CLIMATE AND WATER IN THE WEST: SCIENCE, INFORMATION AND DECISION-MAKING

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INTRODUCTION

The U.S. West is a place of varying and changing physical and ecological conditions that control regional climate, hydrology, and geomorphology. It is also a place of evolving social demographics, settlement, resource use and values. The factors conditioning present and future water resources management in the Western U.S. have been summarized as: increasing population and consumption, uncertain reserved water rights (in particular quantification of Native American rights), increasing transfer of water rights to cities, deteriorating water quality, environmental water allocation, ground water overdraft, outmoded institutions, aging urban water infrastructures, and the changing nature of federal, state and local interaction.

Climate change is expected to have major effects on precipitation, temperature, and land-surface feedbacks including evapotranspiration. In particular the Southwest could face higher temperatures with reduced water flow in the Colorado. Snowpack could also likely melt earlier in the season leading to earlier season flooding and less water to meet summer demands. In the semiarid Southwest even relatively small changes in precipitation can have large impacts on water supplies. Water managers have available tools for dealing with risk and uncertainty mostly derived from relatively short climatic records (<100 years). As is clear from numerous paleoclimatic records and sources climate has never been “stable” for long periods even if we have created statistical artifacts such as climate averages and event recurrence estimations based on short records. For example in most parts of Colorado reliable flow measurements for major streams have been recorded only over the last 50 to 100 years and precipitation measurements over the last 20 to 60 years.

Water banking and inter-basin transfers have been used to mitigate the effects of short-term drought. The lessons and impacts of these adjustment strategies are still being gathered. However the maintenance of reliable supply during periods of severe long-term droughts of 10 years to 100 years (the timescales of project implementation and ecosystem management efforts) known to have occurred in the West over the past 1000 years is as yet untested. The spatial extent and persistence of drought may produce shortages not only in the locale considered but also in neighboring regions that otherwise are supposed to make surplus water available for inter-basin transfers. On the other hand, the transformation of the Red River in North Dakota in the spring of 1997 provides a recent reminder of what can happen when too much water arrives in too short a time (Downton and Pielke, 2001). Increases in flood and drought variability would thus require a re-examination of emergency design assumptions, operating rules, system optimization, and contingency measures for existing and planned water management systems (Stakhiv, 1998).

Measures undertaken by Federal and State agencies to inform management include improvements in streamflow and demand forecasting, use of advance decision support systems, development of drought indicators, conjunctive ground water/surface water use models, monitoring of water supply and distribution, water-use efficiency technologies and public information communication and coordination. The sectors and stakeholders (including instream and withdrawal uses) affected in each region are (1) water rights holders, (2) agriculture (including business and farmers in area of origin), (3) hydropower, (4) the environment (including instream flows and water quality), (5) urban interests, (6) Indian tribes, and (7) non-agricultural rural areas. These sectors and the adaptive mechanisms developed over time are all sensitive to climatic variations and changes.

For the most part, studies of the potential impacts of future climate change fall between two poles: (1) no adaptation is too great for societies or ecosystems to make; or (2) impose possible future climates on today's ecological, demographic, industrial, urban distributions and tally the resulting disruptions, itself resulting in extremely uncertain estimates (Clark, 1985). The primary reason offered for responding to climate change now is that immediate benefits can be gained by removing maladaptive policies and practices. In addition it is argued that climate change may be more rapid and more pronounced than current estimates suggest. Estimating the nature, timing and even direction of the physical changes at regional and local scales is of primary interest to water planners and managers and involves many uncertainties (Frederick and Gleick, 1999). Even if the physical risk can be specified, assessing vulnerability (in terms of risk, impacts and capacity to act) remains problematic.

Unexpected events are possible. However, devising effective societal responses to potential climate change impacts face several practical constraints based on the way the climate change problem is defined (see Brooks, 1977 among others):

- By definition, the effects lie just far enough into the future. Their assessment and control involves trade-off between the interests of current and future generations.
- Predicted effects are highly uncertain and difficult to prove to the satisfaction of all experts.
- When effects are long-term and cumulative, the costs of delaying action often appear small compared with the immediate economic costs.
- Long-term environmental problems can seldom be dealt with by single discrete actions or policies but respond only to a continuing, sustained effort, supported by steady public attention and visibility.

