collect, analyze, translate, and use information to reach accord over allocation limits and water uses – the negotiations have been targeted on first determining a formula for allocation based on need (Feldman, 2007). As we have seen in the previous case on drought management in Georgia, climate forecast information is being used to enhance drought preparedness and impact mitigation. Nevertheless, as noted in that case, conservation measures in one state alone cannot mitigate region-wide problems affecting large, multi-state watersheds. The same holds true for regional water supply dispute-resolution. Until a cooperative decision-making platform emerges whereby regional climate forecast data can be used for conjoint drought planning, water allocation prescriptions, and incorporation of regional population and economic growth (not currently done on an individual state-level), effective use of decision-support information (i.e., transformation) will remain an elusive goal.

3.3.1.1 Researchers often develop products and tools that they believe will be useful, and make them available for use without verifying whether they are needed:

This is sometimes referred to as the "loading dock" phenomenon (Sarewitz and Pielke, 2005), and generally results from one-way communication, without sufficient evaluation of the needs of stakeholders. As seen below in the case of northeast *Brazil*, this challenge in integrating information and tools into decision-making is a problem endemic to all societies – but in the case of climate variability and water management is exacerbated by sufficiency of resources in developing nation contexts.

Case Study: Policy learning and seasonal climate forecasting application in Northeast Brazil – integrating information into decisions

Introduction

The story of climate variability forecast application in the state of Ceará (N.E. Brazil) chronicles a policy process in which managers have deployed seasonal climate forecasting experimentally for over ten years for water and agriculture, and have slowly learned different ways in which seasonal forecasting works, does not work, and could be improved for decision making (Lemos *et al.*, 2002; Lemos, 2003 Lemos and Oliveira, 2004; Taddei 2005; Pfaff *et al.*, 1999).

The *Hora de Plantar* ("Time to Plant") Program, begun in 1988, aimed at distributing high-quality, selected seed to poor subsistence farmers in Ceará and at maintaining a strict planting calendar to decrease rain-fed farmers sensitivity to climate variability (Lemos, 2003). In exchange for selected seeds, farmers "paid" back the government with grain harvested during the previous season or received credit to be paid the following year. The rationale for the program was to provide farmers with high quality seeds (corn, beans, rice, and cotton), but to distribute them only when planting conditions were appropriate. Because farmers tend to plant with the first rains (sometimes called the "pre-season") and often have to replant, the goal of this program was to use a simplified soil/climate model, developed by the state meteorology agency (FUNCEME) to orient farmers with regard to the actual onset of the rainy season (Andrade, 1995).

While the program was deemed a success (Golnaraghi and Kaul, 1995), a closer look revealed many drawbacks. First, it was plagued by a series of logistical and enforcement problems (transportation and storage of seed, lack of enough distribution centers, poor access to information and seeds by those most in need, fraud, outdate client lists, etc) (Lemos *et al.*, 1999). Second, local and lay knowledge accumulated for years to inform its design was initially ignored. Instead the program relied on a model of knowledge use that privileged the use of technical information imposed on the farmers in a exclusionary and insulated form that alienated stakeholders and hampered buying in from clients (Lemos, 2003). Third, farmers strongly resented *Hora de Plantar*'s planting calendar and its imposition over their own best judgment. Finally, there was the widespread perception among farmers (and confirmed by a few bank managers) that a "bad" forecast negatively affected the availability of rural credit (Lemos *et al.*, 1999). And while many of the reasons farmers disliked the program had little to do with climate forecasting, the overall perception was that FUNCEME was to blame for its negative impact on their livelihoods (Lemos *et al.,* 2002; Lemos, 2003; Meinke *et al.*, 2006). As a result, there was both a backlash against the program and a relative discredit of FUNCEME as a technical agency and of the forecast by association. The program is still active, although by 2002, the strict coupling of seed distribution and the planting calendar had been phased out (Lemos, 2003).

In 1992, as part of Ceará's modernizing government administration, and in response to a long period of drought, the state enacted Law 11.996 that defined its policy for water resources management. This new law created several levels of water management, including watershed Users' Commissions, Watershed Committees and a state level Water Resources Council. The law also defined the watershed as the planning unit of action; spelled out the instruments of allocation of water permits and fees for the use of water resources; and regulated further construction in the context of the watershed (Lemos and Oliveira, 2004; Formiga-Johnsson and Kemper, 2005; Pfaff *et al.*, 1999).

Innovation – Using Information More Effectively

One of the most innovative aspects of water reform in Ceará was creation of an interdisciplinary group within the state water management agency (COGERH) to develop and implement reforms. The inclusion of social and physical scientists within the agency allowed for the combination of ideas and technologies that critically affected the way the network of *técnicos* and their supporters went about implementing water reform in the state. From the start, COGERH sought to engage stakeholders, taking advantage of previous political and social organization within the different basins to create new water organizations (Lemos and Oliveira, 2005). In the Lower Jaguaribe-Banabuiú river basin, for example, the implementation of participatory councils went further than the suggested framework of River Basin Committees to include the Users Commission to negotiate water allocation among different users directly (Garjulli, 2001; Lemos and Oliveira, 2004; Taddei, 2005; Pfaff *et al.*, 1999). COGERH *técnicos* specifically created the Commission independently of the "official" state structure to emphasize their autonomy vis-à-vis the state (Lemos and Oliveira, 2005). This agenda openly challenged a pattern of exclusionary water policymaking prevalent in Ceará and was a substantial departure from the top-down, insulated manner of water allocation in the past (Lemos and Oliveira, 2004). The ability of these *técnicos* to implement the most innovative aspects of the Ceará reform can be explained partly by their insertion into policy networks that were instrumental in overcoming the opposition of more conservative sectors of the state apparatus and their supporters in the water user community (Lemos and Oliveira, 2004).

The role of knowledge in building adaptive capacity in the system was also important because it helped democratize decision-making. In Ceará, the organization of stakeholder councils and the effort to use technical knowledge, especially reservoir scenarios to inform water release, may have enhanced the system's adaptive capacity to climate variability as well as improved water resources sustainability (Formiga-Johnson and Kemper, 2005; Engle, 2007). In a recent evaluation of the role of governance institutions in influencing adaptive capacity building in two basins in NE Brazil (Lower Jaguaribe in Ceará and Pirapama in Pernambuco), Engle (2007) found that water reform played a critical role in increasing adaptive capacity across the two basins. And while the use of seasonal climate knowledge has been limited so far (the scenarios assume zero inflows from future rainfall), there is great potential that use of seasonal forecasts could affect several aspects of water management and use in the region and increase forecast value.

In the context of Ceará's Users Commissions, the advantages are twofold. First, by making simplified reservoir models available to users, COGERH is not only enhancing public knowledge about the river basin but also is crystallizing the idea of collective risk. While individual users may be willing to "free-ride", collective decision-making processes may be much more effective in curbing overuse. Second, information can play a critical role in democratization of decision-making at the river basin level by training users to make decisions, and dispelling the widespread distrust that has developed as a result of previous applications of climate information. Finally, the case suggests that incorporating social science into processes that are being designed to optimize the use of climate forecast tools in specific water management contexts can enhance outcomes by helping poorer communities better adapt to, and build capacity for managing climate variability impacts on water resources.

3.3.1.2 Information may not be available at the time it could be useful

It is well established in the climate science community that information must be timely in order to be useful to decision makers. This requires that researchers understand and be responsive to the time frames during the year for which specific types of decisions are made. Pulwarty and Melis (2001) and Ray and Webb (2000) have developed the concept of "decision calendars" in the context of the Western Water Assessment in Boulder, Colorado (see figure 3.4). Failure to provide information at a time when it can be inserted into the annual series of decisions made in managing water levels in reservoirs, for example, may result in the information losing virtually all of its value to the decision-maker. Likewise, decision-makers need to understand the types of predictions that can be made and tradeoffs between longer-term predictions of information at the local or regional scale and potential decreases in accuracy. They also need to help scientists in formulating research questions.