Non-technical considerations are thus always present. In this paper the focus will be on some of these considerations and will include recommendations for potentially overcoming barriers to using climate information more effectively. Most policy measures being proposed are unconstrained by the contingencies of the dynamic social, political and economic contexts in which implementation is supposed to occur. Multiple studies (e.g., Changnon, 2000) indicate that water managers do not believe there is enough certainty associated with climate-related predictions to justify a change in management approach. Some of that belief may be based on an incomplete understanding of the basis and meaning of those predictions. In these instances, new tools to evaluate alternatives in the context of uncertainty and risk could help water managers "know enough to act." Indeed, as is well-documented, "uncertainty" may be used as an excuse to escape what are in fact difficult political decisions (Pulwarty and Redmond, 1997; Rayner et al., 2001). As note by George Brown, the late Chair of the U.S. House of Representatives Science Committee, "Uncertainty is not the hallmark of bad science, it is the hallmark of honest science. This perennial question, 'Do we know enough to act?' is inherently a policy question not a scientific one."

While there have been increasing calls for research to be "stakeholder driven," the risk is run of rushing preliminary untested research results and products into practical settings. Scientists may appear to be advocates of particular groups over others. Primarily, it is argued here that there is limited appreciation and understanding of how knowledge is incorporated in practice, especially in situations with high decision stakes and system uncertainty. The discussion of the physical aspects of climate change, and its associated uncertainties will be left to others.

CLIMATE VARIABILITY AND CHANGE: CHARACTERISTICS OF PROBLEMS

The U.S. Bureau of Reclamation has indicated that during a dry period such as occurred from 1931-40 the water needs of the lower Colorado River Basin would not be met (NRC, 1991). A repeat of such an event would also have significant impacts on both the Missouri and Rio Grande Basins. For instance, one study showed that hydropower production and reservoir storage would decline to about half their present values under 1931-1940 conditions (Frederick, 1999). More recently, using a composite index of water resource sensitivity (including ground water and surface water withdrawals, streamflow volume, precipitation lost through evaporation, barriers to water trading, share of industrial water not recycled, expenditures on dredging navigable waters, extremes of heat and cold, dissolved oxygen in water and species at risk). Hurd et al. (1999) showed that many major river basins of the US have reached critical thresholds in their vulnerability to present day climate variations and extremes.

Most basins in the West exhibit the characteristics of a "closed or closing" water system (Rogers, 1997). In such systems, management of interdependence becomes a public function, and the development of mechanisms to allow resource users to acknowledge interdependence and to engage in negotiations and binding agreements on resource allocation become increasingly necessary. These cumulative pressures have resulted in an almost total lack of regional capacity to implement plans for responding to environmental variability and change. Even without projected anthropogenic changes, therefore, building in flexibility in operation systems (reservoirs, etc.) in terms of efficiency and buffers to climate variations requires re-examination of design criteria, operating rules, assumptions about the climate record and attendant contingency planning. The costs, benefits and tradeoffs in pursuing and securing diverse values of river systems (e.g. hydropower, environment, irrigation, recreation, aesthetics) are not easy to document accurately. As a result, decision-making is very much a process of negotiating acceptable outcomes among various interests as opposed to one of simply reducing the uncertainty of our knowledge of the physical system or increasing the operating efficiency of designed systems (e.g. dams).

We argue that given these conditions (uncertainty about future changes, limited historical records and the nature of decision-making about water resources), one of the key steps forward is to ensure a solid cooperative foundation for research and management. There is much to be learned about present day management and flexibilities developed in response to interannual and decadal scale variations.

VULNERABILITY AND DECISION-MAKING: IMPACTS AND SCALES

"Flexibility" has been a resurgent watchword for future water management. This recommendation, however, begs the question: How can strategies for flexibility be best designed and effectively undertaken? Again the only rigorous documented knowledge that can provide a reasonable answer to such a question has to be based on past experience. What has been done is probably the best place to begin an understanding and evaluation of what can be done. More generally, as discussed by Luecke et al. (2003) three elements of Colorado's (and many other states') water future lie in (1) conservation and demand management; (2) municipal-agricultural cooperation; and (3) supply integration. The range of cost estimates for these management options are only recently being estimated.