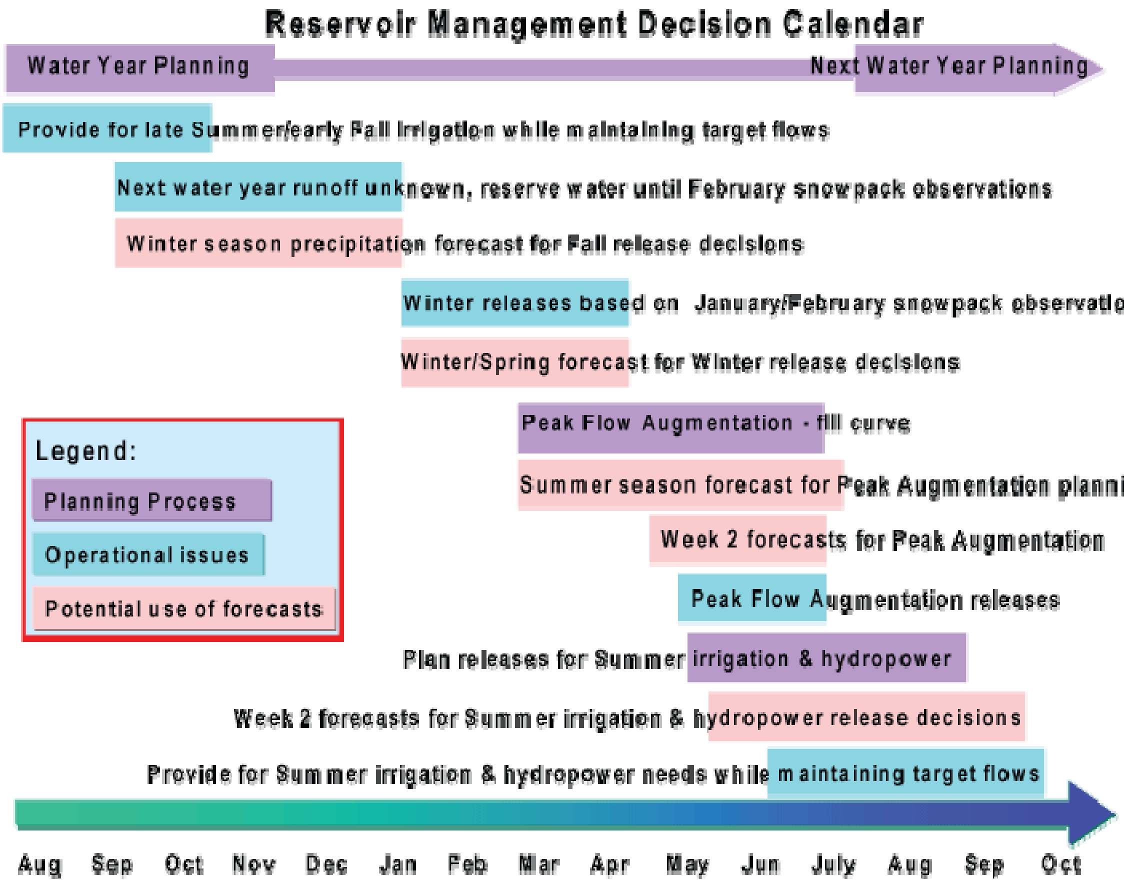

Figure 3.4 An example of a decision calendar for reservoir management planning. Shaded bars indicate the timing of information needs for planning and operational issues over the year. (Source: Ray and Webb, 2000)

The importance of leadership in initiating change cannot be overestimated (see chapter 4), and its importance in facilitating information exchange is also essential – particularly with regard to making connections with on-the-ground operational personnel and data managers are also important to facilitate information exchange. The presence of a “champion” within stakeholder groups or agencies may make the difference in successful integration of new information. Identifying people with leadership qualities and working through them will facilitate adoption of new applications and techniques. Recently hired water managers have been found to be more likely to take risks and deviate from precedent and "craft skills" that are unique to a particular water organization (Rayner, *et al.*, 2005).

The following vignette on the Advanced Hydrologic Prediction System (AHPS), established in 1997, exemplifies a conscious effort by the National Weather Service to respond to many of these chronic relational problems in a decisional context. AHPS is an effort to go beyond traditional river stage forecasts which are short-term (1-3 days), and are the product of applied historical weather data, stream gage data, channel cross-section data, water supply operations information, and hydrologic model characteristics representing large regions. It is an effort that has worked, in part, because it has many "champions" – however, questions remain over how extensively the initiative has been supported with resources.

AHPS responds directly to the problem of timely information availability by: trying to provide forecasting information sooner, particularly on potential flooding – linking it directly to local decision-makers, providing the information in a visual format; and, perhaps most of all, providing a dedicated program within NOAA (and the National Weather Service) that has the capacity to work directly with the user community and monitor ongoing, evolving decision-support needs.

Vignette: AHPS – Advantages over conventional forecasting

Applying the same hydrologic data used in current methods, AHPS also employs advanced hydrologic models with characteristics *specific to local watersheds and tributaries*. These advanced, localized hydrologic models increase forecast accuracy by 20% over existing models. Its outputs are more accurate, detailed, and visually oriented – and are able to provide decision-makers and the public with information on, among other variables: how high a river will rise, when it will reach its peak, where properties will be subject to flooding, and how long a flood event will continue. It is estimated that national implementation of AHPS will save at least $200 million per year in reduced flood losses and contribute an additional $400 million a year in economic benefits to water resource users (Advanced Hydrologic Prediction Service/ http://www.state.nj.us/drbc/Flood_Website/AHPS.htm).

Benefits and application

AHPS provides greater-detailed products in an improved format. Because it is visually oriented, it provides information in a format that is easier to understand and use by the general public as well as planners and scientists. AHPS depicts the magnitude and probability of hydrologic events, and gives users an idea of worst case scenario situations. Finally, AHPS provides forecasts farther in advance of current methods, allowing people additional time to protect themselves, their families, and their property from floods.

Following the Great Flood of 1993 in the Midwest, the Des Moines River Basin in Iowa was selected to be the first phase toward national implementation of AHPS. Residents, via the Internet, can now access interactive maps displaying flood forecast points. Selecting any of the flood forecast points on the map allows Internet users to obtain river stage forecast information for the point of interest. Available information includes: river flood stages, flow and volume probabilities, site maps, and damage tables projecting areas are likely to be subject to flooding.

Status and assessment

A 2006 MRC report found AHPS to be an ambitious climate forecast program that promises to provide services and products that are timely and necessary. However, it expressed concerns about “human and fiscal resources” – recommending that there is a need for trained hydrologic scientists to conduct hydrologic work in the NWS. Regarding fiscal resources, “the budgetary history and current allocation seem misaligned with the ambitious goals of the program.” Thus, the program’s goals and budget should be brought into closer alignment (NRC, 2006).

3.3.2 Scientists Need to Communicate Better and Decision-Makers Need a Better Understanding of Uncertainty – It Is Embedded In Science.

Discussions of uncertainty are at the center of many debates about forecast information and its usefulness. Uncertainties result from: the relevance and reliability of data, the appropriateness of theories used to structure analyses, the completeness of the specification of the problem, and in the “fit” between a forecast and the social and political matters of fact on the ground (NRC, 2005). While few would disagree that uncertainties are inevitable, there is less agreement as to how to improve ways of describing uncertainties in forecasts to provide widespread benefits (NRC, 2005).

It is important to recognize that expectations of certainty are unrealistic in regards to climate variability. Weather forecasts are only an estimate; the risk tolerance (sect. 3.2.3) of the public is often unrealistically low. As we have seen in multiple cases, one mistaken forecast (*e.g.*, the Yakima basin case) can have an impact out of proportion to the gravity of its consequences. Some starting points from the literature include helping decision-makers understand that uncertainty does not make a forecast scientifically flawed – only imperfect. Along these lines, decision-makers must understand the types of predictions that can be made and tradeoffs between predictions of information at the local or regional scale that are less accurate than larger scale predictions (Jacobs, 2005). They also need to help scientists formulate research questions that result in relevant decision support tools.

Second, uncertainty is not only inevitable, but necessary and desirable. It helps to advance and motivate scientific efforts to refine data, analysis, and forecaster skills; replicate research results; revise previous studies – especially through peer review discussed below, and improve observation. As one observer has noted, "(un)certainty is not the hallmark of bad science, it is the hallmark of honest science (when) we know enough to act is inherently a policy question, not a scientific one" (Brown, 1997).

Finally, the characterization of uncertainty should consider the decision relevance of different aspects of the uncertainties. Failure to appreciate such uncertainties results in poor decisions, misinterpretation of forecasts, and to diminish trust of analysts. Considerable work on uncertainty in environmental assessments and models make this topic ripe for progress (*e.g.*, National Research Council, 1999a).

Vignette: Interpreting Climate Forecasts – uncertainties and temporal variability

Introduction

Lack of information about geographical and temporal variability in climate processes is one of the primary barriers to adoption and use of specific products. El Niño/Southern Oscillation (ENSO) forecasts are an excellent example of this issue. While today El Niño and La Niña are part of the public vocabulary, operational ENSO-based forecasts have only been made since the late 1980s. Yet making a decision based only on the forecasts themselves may expose a manager to unanticipated consequences. Additional information can mitigate such risk. ENSO-related ancillary products, such as those illustrated in Figures 3.5 and 3.6, can provide information about which forecasts are likely to be most reliable for what time periods, in which areas. As Figure 3.5 shows, informed use of ENSO forecasts requires understanding of the temporal and geographical domain of ENSO impacts. El Niño (EN) events tend to bring higher than average winter precipitation to the U.S. Southwest and Southeast while producing below-average precipitation in the Pacific Northwest. La Niña (LN) events (*e.g.*, the El Nino Lower Colorado Basin case discussed earlier). Further, not all ENs or LNs are the same with regard to the amount of precipitation they produce. As illustrated in Figure 3.7, which provides this kind of information for Arizona, the EN phase of ENSO tends to produce above-average winter precipitation less dependably than the LN phase produces below-average winter precipitation.

An example of the value of combining ENSO forecasts with information about how ENSO tended to affect local systems arose during the 1997-98 ENSO event. In this case, the Arizona-based Salt River Project (SRP) made a series of decisions based on the 1997-98 EN forecast plus analysis of how ENs tended to affect their system of rivers and reservoirs. Knowing that ENs tended to produce larger streamflows late in the winter season, SRP managers reduced groundwater pumping in August 1997 in anticipation of a wet winter. Their contingency plan called for resuming groundwater pumping if increased streamflows did not materialize by March 1, 1998. As the winter progressed, it became apparent that the EN had produced a wet winter and plentiful water supplies in SRP’s reservoirs. The long-lead decision to defer groundwater pumping in this instance saved SRP $1 million (Pagano *et al*., 2001). SRP was uniquely well positioned to take this kind of risk because the managers making the decisions had the support of upper-level administrators and because the organization had unusually straightforward access to information. First, a National Weather Service office is co-located in the SRP administrative headquarters, and second, key decision makers had been interacting regularly with climate and hydrology experts associated with the NOAA-funded Climate Assessment for the Southwest (CLIMAS) project, located at the University of Arizona. Relatively few decision makers have this level of support for using climate forecasts and associated information. The absence of such support systems may increase managers’ exposure to risk, in turn generating a strong disincentive to use climate forecasts.

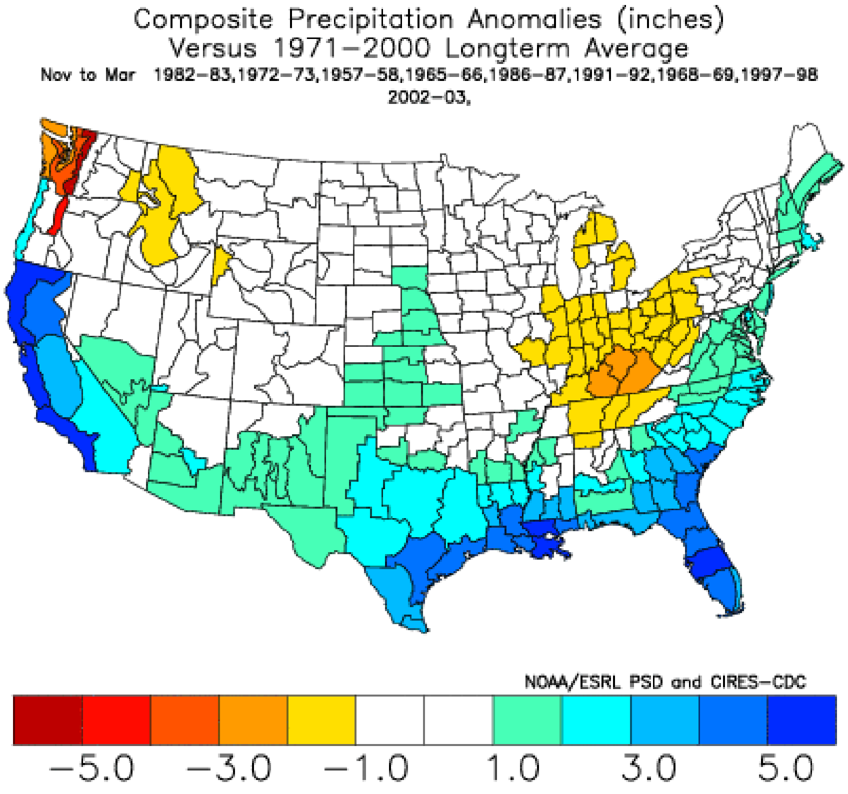

Figure 3.5 El Nino precipitation anomalies (in.). Source: NOAA Earth System Research Laboratory

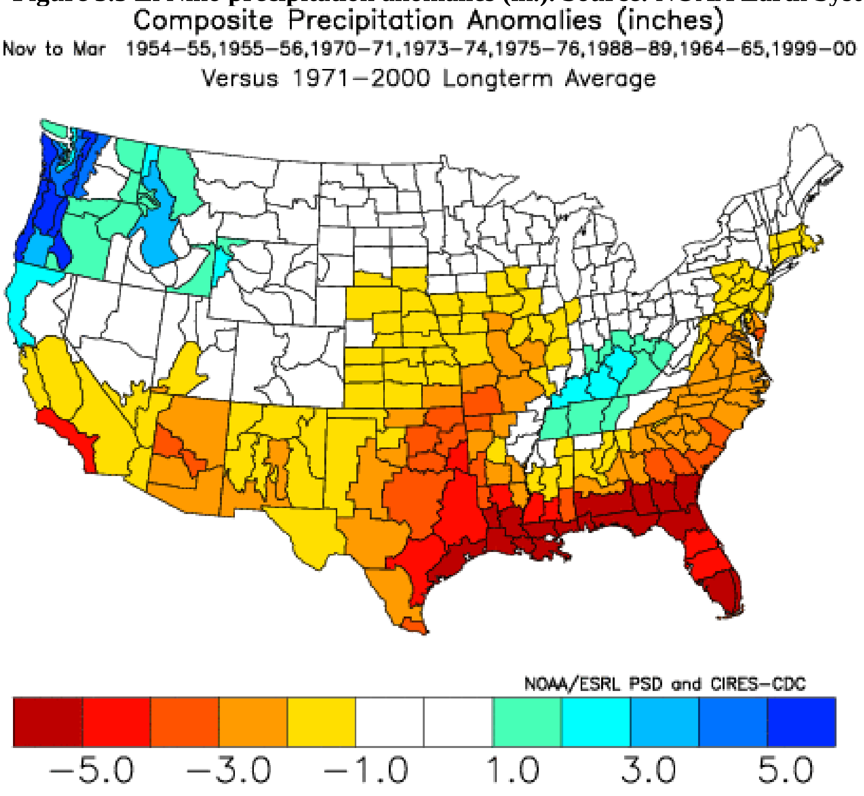

Figure 3.6 La Nina precipitation anomalies (in.). Source: NOAA Earth System Research Laboratory

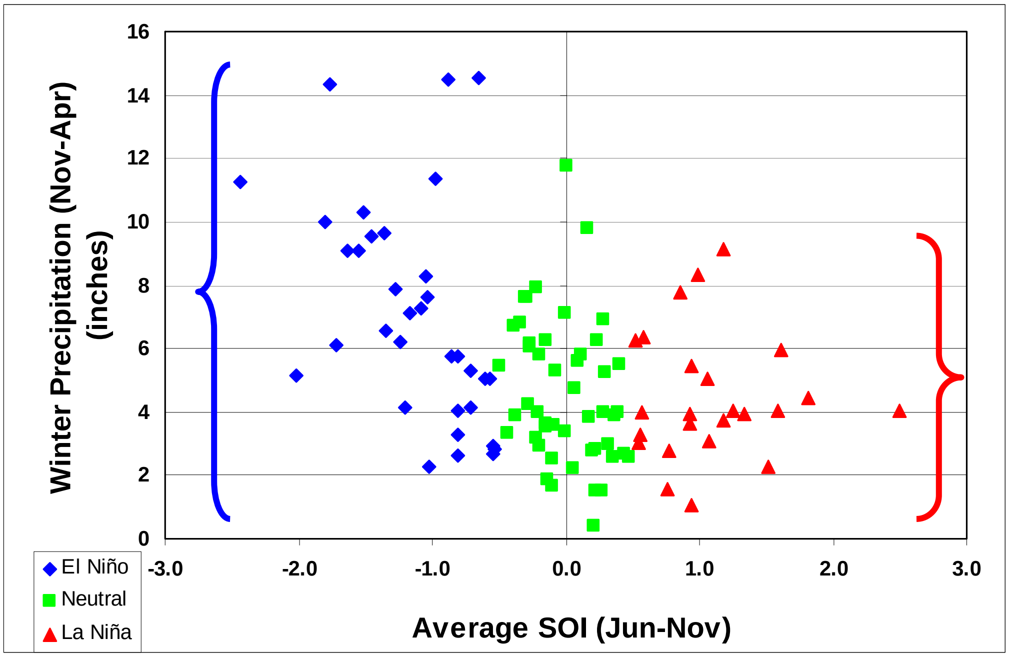

Figure 3.7 SOI (Jun-Nov) vs. Winter precipitation (Nov-Apr) for three phases of ENSO, El Nino, La Nina, and Neutral, for Arizona climate division 6. Note the greater variation in El Nino precipitation (blue) than in La Nina precipitation (red).

3.4 Summary

Decision-support systems are not often well integrated into policy networks to support planning and management, making it difficult to convey information. Among the reasons for this are a tendency toward institutional conservatism by water agencies, a decision-making climate that discourages innovation, lack of national-scale coordination of decisions, difficulties in providing support for decisions at varying spatial and temporal scales due to vast variability in "target audiences" for products, and growing recognition that rational choice models of information transfer are overly simplistic. The case of information use in response to Georgia's recent drought brings to light problems that students of water decision-making have long predicated about resistance to innovation.

The use of climate products requires special training or access to data that are not easily available, making access to decision-support products challenging. As we have seen, equity of access is partly a function of the fact that decision-support tools are intended to translate risks, hazards, and vulnerabilities to water resources from seasonal to inter-annual climate variation. These factors are themselves subject to socially constructed processes of trust, confidence, and perceived credibility, reliability and certainty. Sources of distrust – including uncertainties that lead to wrong forecasts are underscored in the Yakima and upper Colorado basin cases, while the problems of drought and water supply along the Colorado and Rio Grande basins in the Southwest illustrate the challenges afforded by reliability and uncertainty. For their part, institutional factors that inhibit access to decision-support service to, for example, prevent flooding, are revealed by the Red River of the North case. In some respects, the discussion of the Advanced Hydrologic Prediction System is the reverse of this discussion – by showing how scientists and decision-makers can design a dedicated decision-support enterprise that incorporates useful information, in near real time, and which utilizes platforms accessible to the public - and generates information salient to the public and local decision-makers.