Water managers have differing needs for scientific information relative to the scale of management, the type of decision being made, and the training and structure of local management organizations (e.g., elected board vs. professional managers). Decisions that have long-term implications, such as development of new infrastructure, require greater accuracy than decisions that require no capital investment. Likewise, decisions that affect millions of users, such as managing the water levels in the reservoirs along the Colorado, are made with great care because of the significant implications for both water supply and flood damage. Researchers do not need to assess all of these factors but a working knowledge is needed in order to devise potentially useful climate products, and to identify potential customers for those products. Developing a good understanding of the water policy decision environment will be one of the most difficult challenges of developing climate products and identifying clients for those products. In order to produce relevant information, researchers need to understand what issues are relevant, who will be making each decision, the fora in which those decisions are made, the timing of particular decisions and the legal and political context surrounding particular issues. In the case of large watersheds, such as the Colorado and the Columbia, these factors cross several time and space scales. Table 1 shows the scales across which decisions are to be encountered in operation of the Glen Canyon Dam. Given the trade-offs and priorities involved, the problem is thus not one of simply optimizing or increasing efficiency at each step. Water managers need information at the right scale, which is generally at the watershed or smaller level. Because most of the recently developed predictive capability related to climate is at the global scale, downscaling to the local level is a key need. Significant progress has been made in downscaling from global models to watershed scale hydrologic models by researchers in the Pacific Northwest, California and the Southwest (U.S. Global Change Research Program, 2001). However, substantial work is still needed to increase predictive capability, appropriate applications and joint learning opportunities at the regional scale, especially where there is substantial topographic variability.

Major trade-offs lie in the degree of accuracy versus the degree of precision (local scale information) that can be provided by climate models. Regional models can produce very precise but inaccurate numbers for small areas. It is tempting to produce such information. A consistent result across most studies of information use is that people want information pertinent to their locale (farm, stream, etc.). At the level of small watersheds it becomes extremely important not to oversell the precision of forecasts at the expense of being clear about their accuracy. Thus scaling up from local data is as important as scaling down from globally forced regional models.

INFORMATION NEEDS:
THE CASE OF DROUGHT

Extreme events are the chief drivers of water resources system adjustments to environmental and social change (Riebsame, 1993). How well water systems handle the extreme tails of current or altered climate distributions is likely to be an overriding concern as systems become more constrained. The behavioral problem is that resource managers (and researchers) have difficulty anticipating how complex systems will respond to environmental stresses.

Temporal scales	
Indeterminate:	Flows necessary to protect endangered species
Long-term:	Inter-basin allocations and allocations among basin states
Decade:	Upper Basin delivery obligations, life-cycle of humpback chub (Gila *cypha*)
Year:	Lake Powell fill obligations to achieve equalization with Lake Mead storage
Seasonal:	Peak heating and cooling months
Daily-monthly:	Flood control operations, Kanab Ambersnail impacts
Hourly:	Western Area Power Administration's power generation
Spatial scales	
Global-	Climate influences, Grand Canyon National Park World Heritage Site
National-	Western water development: irrigation, Grand Canyon Protection Act (1992)
Regional-	Prior appropriation, Upper Colorado River Commission, Upper and Lower Basin Agreements, energy grid
State-	Different agreements on water marketing within and out-of-state, water districts
Municipal-	
Community-	
Household-	

Table 1. Examples of cross-scale issues in river management in the Glen and Grand Canyons (Pulwarty and Melis, 2001)

At present the Drought Impact Task Force for the State of Colorado provides other task forces (e.g. Municipal Water, Wildfire Protection, Agriculture, Economic Impact, Torusim, Wildlife) with the drought forecasts and climatic conditions garnered from a combination of federal, local and state agencies. Information needs include projections of the following variables and indices at a basin scale: snowpack, soil moisture, streamflow reservoir levels, ground water levels, precipitation, surface Water Supply Index, Standardized Pressure Index and the Palmer Indexes. In addition, the Drought Task Force identifies resource information gaps and makes recommendations to address them.

The mechanisms for responding to drought usually entail (1) efficiency requirements and mandatory cutbacks, (2) supplementing surface with ground water, (3) increasing interbasin withdrawals, and (4) increasing storage facilities. Interbasin relations form part of an exceedingly complex legal and political environment (Powell Consortium, 1995).