Ensuring information relevance requires overcoming the barriers of over-specialization by encouraging inter-disciplinary collaboration in product and tool development. Decision-makers need to learn to appreciate the inevitability and desirability of forecast uncertainties regional scale on the one hand, and potential decreases in accuracy on the other. Scientists must understand both internal institutional impediments (agency rules and regulations) as well as external ones (*e.g.*, political-level conflicts over water allocation as exemplified in the Southeast U.S., asymmetries in information access in the case of Northeast Brazil) as factors constraining decision-support translation and decision transformation. Decision-makers and scientists must conjointly formulate research questions relevant to the spatial and temporal scale of problems the former manage and to ensure accessibility of information, while scientists should aim to generate findings viewed as accurate and trustworthy, contextually specific, and peer reviewed. While the nine cases discussed here have been useful and instructive, more generalizable findings are needed in order to develop a strong, theoretically-grounded understanding of processes that facilitate information dissemination, communication, use, and evaluation – and to predict effective methods of boundary spanning between decision-makers and information generators. We discuss this set of problems in Chapter 4.

CHAPTER 3 REFERENCES

Adeel, Z., and M. Glantz, 2001: El Niño of the Century: Once Burnt, Twice Shy? *Global Environmental Change*, **11**: 171–174.

Allen, C. D., and D. D. Breshears, 1998: Drought-induced shift of a forest-woodland ecotone: Rapid landscape response to climate variation. Proceedings of the National Academy of Sciences, **95,** 14839-42.

Allen Orchards H.F., et al., Elbert B. Schinmann, et al.,R.E. Redman & Sons, Inc., Appellants,v.The UNITED STATES, Appellee. United States Court of Appeals, Federal Circuit. - 749 F.2d 1571 Dec. 10, 1984

Anderson, M.T. and L.H. Woosley, Jr., 2005: Water Availability for the Western United States – Key Scientific Challenges. *U.S. Geological Survey Circular*, 1261, 85 p.

Andrade, E.R., and W.D. Sellers, 1988: El Niño and its effect on precipitation in Arizona and Western New Mexico. *Journal of Climate*, **8**, 403-410.

Andrade, F.C., 1995: Modelo de Umidade do Solo para Atividades Agrícolas: Teoria e Prática. Fortaleza: FUNCEME.

Annear, T., I. Chisholm, H. Beecher, A. Locke, P. Aarrestad, N. Burkhardt, C. Comer, C. Estes, J. Hunt, R. Jacobson, G. Jobsis, J. Kaufman, J. Marshall, K. Mayes, C. Stalnaker, and R. Wentworth, 2002: *Instream Flows for Riverine Resource Stewardship.* Instream Flow Council.

Bales, R.C., D.M. Liverman, and B.J. Morehouse, 2004: Integrated Assessment as a Step Toward Reducing Climate Vulnerability in the Southwestern United States. *Bulletin of the American Meteorological Society*, **85**, 1727–1734.

Ban, R.J., 2006: Completing the Forecast: Characterizing and Communicating Uncertainty for Better Decisions Using Weather and Climate Forecasts. *National Research Council Committee on Estimating and Communicating Uncertainty in Weather and Climate Forecasts.* 124 pages.

Bormann, B.T., P.G. Cunningham, M.H. Brookes, V.W. Maning, and M.W. Collopy, 1993: *Adaptive Ecosystem Management in the Pacific Northwest.* USDA Forest Service.

Brandon, D., B. Udall, and J. Lowrey, 2005: An Overview of NOAA's Colorado Basin River Forecast Center. In *Colorado River Basin Climate: Paleo, Present, Future,* pp. 30-35. http://wwa.colorado.edu/resources/colorado_river/

Brown, G., 1997: Environmental Science Under Siege in the U.S. Congress. *Environment*, 39, 13-30.

Brown, D.P., and A.C. Comrie, 2004: A winter precipitation 'dipole' in the western United States associated with multidecadal ENSO variability. *Geophysical Research Letters*, **31**(L09203).

Cairo, R.A., 1997: Dealing with Interstate Water Issues: The Federal Interstate Compact Experience, in Richard E. Just and Sinaia Netanyahu (eds.) *Conflict and Cooperation on Trans-Boundary Water Resources.* Boston: Kluwer.

Carbone, G.J., and K. Dow, 2005: Water resource management and drought forecasts in South Carolina. *Journal American Water Resources Association*, **4**, 44-155.

Cash, D.W., W.C. Clark, F. Alcock, N.M. Dickson, N. Eckley, D.H. Guston, J. Jager, and R.B.H. Mitchell, 2003: Knowledge Systems for Sustainable Development. Proceedings of the National Academy of Science – Science and Technology for Sustainable Development 100: 8086-8091.

Cayan, D.R., K.T. Redmond, and L.G. Riddle, 1999: ENSO and hydrologic extremes in the western United States. *Journal of Climate*, **12**, 2881– 2893.

Cayan, D.R., S.A. Kammerdiener *et al*., 2001: Changes in the Onset of Spring in the Western United States. *Bulletin of the American Meteorological Society*, 399-415.

Cayan, D.R., and R.H. Webb, 1992: El Niño/Southern Oscillation and Streamflow in the Western United States. Historical and Paleoclimate Aspects of the Southern

Oscillation. H. F. Diaz and V. Markgraf (eds), Cambridge University Press: 29-68.

CCSP (Climate Change Science Program), 2007: Effects of climate change on energy production and use in the United States. U.S. Department of Energy, Washington, DC. <http://www.ornl.gov/sci/sap_4.5/energy_impacts/team.shtml>

Chang, H., B.M. Evans, and D.R. Easterling, 2001: Potential effects of climate change on surface-water quality in North America. *Journal of the American Water Resources Association*, **37(4)**, 973-985.

Changnon, S.A., 2002: Impacts of the Midwestern Drought Forecasts of 2000. *Journal of Applied Meteorology*, **41**, 1042-1052.

Chen, C.C., D. Gillig, B.A. McCarl, and R.L. Williams, 2005: ENSO Impacts on Regional Water Management: A Case Study of the Edwards Aquifer Region. *Climate Research*, **28(2)**, 175-182.

Clark, M.P., L.E. Hay, G.J. McCabe, G.H. Leavesley, M.C. Serreze, and R.L. Wilby, 2003: The use of weather and climate information in management of water resources in the western United States. In: Lewis, W.M. (Ed.) *Water and Climate in the Western United States*, University Press of Colorado, 294pp.

Cody, B.A., 1999: Western Water Resource Issues: A Congressional Research Service Brief for Congress. Washington, D.C.: *Congressional Research Service*, March 18.

Cook, E.R., C.A. Woodhouse, C.M. Eakin, and D.M. Meko, 2004: Long-Term Aridity Changes in the Western United States. *Science 5*, **306(5698)**, 1015-1018.

Cortner, H.A., and M.A. Moote, 1994: Setting the Political Agenda: Paradigmatic Shifts in Land and Water Policy, pp. 365-377, in R.E. Grumbine, ed., *Environmental Policy and Biodiversity*. Washington, D.C.: Island Press.

Covello, V., E. Donovan, and J.E. Slavick, 1990: Community Outreach. Washington, D.C.: Chemical Manufacturers Association.

Cutter, S.L., 1996: Vulnerability to environmental hazards. *Progress in Human Geography*, **20**, 529-39.

Cutter, S.L., B.J. Boruff, and W.L. Shirley, 2002: Social vulnerability to environmental hazards. *Social Science Quarterly*, **84**, 242-261.

D'Arrigo, R.D., and G.C. Jacoby, 1991: A 1000-year record of winter precipitation from northwestern New Mexico, USA: a reconstruction from tree-rings and its relation to El Niño and the Southern Oscillation. *The Holocene*, **1(2)**, 95-101.

Dettinger, M.D., D.R. Cayan, H.F. Diaz, and D.M. Meko, 1998: North-south precipitation patterns in western North America on interannual-to-decadal timescales. *Journal of Climate*, **11**, 3095-3111.

Dewalle, D., J. Eismeier, and A. Rango, 2003: Early forecasts of snowmelt runoff using SNOTEL data in the upper Rio Grande Basin. In: *Proceedings of the Western Snow Conference,* April 21-25, 2003, Scottsdale, Arizona. p. 17-22.

DOE (U.S. Department of Energy), 2006: Energy Demands on Water Resources. Report to Congress on the Interdependency of Energy and Water. Washington, DC. <http://www.sandia.gov/energy-water/congress_report.htm>

Dole, R.M., 2003: Predicting Climate Variations in the American West: What Are Our Prospects? In William M. Lewis, Jr. (ed.), *Water and Climate in the Western United States*. Boulder, CO: The University Press of Colorado.

Dorner, S.M., W.B. Anderson, R.M. Slawson, N. Kouwen, and P.M. Huck, 2006: Hydrologic Modeling of Pathogen Fate and Transport. *Environmental Science and Technology*, **40(15),** 4746-4753.