Reactive mechanisms such as drought relief do little if anything to reduce the vulnerability of the affected area to future drought (Wilhite, 2000). Luecke et al. (2003) and others have reviewed the planning, impacts and costs of the 2001-2002 drought in Colorado. As in most Front Range towns, Denver adopted Stage 1 drought response measures (10% voluntary water use reduction goal) on June 5, 2002. Due to the rapidly increasing severity of the drought, Denver then declared a Stage 2 drought response on June 26 with mandatory restrictions effective July 1 designed to achieve system-wide reduction of 30%. From July to August, the severity of the drought (10% flow in some areas, 3-50% less than the lowest recorded flows) was more apparent. Denver Water reported that restrictions adopted by the board had not resulted in the desired 30% savings. On average for 2002, Colorado cities reduced demand by about 10%. Even so, providers generally had enough water to distribute sufficient supplies without disruption. Most providers invoked restrictions in recognition that the current drought was not necessarily over and as a precaution against running out of water over the next 12 months. The real concern for water providers was that storage reserves would not last through another year like 2002. Most importantly, few providers had procedures in place to closely monitor rapidly evolving drought conditions. Actions had to be taken quickly in a strictly reactive mode as snowpack and streamflow conditions rapidly declined (Luecke et al. 2003). Thus, a major need is to increase the time frame over which the Drought Task Force operates (i.e., not just when a drought is underway) and to have the activities for different states be coordinated e.g. such as under a Western Drought Coordination Council (Wilhite, 2000).

Areas such as Douglas County used water from the Denver Basin aquifer with little or no annual recharge. In the case of surface water/ground water interactions, lack of a full understanding of the role of ground water in supporting surface water flows has led to multiple cases of unanticipated consequences and substantial

Factor	Scientist's Perspective	Water Manager's Perspective
Identifying a critical issue	Based on a broad understanding of the nature of water management	Based on experience of a particular system
Time frame	Variable	Immediate (operations) Long-term (infrastructure)
Spatial resolution	Defined by data availability or funding	Defined by institutional boundaries or authorities
Goals	Prediction Explanation Understanding of natural system	Optimization of multiple conditions and minimization of risk
Basis for Decisions	Generalizing multiple facts and observations Use of scientific procedures and methods Availability of research funding Disciplinary perspective	Tradition Procedure Professional judgment Training Economics Politics Job risks
Expectation	Understanding Prediction Ongoing improvement (project is never actually complete) Statistical significance of results Innovations in methods/theory	Accuracy of information Appropriate methodology Save money and time Protect the public Protect their jobs, agendas or institutions
Product Characteristics	Complex Scientifically defensible	As simple as possible without losing accuracy Importance of context
Frame	Physical (atmospheric, hydrologic, etc.) conditions as drivers Dependent on scientific discipline	Safety and well being Profit Consistency with institutional culture, policy, etc.
Nature of Use	Conceptual	Applied

Table 2. Differences in Perspective on the Use of Climate Information Between Scientists and Water Managers (Jacobs and Pulwarty, 2003)

habitat damage (Glennon and Maddock, 1994). This outcome is more likely in cases similar to that in Arizona, where the legal framework for ground water is separate from that of surface water. For example, there is currently no legal mechanism for considering impacts on surface water caused by new permits to pump ground water (Glennon and Maddock, 1994). As discussed by Luecke et al. (2003), a major problem with building extra storage is that new reservoirs would have to be kept full (i.e., no new developments) until severe sustained drought is actually underway. As discussed by Nichols et al. (2001) climate information (both present variability and future change) will be useful to evaluate several questions such as: How does drought in the Upper Colorado system influence decision-making in the South Platte (and vice-versa)? How will the fate of future transbasin diversions influence, and be influenced by, agricultural-to-urban water transfers? How does climate fit into that issue and issues of water quality and environmental regulations? "Slack" is thus a resource. Formalizing use of this resource apriori may in fact reduce flexibility for responding to extreme events outside the range of changes predicted by climate change models. (Note that the 2002 drought was one such event).