Dow, K., R.E. O'Connor, B.Yarnal, G.J. Carbone, and C.L. Jocoy, 2007: Why Worry? Community water system managers' perceptions of climate vulnerability. *Global Environmental Change*, **17**, 228-237.

(**DRBC**) Delaware River Basin Commission, 1998: *Annual Report 1997*. West Trenton, New Jersey: DRBC.

Enfield, D.B., A.M. Nunez, and P.J. Trimble, 2001: The AMO and its Relationship to Rainfall and River Flow in the Continental U.S. *Geophysical Research Letters*, **28,** 2077-2080.

Engle, N.L., 2007: Adaptive capacity of water management to climate change in Brazil: A case study analysis of the Baixo Jaguaribe and Pirapama river basins. Master's thesis, University of Michigan, United States.

Feldman, D.L., 2007: Water Policy for Sustainable Development. Baltimore, MD: Johns Hopkins University Press.

Feldman, D.L., 1995: Water Resources Management: In Search of an Environmental Ethic, Baltimore, Maryland: Johns Hopkins University Press.

FET (Forecast Evaluation Tool), 2008; accessed 1-27-2008. <http://fet.hwr.arizona.edu/ForecastEvaluationTool/>

Formiga-Johnsson R.M., and K.E. Kemper, 2005: Institutional and policy analysis of river basin management – the Jaguaribe River Basin, Ceará, Brazil. World Bank Policy Research Working Paper 3649, June 2005,Washington, D.C.

Freudenburg, W.R., and J.A. Rursch, 1994: The Risks of putting the Numbers in Context. *Risk Analysis*, **14(6)**, 949-958.

Fulp, T., 2003: Management of Colorado River Resources. In William M. Lewis, Jr. (ed.), Water and Climate in the Western United States. Boulder, CO: The University Press of Colorado, pp. 143-152.

Furlow, J., 2006: The future ain't what it used to be; climate change and water resources management. *Water Resources IMPACT*, **8(5)**, 5-7.

Garcia, P., P.F. Folliott, D.G. Neary, 2005: Soil erosion following the Rodeo-Chediski wildfire: an initial assessment. *Hydrology and Water Resources in Arizona and the Southwest*, **34**, 51-56.

Garfin, G., M.A. Crimmins, and K.L. Jacobs, 2007: Drought, Climate Variability, and Implications for Water Supply. In B. Colby and K. Jacobs (eds.) Arizona Water Policy: Management Innovations in an Urbanizing Arid Region. Washington, DC: *Resources for the Future*, pp. 61-78.

Garrick, D., K. Jacobs, and G. Garfin, 2006: "Decision Making Under Uncertainty: Shortage, Stakeholders, and Modeling in the Colorado River Basin," submitted to *Journal of the American Water Resources Association,* March.

Garjulli, R., 2001: Experiência de Gestão Participativa de Recursos Hídricos: a Caso do Ceará. In: Alves RFF, de Carvalho GBB (eds) Experiências de Gestão dos Recursos Hídricos. MMA/ANA, Brasília.

Georgia Forestry Commission 2007: Georgia Wildfires of 2007 Summary of Facts and Costs for Recovery <http://www.gfc.state.ga.us/GFCNews/CFI.cfm> accessed 1-29-08

Georgia Environmental Protection Division, Department of Natural Resources 2002a: *Progress on Interstate Water Compact.* Atlanta: Georgia DNR, January 16.

GDTF (Governor's Drought Task Force), 2004: Arizona Drought Preparedness Plan: Operational Drought Plan. Phoenix: Arizona Department of Water Resources, 107 p. <http://www.azwater.gov/dwr/drought/ADPPlan.html>

Georgakakos, A., 2006a: Decision-Support Systems for Integrated Water Resources Management with an Application to the Nile Basin. Chapter 6 in Topics on

System Analysis and Integrated Water Resources Management, eds. A. Castelletti and R. Soncini-Sessa, Elsevier.

Georgakakos, K. P., N.E. Graham, T.M. Carpenter, A.P. Georgakakos, and H. Yao, 2005: Integrating climate-hydrology forecasts and multi-objective reservoir management for Northern California. *EOS*, **86(12)**, 122-127.

Georgia DNR (Department of Natural Resources), 2003: Georgia Drought Management Plan. 23 p., accessed 1-29-08. <http://www.gaepd.org/Files_PDF/gaenviron/drought/drought_mgmtplan_2003.pdf>

Gibbons, M., 1999: Science's new social contract with society. *Nature* 402, C81–C84 (Supplemental).

Gillilan, D., and T.C. Brown, 1997: Instream Flow Protection: Seeking a Balance in Western Water Use. Washington, D.C.: Island Press.

Glantz, M., 1982: Consequences and responsibilities in drought forecasting: the case of the Yakima, 1977. *Water Resources Research*, **18**, 3-13.

Gleick, P.H., D.B. Adams *et.al*., 2000: Water: The Potential Consequences of Climate Variability and Change for the Water Resources of the United States. *Report of the Water Sector Assessment Team - National Assessment of the Potential Consequences of Climate Change.* U.S. Global Change Research Program. Oakland, CA: Prepared by the Pacific Institute for Studies in Development, Environment, and Security, September.

Golnaraghi, M, and R. Kaul, 1995: The Science of Policymaking: Responding to El Nino. *Environment*, **37(4)**, 16-44.

Goodman, B., 2008: Georgia Loses Federal Case in a Dispute About water, New York Times, February 6. <http://www.nytimes.come/2008/02/06/us/06water.html?ei=5070&en=5>

Goodrich, G.B., A.W. Ellis, 2006: Climatological Drought in Arizona: An Analysis of Indicators for Guiding the Governor's Drought Task Force. *Professional Geographer*, **58(4)**, 460–469.

Gunaji, N.N., 1995: Anatomy of the Extraordinary Drought at the U.S.- Mexico Border, pp. 139 – 148. In *Management of Water Resources in North America III – Anticipating the 21st Century*, edited by Nathan Buras. Proceedings of the Engineering Foundation Conference. New York: American Society of Civil Engineers.

Gutzler, D.S., D.M. Kann *et al*., 2002: Modulation of ENSO-Based Long-Lead Outlooks of Southwestern U.S. Winter Precipitation by the Pacific Decadal Oscillation. *Weather and Forecasting*, **17**, 1163-72.

Handmer, J., 2004: Global Flooding, pp. 87-106, in J. P. Stoltman, J. Lidstone, and Lisa M. DeChano, eds. *International Perspectives on Natural Disasters: Occurrence, Mitigation, and Consequences.* Dordrecht, Netherlands: Kluwer Academic Publishers.

Hanson, R.T. and Dettinger, M.D., 2005: Ground-water/surface-water responses to global climate simulations, Santa Clara-Calleguas basin, Ventura County, California, 1950-93: *Journal of the American Water Resources Association*, **43**, p. 517-536.

Hartig, J. H., D.P. Dodge, L. Lovett-Doust, and K. Fuller, 1992: Identifying the Critical Path and Building Coalitions for Restoring Degraded Areas of the Great Lakes, pp. 823-830, in *Water Resources Planning and Management: Saving a Threatened Resource.* New York: Conference on Water Resources Planning and Management, ASCE.

Hartmann, H., 2001: Stakeholder Driven Research in a Hydroclimatic Context, Dissertation, Dept. of Hydrology and Water Resources, University of Arizona.

Hartmann, H.C., T.C. Pagano, S. Sorooshian, and R. Bales, 2002: Confidence Builders: Evaluating Seasonal Climate Forecasts from User Perspectives. *Bulletin of the American Meteorological Society,* 683-698.

Hawkins, T.W., A.W. Ellis, J.A. Skindlov, and D. Reigle, 2002: Intra-annual Analysis of the North American Snow Cover-Monsoon Teleconnection: Seasonal Forecasting Utility. *Journal of Climate*, **15**, 1743-1753.

Hayes, M., O. Wilhelmi, and C. Knutson. 2004: Reducing drought risk: Bridging theory and practice. Natural Hazards Review, 5(2): 106-113.

Higgins, R.W., Y. Chen, and A.V. Douglass, 1999: Internannual Variability of the North American Warm Season Precipitation Regime. Journal of Climate, 12(3), 653-680.

Hirschboeck, K.K., and D.M. Meko, 2005: A Tree-Ring Based Assessment of Synchronous Extreme Streamflow Episodes in the Upper Colorado & Salt-Verde-Tonto River Basins. Tucson, AZ: University of Arizona Laboratory of Tree-Ring Research. <http://fpcluster.ccit.arizona.edu/khirschboeck/srp.htm>

Holling, C. S. (ed.). 1978: Adaptive Environmental Assessment and Management. New York, NY: John Wiley and Sons.

Holmes, B.H., 1979: A History of Federal Water Resources Programs and Policies, 1961-1970. Washington, D. C.: Economics, Statistics, and Cooperatives Service, U.S. Department of Agriculture.

Holway, J., 2007: Urban growth and water supply. In B. Colby and K. Jacobs (eds.) Arizona Water Policy: Management Innovations in an Urbanizing Arid Region. Washington, DC: *Resources for the Future,* pp. 157-172.