PROBLEM FRAMING AND USABILITY: RESEARCH AND INFORMATION USE

Apart from the significant political and economic issues surrounding decision-making, there are problems with the development and usability of relevant research-based information that need to be addressed. These exist even if a Western Drought Coordination Council was to be created (and a lead agency be designated). Experience shows that possession of information does not mean that it will be used or that all uses are beneficial. Indeed, successful risk communication does not always lead to better decisions or consensus about controversial issues, because risk communication is only part of risk management. The barriers to climate information acceptability and use reflect combinations of technical, cognitive, financial, institutional and cultural conditions that influence the processes of information generation, content, dissemination, communication, utilization and evaluation (Pulwarty and Redmond, 1997). Previous assumptions that the purpose of dissemination was to primarily cast knowledge out into the world of practice has given way to an approach that incorporates ideas about two-way communication and creating dialogs about risks. A formidable barrier within these dialogs is shaped by how the research community and the water management communities view and define particular problems and solutions. Table 2 shows a highly aggregated, but empirically-based subset of differences in perspectives on the use of climate information between these two (varied) communities (Jacobs and Pulwarty, 2003).

Quite clearly, mechanisms for information flows between scientists and water managers (and vice-versa) need to be carefully designed in order to be effective (e.g., so that knowledge is actually relevant and usable or simply to minimize the likelihood of doing the wrong thing more precisely). As noted by Pulwarty and Redmond (1997), Miles et al. (2000), Rayner et al. (2001), "Timing and form of climatic information (including forecasts), and access to expertise to help implement the information and projections in decision-making processes may be more important to individual users than improved reliability." Graphical products are particularly useful in providing large amounts of information quickly, but may not be as successful in communicating the relevant caveats. In this case, the issue is not failure to communicate, but communicating complex ideas too simply. Scientists who are enthusiastic about their findings frequently encourage decision-makers to use information before it is sufficiently robust. Kirby (2000) recommends that scientists know more and say less to develop credibility. In addition, because there are so many types of water managers and so many different levels of sophistication, translations of scientific information are needed for particular audiences (Rayner, et al., 2001).

Multi-objective management is a tool used to optimize complex systems where there are multiple constraints, and provides a theoretical framework for decision-making (Schwartz, 2000). Unfortunately, many water management decisions are made under time and resource constraints that limit the utility of comprehensive modeling exercises. In addition, the modeling approach focuses primarily on efficiency from an economic perspective and may not be able to accommodate other management objectives such as equity.

Decision-makers repeatedly state that climate forecasts are unreliable, and that there are no quantitative ways to evaluate their credibility. Hartmann et al. (2001) note:

> Forecast evaluations should focus on specific regions, seasons, and lead times of interest to different decision-makers. CPC seasonal climate outlooks clearly perform better for some users than others. From the perspective of water managers in the Southwest, winter precipitation outlooks made during fall and winter are better than climatology forecasts according to all criteria. Winter and spring forecasts of summer precipitation lack skill…Compared to the Upper Colorado River Basin, not only does the Lower Basin benefit from greater storage capacity… but from greater climate predictability as well (p. 14).

The nature of climate information and its development

- The impact and criticality of climate variability on issue of interest
- Identification of those impacted (positive and negative): actual and potential
- Identification of competitive applications and users

The decision characteristics, communication process and the communicator/provider experience

- Knowledge of the systems and its management: The nature of decisions and context of use (formal and informal)
- Getting the partnerships right and getting the right partners
- Identification of entry points for information

The acceptability of information and participatory implementation

- Role of the partnerships in determining the relevance of information produced and the development of products: what is provided and what is actually being asked for?
- Capacity of practitioners to validate knowledge claims of providers
- Clear identification of benefits: evaluation of consequences of use
- Practical opportunities for effective applications

Monitoring and continual revision of interventions

- Measures of feedback, refinement, interaction over time i.e., learning and innovation among practitioners, providers and intermediaries

Table 3. Factors identified as affecting the degree of climate information utilization

One suggestion for improving the relevance of forecast and other climatic information is to identify appropriate entry points into the decision-making process, through so-called hydro-climatic “decision calendars” (Pulwarty and Melis, 2001). Such calendars have been used to identify decision needs within planning and operational activities on the Upper Colorado River and at Glen Canyon Dam. These calendars are time-frame maps of the appropriate climate-related information needed for decision-making throughout the year for developing ecological restoration programs in the context of basin operating plans. Because they are developed in collaboration between the researcher(s) and practitioner(s) they can also provide a context for discussion, and act a mechanism to encourage relationships between scientists and water managers that facilitate development of common knowledge (i.e., beyond simply “communicating” scientific information).

CONCLUSIONS

Future impacts may be larger (than at present) from cumulative smaller-scale events because of demographic and economic changes and habitat loss. Precise definitions of future physical effects and socio-economic impacts of weather and climate extremes may be impossible to determine. Some sensitivities are well known but are changing over time. As demands for water have changed and expanded, the costs of developing additional water sources through large-scale structural solutions have become both prohibitively expensive and socially unacceptable.

The limited opportunities for increasing freshwater supplies suggest that demand management will play an increasing role in balancing the demand-supply relationship and determining the overall benefits derived (Frederick, 1999). The goals of water resources research should evolve to identify: (1) critical water-related problems, (2) social and economic trends altering demands and influencing the degree of vulnerability of system outputs (agriculture, recreation, power and water quality) to extremes of climate variations and to sequences of events, (3) lessons from past events and measures to increase the flexibility of water allocation among users in response to interannual variability and longer-term trends, (4) the types of information that scientists can and should produce to substantiate environmental change, and (5) entry points for the application of scientific information in mitigation measures employed by water managers and decision-makers. The term "applications" as used here means the transformation and communication of relevant research, including forecasts, to meet specific needs of decision-makers in the public and private sectors and the development of the capacity needed to facilitate this process (Crowley et al., 1995). It is difficult for scientists, by themselves, to produce usable information even after the needs of stakeholders are identified. For many scientists, additional risks include overconfidence in the practical values of their research, and underestimating the management of diverse values involved in both assessments and management of risks. Interaction should focus on an understanding of problem definition, framing, and symmetric learning between the two groups or among individuals within them rather than simple advocacy of particular outcomes (Table 3). Thus, one factor in closing the gap between research and practice is a need for researchers to understand the beliefs and assumptions they themselves bring to their work.

Some attention to climate change information is emerging. In the case of California, projected snowpack losses under climate scenarios were so dramatic (up to 90% loss by 2090) that the State scheduled hearings on the issue and has ~~provided~~ offered research resources to provide more detailed studies (Knowles and Cayan, 2002). Importantly, interest has been increasing in paleoclimatic data (i.e., not just the traditional baseline or climate change scenarios). However, in preliminary studies many managers felt that scenarios were good for determining upper and lower bounds but did not address the most likely or relevant outcomes. For the most part, water agencies believe that they can withstand a repeat of past drought patterns given current capacity, and that a significant adaptive response is not necessary.

The gap between conceptual feasibility and practical implementation is immense. A major problem lies in finding new modes of penetrating water management (Jacobs and Pulwarty, 2003). One of Gilbert White's (1966) most important contributions to understanding decision-making about environmental risks was in developing a framework for structuring the analysis of adjustment decisions. He distinguished between the theoretical and practical ranges of choices. The physical environment at a given stage of technology sets the theoretical range of choice open to any resource manager. The practical range of choice is set by culture and institutions, which permit, prohibit, or discourage a given choice. As argued in this paper, an avenue for integration between these two frames may lie in collaborative explorations of information communication and use. While there has been increasing focus on the processes by which knowledge has been produced, less time has been spent examining the capacity of audiences to critically assess knowledge claims made by others for their reliability and relevance to those communities (Fischoff, 1996). The ability of practitioners themselves to manipulate data and to reconcile scientific claims with their own knowledge plays important roles in their choices. There is a strong need for the inquiry into and development of interactive approaches between decisive (policy and operations) and non-decisive (research) participants to take advantage of new opportunities as systems evolve. However, to avoid appearance of advocacy researchers interested in effective use of information should focus on system management needs, as opposed to single stakeholder consultancies. Addressing future climate change will only be effective if careful distillation of lessons of experience (current and past practices) is used to inform planning. In particular it will involve clarification of management goals at the human-environment interface to identify appropriate entry points to support decision-making.

AUTHOR INFORMATION

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