Homer-Dixon, T.F., 1999: Environment, Scarcity, and Violence. Princeton, NJ: Princeton University Press.

HRC-GWRI, 2006: Integrated Forecast and Reservoir Management (INFORM) for Northern California: System Development and Initial Demonstration. California Energy Commission, PIER Energy-Related Environmental Research, CEC-500-2006-109, Sacramento, CA, 243pp. + 9 Appendices. <http://www.energy.ca.gov/pier/final_project_reports/CEC-500-2006-109.html>

Hull, J.W. 2000: The War Over Water. *Regional Resource*. Atlanta, Georgia: The Council of State Governments, October.

Hurd, B.H., N. Leary, R. Jones, and J.B. Smith, 1999: Relative Regional Vulnerability of Water Resources to Climate Change. *Journal of the American Water Resources Association (JAWRA)*, **35(6)**, 1399-1410.

Hutson, S.S., N.L. Barber, J.F. Kenny, K.S. Linsey, D.S. Lumia, and M.A. Maupin, 2004: *Estimated Use of Water in the United States in 2000*. U.S. Geological Survey Circular 1268. Reston, VA: USGS.

Ingram, H. and L. Fraser, 2006: Path dependency and adroit innovation: The case of California water. In R. Repetto, (Ed.). *By fits and starts: Punctuated equilibrium and the dynamics of U.S. environmental policy*. New Haven: Yale University Press.

International Joint Commission, 2000: Protection of the Waters of the Great Lakes: Final Report to the Governments of Canada and the United States. Ottawa, CN: IJC.

IPCC, 2007a: Climate Change 2007. The Physical Science Basis. Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change (Solomon, S., D. Qin, M. Manning, Z. Chen, M. Marquis, K.B. Averyt, M. Tignor, and H. L. Miller (eds.) Cambridge University Press, Cambridge, U.K., and New York, NY, U.S.A.

IPCC, 2007b: Climate Change 2007. Impacts, Adaptation, and Vulnerability. Working Group II Contribution to the Intergovernmental Panel on Climate Change Fourth

Assessment Report. Summary for Policymakers Geneva, Switzerland: IPCC Secretariat, April.

Jacoby, H.D., 1990: Water quality. In P.E. Wagonner (ed.), Climate Change and U.S. Water Resources. John Wiley and Sons, New York, pp. 307-328.

Jacobs, K.L., G.M. Garfin, and M. Lenart, 2005: More than Just Talk: Connecting Science and Decisionmaking, Environment, 47(9), 6-22.

Jacobs, K.L., and J.M. Holway, 2004: Managing for sustainability in an arid climate: lessons learned from 20 years of groundwater management in Arizona, USA. *Hydrogeology Journal*, **12**,52-65.

Jasanoff, S., 1987: EPA's regulation of Daminozide: Unscrambling the messages of risk. *Science, Technology, and Human Values,* **12(3&4),** 116-124.

Kahneman, D., P. Slovic, and A. Tversky, eds., 1982: Judgment Under Uncertainty: Heuristics and Biases. New York: Cambridge University Press.

Keeney, R.L., 1992: Value-Focused Thinking: A Path to Creative Decision-making. Cambridge, MA: Harvard University Press.

Kenney, D.S., and W.B. Lord, 1994: Coordination Mechanisms for the Control of Interstate Water Resources: A Synthesis and Review of the Literature. Report for the ACF-ACT Comprehensive Study. U.S. Army Corps of Engineers, Mobile District, July.

Kingdon, J., 1995: Agendas, Alternatives, and Public Policies, 2nd Edition. New York: Harper Collins.

Kirby, K., 2000: Beyond Common Knowledge: The Use of Technical Information in Policymaking. Ph.D. Dissertation, University of California, Davis.

Kirshen, P., M. Ruth, and W. Anderson. Climate's Long-term Impacts on Urban Infrastructures and Services: The Case of Metro Boston. Chapter 7 in Ruth, M., P.H. Kirshen, and K. Donaghy, (co-editors), Climate Change and Variability: Consequences and Responses, (on research conducted as part of the 1999 and 2000 EPA STAR grant program*), in press.*

Kundell, J E, and D. Tetens 1998: Whose Water Is It? Major Water Allocation Issues Facing Georgia. *Public Policy Research Series*, Campbell, R W. Series Editor. Athens, Georgia: Carl Vinson Institute of Government, The University of Georgia.

Kundell, J.E., T.A. DeMeo, M. Myszewski, 2001: Developing a Comprehensive State Water Management Plan - A Framework for Managing Georgia's Water Resources. Sponsored by Home Depot and Georgia Power. Atlanta, GA: Research Atlanta, Inc./Georgia State University, Andrew Young School of Policy Studies.

Landre, B.K., and B.A. Knuth, 1993: Success of Citizen Advisory Committees in Consensus Based Water Resources Planning in the Great Lakes Basin. *Society and Natural Resources*, **6(3)**, July-September: 229.

Leatherman, S.P., and G. White, 2005: Living on the Edge: The Coastal collision Course. *Natural Hazards Observer*, **30(2)**, 5-6.

Lee, K.N., 1993: Compass and Gyroscope: Integrating Science and Politics for the Environment. Washington, D.C.: Island Press.

Lemos M.C., 2003: A tale of two polices: climate forecasting and drought relief in Ceará, Brazil. *Policy Sciences*, **36**,101–123

Lemos M.C., and J.L.F. Oliveira, 2004: Can water reform survive politics? Institutional change and river basin management in Ceará, Northeast Brazil. *World Development*, **32(12)**, 2121-2137

Lemos, M.C. and J.L.F. Oliveira, 2005: Water reform across the state/society divide: the case of Ceará, Brazil. *International Journal of Water Resources Development*, **21(1)**, 93-107.

Lemos M.C., D. Nelson, T. Finan, R. Fox, D. Mayorga, and I. Mayorga, 1999: The social and policy implications of seasonal forecasting: a case study of Ceará. Northeast Brazil. NOAA Final Report, Award no. NA76GPO385.

Lemos M.C., T. Finan, R. Fox, D. Nelson J. Tucker, 2002: The use of seasonal climate forecasting in policymaking: lessons from Northeast Brazil. *Climatic Change*, **55**, 479–507.

Loáiciga, H.A., 2003: Climate Change and Ground Water. *Annals of the Association of American Geographers*, **93(1)**, 30–41.

Lyon, B., N. Christie-Blick, and Y. Gluzberg, 2005: Water shortages, development, and drought in Rockland County, New York. *Journal of the American Water Resources Association*, **41**, 1457-1469.

Mantua, N.J., S. Hare, Y. Zhang, J.M. Wallace, and R.C. Francis, 1997: *Bulletin of the American Meteorological Society*, **78,** 1069–1079.

Mantua, N.J., 2004: Methods for detecting regime shifts in large marine ecosystems: a review with approaches applied to North Pacific data. *Progress in Oceanography*, **60(2-4)**, 165-82.

May, P.J.,R.J. Burby, N.J. Ericksen, J.W. Handmer,.J.E. Dixon, S. Michael, and S.D. Ingle. 1996: *Environmental Management and Governance: Intergovernmental Approaches to Hazards and Sustainability*. New York: Routledge.

McCabe, G.J., M.A. Palecki, and J.L. Betancourt, 2004: Pacific and Atlantic Ocean Influences on Multidecadal Drought Frequency in the United States. *Proceedings of the National Academy of Sciences*, **101(12)**, 4136-4141.

McGinnis, M.V., 1995: On the Verge of Collapse: The Columbia River System, Wild Salmon, and the Northwest Power Planning Council. *Natural Resources Journal*, **35**, 63-92.

Meinke H., R. Nelson, R. Stone, R. Selvaraju, and W. Baethgen, 2006: Actionable climate knowledge: from analysis to synthesis. *Climate Research*, **33**, 101–110.

Meko, D.M., C.W. Stockton, and W.R. Boggess, 1995: The tree-ring record of severe sustained drought. *Water Resources Bulletin*, **31(5)**, 789-801.

Meko D.M., C.A. Woodhouse, C.H. Baisan, T. Knight, J.J. Lukas, M.K. Hughes, and M.W. Salzer, 2007: Medieval drought in the Upper Colorado River Basin. *Geophysical Research Letters*, **34**(10, L10705), 10.1029/2007GL029988.

Merritt, R.H., 1979: Creativity, Conflict, and Controversy: A History of the St. Paul District, U.S. Army Corps of Engineers. Washington, D.C.: Government Printing Office.

Miller, K., S.L. Rhodes, and L.J. MacDonnell, 1996: Global Change in Microcosm: The Case of U. S. Water Institutions. *Policy Sciences*, **29**, 271-2.

Miller, K., and D. Yates, 2005: Climate Change and Water Resources: A Primer for Municipal Water Providers. AWWA Research Foundation, Denver, CO and University Corporation for Atmospheric Research, Boulder, CO, 83 p.

Milly, P.C.D., K.A. Dunne, and A.V. Vecchia, 2005: Global Pattern of Trends in Streamflow and Water Availability in a Changing Climate, *Nature* 438, November, 347-350.

Moody, J.A., and D.A. Martin, 2001: Post-fire, rainfall intensity-peak discharge relations for three mountainous watersheds in the western USA. *Hydrological Processes*, **15(15)**, 2981-2993

Morehouse, B.J., R.H. Carter, and P. Tschakert, 2002: Sensitivity of Urban Water Resources in Phoenix, Tucson, and Sierra Vista, Arizona, to Severe Drought. *Climate Research*, **21,** 283–297.

Morehouse, B. (ed.), 2000: The Implications of La Niña and El Niño for Fire Management. Proceedings of workshop held February 23-24, 2000, Tucson, Arizona. *Climate Assessment for the Southwest,* Institute for the Study of Planet Earth, The University of Arizona, Tucson, AZ. <http://www.ispe.arizona.edu/climas/conferences/fire2000/fireproc.pdf>

Mumme, S.P., 1995: The New Regime for Managing U.S.-Mexican Water Resources. *Environmental Management*, **19(6)**, 827-835.

Mumme, S.P., 2003: Strengthening Binational Drought Management. *Utton Center Report: University of New Mexico School of Law*, **2(1)**, Winter: 3-7.

Murdoch, P.S., J.S. Baron, and T.L. Miller, 2000: Potential effects of climate change on surface-water quality in North America. *Journal of the American Water Resources Association*, 36(2): 347-336.

Naim, M., 2003: The Five Wars of Globalization, *Foreign Policy* (January-February): 29-37.

Nelson, R. R. and S.G. Winter 1960: *Weather Information and Economic Decisions*, RM-2670-NASA, RAND Corporation, Santa Monica.

NRC (National Research Council), 2008: Research and Networks for Decision Support in the NOAA Sectoral Applications Research Program Panel on Design Issues for the NOAA Sector Applications Research Program, Helen M. Ingram and Paul C. Stern, Editors, National Research Council <http://www.nap.edu/catalog/12015.html>

NRC (National Research Council), 2007: Colorado River Basin Water Management: Evaluating and Adjusting to Hydroclimatic Variability. Committee on the Scientific Bases of Colorado River Basin Water Management. Washington, D.C., The National Academies Press, 222 p

NRC (National Research Council), 2006: Toward a New Advanced Hydrologic Prediction Service (AHPS) Committee to Assess the National Weather Service

Advanced Hydrologic Prediction Service Initiative. Washington, DC: National Research Council ISBN: 0-309-65847-0. <http://www.nap.edu/catalog/11598.html>

NRC (National Research Council), 2005: Decision Making for the Environment: Social and Behavioral Science Research Priorities. Garry D. Brewer and Paul C. Stern, *Editors*, Panel on Social and Behavioral Science Research Priorities for Environmental Decision Making, Committee on the Human Dimensions of Global Change. Washington, DC.

NRC (National Research Council), 1996: Understanding Risk: Informing decisions in a Democratic Society. P.C. stern and H.V. Fineberg, editors. Committee on Risk characterization, Commission on Behavioral and Social Sciences and Education. Washington, D.C.: National Academy Press.

NRC (National Research Council), 1989: Improving Risk Communication. Committee on Risk Perception and Communication. Commission on Behavioral and Social Sciences and Education and Commission on Physical Sciences, Mathematics, and Resources. Washington, D.C.: National Academy Press.

Neary, Daniel G.; K.C. Ryan, L.F. DeBano, eds., 2005: Wildland fire in ecosystems: effects of fire on soils and water. *Gen. Tech. Rep.* RMRS-GTR-42-vol.4. Ogden, UT: U.S. Department of Agriculture, Forest Service, Rocky Mountain Research Station. 250 p.

NMDTF (New Mexico Drought Task Force), 2006: New Mexico Drought Plan: Update December 2006. Albuquerque: New Mexico Office of the State Engineer, 37 p. <http://www.nmdrought.state.nm.us/droughtplans.html>

NOAA Office of Hydrology, 1998: Service Assessment and Hydraulic Analysis of the Red River of the North 1997 Floods: Actions Taken Following the Red River of the North Flood of 1997. 45 pages. <http://www.nws.noaa.gov/oh/Dis_Svy/RedR_Apr97/>

Obeysekera, J., P. Trimble, C. Neidrauer, C. Pathak, J. VanArman, T. Strowd, and C. Hall, 2007: Appendix 2-2: Consideration of long-term climatic variability in regional modeling for SFWMD planning and operations. *2007 South Florida Environmental Report*, Florida Department of Environmental Protection and South Florida Water Management District, 47 pp. Available online at <http://www.sfwmd.gov/sfer/SFER_2007/Appendices/v1_app_2-2.pdf>

O'Connor, R. E., B. Yarnal, K. Dow, C. L. Jocoy, and G. J. Carbone, 2005: Feeling at-risk matters: Water managers and the decision to use forecasts. *Risk Analysis*, **25,** 1265-1275.

O'Connor, R. E., B. Yarnal, R. Neff, R. Bord, N. Wiefek, C. Reenock, R. Shudak, C. L. Jocoy, P. Pascale, and C. G. Knight, 1999: Community water systems and climate variation and change: Current sensitivity and planning in Pennsylvania's Susquehanna River Basin. *Journal of the American Water Resources Association*, **35,** 1411-1419.

Pagano, T., H. Hartmann, and S. Sorooshian, 2001: Using Climate Forecasts for Water Management: Arizona and the 1997-98 El Nino, *Journal of the American Water Resources Association* 37, No. 5, pp 1139-1153.

Pagano, T. C., H. C. Hartmann, and S. Sorooshian, 2001: Using climate forecasts for water management: Arizona and the 1997-1998 El Niño. *Journal of the American Water Resources Association* 37(5): 1139-1153.

Pagano, T., H. C. Hartmann, and S. Sorooshian, 2002: "Factors affecting seasonal forecast use in Arizona water Management: a case study of the 1997-98 El Niño." Climate Research 21: 259-269.

Papadakis, Elim, 1996: Environmental Politics and Institutional Change. London: Cambridge University Press.

Payne, J., J. Bettman, and E. Johnson, 1993: The Adaptive Decision Maker. New York: Cambridge.

Pfaff. A., K. Broad and M. Glantz, 1999: Who Benefits from Climate Forecasts? *Nature,* 397, pp 645-646.

Pielke, Jr., R.A., 1999: Who Decides? Forecasts and Responsibilities in the 1997 Red River Flood. American Behavioral Science Review 7, 2, 83-101.

Polsky, C., R. Neff, and B. Yarnal 2007: Building comparable global change vulnerability assessments: The Vulnerability Scoping Diagram. *Global Environmental Change* 17, 3-4, 472-485.

Pool, D. R., 2005: Variations in climate and ephemeral channel recharge in southeastern Arizona, United States. *Water Resources Research* 41(W11403).

Power, Scott, Brian Sadler, and Neville Nicholls, 2005: The Influence of Climate Science on Water Management in Western Australia: Lesssons for Climate Scientists, *Bulletin of the American Meteorological Society* (June): 839-844.

Pringle, Catherine M., 2000: Threats to U.S. Public Lands from Cumulative Hydrologic Alterations Outside of their Boundaries, *Ecological Applications* 10 (4) August: 971-989.

Proceedings: Western Governors Association, Western States Water Council, and California Department of Water Resources, 2007: *May 2007 Climate Change Research Needs Workshop,* September.

Pulwarty, R. and T. Melis, 2001: Climate Extremes and Adaptive Management on the Colorado River: Lessons from the 1997-1998 ENSO event, *Journal of Environmental Management* 63, pp 307-324.

Rango, A., 2006: Snow: The real water supply for the Rio Grande basin. New Mexico *Journal of Science*. 44:99-118.

Ray, A.J., and R.S. Webb. 2000: Demand-side perspective on climate services for reservoir management. *Proceedings of the Climate Diagnostics and Prediction Workshop*, Palisades, NY, 23-27 October 2000. 219-222.

Rayner, Steve, D. Lach, and H. Ingram, 2005: Weather Forecasts are for Wimps: Why Water Resource Managers do not Use Climate Forecasts, *Climate Change* 69: 197-227.

Redmond, Kelly T., 2003: Climate Variability in the West: Complex Spatial Structure Associated with Topography, and Observational Issues. In William M. Lewis, Jr. (ed.), *Water and Climate in the Western United States*. Boulder, CO: The University Press of Colorado.

Restoring the Waters. 1997: Boulder, CO: Natural Resources Law Center, the University of Colorado School of Law, May.

Rhodes, S.L., D. Ely, and J. A. Dracup, 1984: Climate and the Colorado River: the limits to management. *Bulletin of the American Meteorological Society* 65:682-691.

Rosenberg, David M., P. McCully, and C. M. Pringle, 2000: Global-Scale Environmental Effects of Hydrological Alterations: Introduction, *BioScience* 50 (9) September: 746-751.

Roy, S.B., P.F. Ricci, K.V. Summers, C.F. Chung, and R.A. Goldstein, 2005: Evaluation of the Sustainability of Water Withdrawals in the United States, 1995-2025. *Journal of the American Water Resources Association*, 41(5):1091-1108.

Rygel, L., D. O'Sullivan, and B. Yarnal, 2006: A method for constructing a social vulnerability index: An application to hurricane storm surges in a developed country. *Mitigation and Adaptations Strategies for Global Change* 11: 741-764.

Sarewitz, Daniel and R. A. Pielke, Jr., 2007: The Neglected Heart of Science Policy: Reconciling Supply of and Demand for Science, *Environmental Science and Policy* 10: 5-16.

Schneider, S. H. and J. Sarukhan, 2001: Overview of impacts, adaptation, and vulnerability to climate change. Intergovernmental Panel on Climate Change Working Group 2 Report: Climate Change 2001: Impacts, Adaptation and

Vulnerability, J. J. McCarthy, O. F. Canziani, N. A. Leary, D. J. Dokken, and K. S. White, Eds., Cambridge University Press, 75-103.

Schröter, D., C. Polsky, and A. G. Patt, 2005: Assessing vulnerabilities to the effects of global change: An eight step approach. *Mitigation and Adaptation Strategies for Global Change*. 10: 573-596.

Shamir, Eylon, D. M. Meko, N. E. Graham, and K. P. Georgakakos, 2007: Hydrologic Model Framework for Water Resources Planning in the Santa Cruz River, Southern Arizona. *Journal of the American Water Resources Association* 43 (5), 1155–1170. doi:10.1111/j.1752-1688.2007.00095.x

Sheppard, Paul R., A. C. Comrie, G. D. Packin, K. Angersbach and M. K. Hughes, 2002: The Climate of the Southwest. *Climate Research* 21:219-238.

Slovic, P., B. Fischhoff and S. Lichtenstein 1977: Behavioral decision theory. *Annual Review of Psychology* 28:1-39.

Sonnett, J., B. J. Morehouse, T. Finger, G. Garfin, and N. Rattray, 2006: Drought and Declining Reservoirs: Comparing Media Discourse in Arizona and New Mexico, 2002-2004. *Environmental Change* 16(1): 95-113.

Sonnett, John, B. J. Morehouse, T. J. Finger, G. Garfin, and N. Rattray, 2006: Drought and Declining Reservoirs: Comparing Media Discourse in Arizona and New Mexico, 2002-2004, *Global Environmental Change* 16: 95-116.

South Florida Water Management District, 1996: Climate Change and Variability: How Should The District Respond? South Florida Water Management District, West Palm Beach Florida, 27 pp. <http://www.sfwmd.gov/org/pld/hsm/pubs/ptrimble/solar/clim1.pdf>

Steinemann, A. C. and L. F. N. Cavalcanti, 2006: Developing multiple indicators and triggers for drought plans. *Journal of Water Resources Planning and Management* 132(3): 164-174.

Stern, Paul C. and H. V. Fineberg, eds., 1996: Understanding Risk - Informing Decisions in a Democratic Society. Committee on Risk Characterization, Commission on Behavioral and Social Sciences and Education, National Research Council. Washington, D.C.: National Academy Press.

Stewart, I. T. and D. R. Cayan, et al. , 2005: Changes toward Earlier Streamflow Timing across Western North America. *Journal of Climate* 18: 1136-55.

Stoltman, Joseph P., J. Lidstone, and L. M. DeChano, 2004: Introduction, pp. 1-10, in J. P. Stoltman, J. Lidstone, and Lisa M. DeChano, (eds). International Perspectives on Natural Disasters: Occurrence, Mitigation, and Consequences. Dordrecht, Netherlands: Kluwer Academic Publishers.

Stone, Deborah, 1997: Policy Paradox: The Art of Political Decision Making. New York: W.W. Norton.

Subcommittee on Disaster Reduction, 2005: Grand Challenges for Disaster reduction, *Natural Hazards Observer* 30 (2) November; 1-3.

Swetnam, T. W. and J. L. Betancourt, 1998: Mesoscale Disturbance and Ecological Response to Decadal Climatic Variability in the American Southwest. *Journal of Climate* 11: 3128-47.

Taddei, R., 2005: Of clouds and streams, prophets and profits: the political semiotics of climate and water in the Brazilian Northeast. PhD dissertation, Teachers College, Columbia University, New York.

Torgerson, Douglas, 2005: Obsolescent Leviathan: Problems of Order in Administrative Thought, pp 11-24, in R. Paehlke and D. Torgerson, editors. *Managing Leviathan: Environmental Politics and the Administrative State, 2nd edition.* Peterborough, Ontario: Broadview Press.

Trush, B. and S. McBain, 2000: Alluvial River Ecosystem Attributes, *Stream Notes.* Fort Collins, CO: U.S. Forest Service, Stream Systems Technology Center.

Tversky, A. and D. Kahneman, 1974: Judgment Under Uncertainty: Heuristics and Biases, *Science* 185: 1124-1131.

Udall, B. and M. Hoerling, 2005: Seasonal Forecasting: Skill in the Intermountain West? In *Colorado River Basin Climate: Paleo, Present, Future*, pp. 30-35. <http://wwa.colorado.edu/resources/colorado_river/>

USGS, 2004: Climatic Fluctuations, Drought, and Flow in the Colorado River Basin. USGS Fact Sheet 2004-3062 version 2, U.S. Geological Survey.

U.S. Global Change Research Program, 2001: National Assessment Synthesis Team. Climate Change Impacts on the United States: The Potential Consequences of Climate Variability and Change. New York: Cambridge University Press.

Wagner, E. T. 1995: Canada-United States Boundary Waters Management Arrangements, pp. 16-22. In *Management of Water Resources in North America III – Anticipating the 21st Century*, edited by Nathan Buras. Proceedings of the Engineering Foundation Conference. New York: American Society of Civil Engineers.

Wallentine, C.B. and D. Matthews, 2003: Can climate predictions be of practical use in western water management? In William M. Lewis, Jr. (ed.), *Water and Climate in the Western United States*. Boulder, CO: The University Press of Colorado, pp. 161-168.

Walters, C. J. 1986: Adaptive Management of Renewable Resources. New York, NY: Macmillan.

Water in the West: Challenge for the Next Century, 1998: Report of the Western Water Policy Review Advisory Commission. Published by National Technical Information Service: Springfield, Virginia, June.

Weingart, Peter, A. Engels and P. Pansegrau, 2000: Risks of communication: Discourses on climate change in science, politics, and the mass media, *Public Understanding of Science* 9: 261 <http://pus.sagepub.com/cgi/content/abstract/9/3/261>

Weston, R. Timothy, 1999: Interstate Water Rights and River Basin Compacts in the East, unpublished manuscript, Harrisburg, PA: Kirkpatrick and Lockhart, LLP.

Westphal, K.S., R. M. Vogel, P. Kirshen, and S. C. Chapra, 2003: Decision support system for adaptive water supply management. *Journal of Water Resources Planning and Management*,129(3):165-177.

Weston, R. Timothy, 1995: Delaware River Basin - Challenges and Successes in Interstate Water Management. Paper Presented at ASCE Water Resources Engineering Conference, San Antonio, Texas, August 17.

Wilhite, D. A., 2004: Drought, pp. 147-162, in J. P. Stoltman, J. Lidstone, and Lisa M. DeChano, editors. International Perspectives on Natural Disasters: Occurrence, Mitigation, and Consequences. Dordrecht, Netherlands: Kluwer Academic Publishers.

Wilhite, D.A., M.J. Hayes, C. Knutson, and K.H. Smith, 2000: Planning for Drought: Moving from Crisis to Risk Management. *J. of Amer. Water Res. Assoc.* 36:697-710.

Woodhouse, C.A. and J.J. Lukas, 2006: Drought, Tree Rings, and Water Resource Management in Colorado. *Canadian Water Resources Journal* 31(4): 1-14.

Woodhouse, C. A. and J. J. Lukas, 2006: Drought, tree rings, and water resource management. *Canadian Water Resources Journal* 31: 297-310.

Woodhouse, C. A., S. T. Gray, et al. ,2006: Updated streamflow reconstructions for the Upper Colorado River Basin. Water Resources Research 42(W05415).

Woodhouse, C. A. and J. J. Lukas, 2006: Drought, tree rings, and water resource management. *Canadian Water Resources Journal* 31: 297-310.

Yarnal, B., 2007: Vulnerability and all that jazz: Addressing vulnerability in New Orleans after Hurricane Katrina. *Technology in Society*, 29, 249-255.

Yarnal, B., A. L. Heasley, R. E. O'Connor, K. Dow, and C. L. Jocoy, 2006: The potential use of climate forecasts by Community Water System managers. *Land Use and Water Resources Research 6: 3.1-3.8*, <http://www.luwrr.com>

Yarnal, B., R. E. O'Connor, K. Dow, G. J. Carbone, and C. L. Jocoy, 2005: Why don't Community Water System managers use weather and climate forecasts? *Preprints of the 15th Conference on Applied Climatology, Savannah, GA, June 2005*, American Meteorological Society, Boston, Session 7.1.

Zarriello, P. J., and K. G. Ries, 2000: A Precipitation-Runoff Model for Analysis of the Effects of Water Withdrawals on Streamflow, Ipswich River Basin, Massachusetts, U.S. Geol. Survey. *Water Resources. Invest. Rep.*, 00-4029, 99 pp.

Zektser, S.; H.A. Loaiciga, and J.T. Wolf, 2005: Environmental Impacts of Groundwater Overdraft: Selected Case Studies in the Southwestern United States. Environmental Geology, 47(3), 396-404.