Climate Change Science Program

Uses and Limitations of Observations, Data, Forecasts, and Other Projections in Decision Support for Selected Sectors and Regions

Chapter 5. "Decision Support for Water Resources Management"

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1. Introduction

Water resource managers have long been incorporating information related to climate in their decisions. The tremendous, regionally ubiquitous, investments in infrastructure to reduce flooding (e.g., levees and reservoirs) or assure reliable water supplies (e.g., reservoirs, groundwater development, irrigation systems, water allocation, and transfer agreements) reflect societal goals to mitigate the impacts of climate variability at multiple time and space scales. As the financial, political, social, and environmental costs of infrastructure options have become less tractable, water management institutions have undergone comprehensive reform, shifting their focus to optimizing operations of existing projects and managing increasingly diverse, and often conflicting, demands on the services provided by water resources (Bureau of Reclamation [BOR], 1992; Beard, 1993; Congressional Budget Office, 1997; Stakhiv, 2003; National Research Council [NRC], 2004). Governments have also made substantial investments to improve climate information and understanding over the past decades through satellites, *in situ* measuring networks, supercomputers, and research programs. National and international programs have explicitly identified as an important objective ensuring that improved data products, conceptual models, and predictions are useful to the water resources management community (Endreny et al., 2003; Lawford et al., 2005). Although exact accounting is difficult, potential values associated with appropriate use of accurate hydrometeorologic predictions generally range from the millions to the billions of dollars (e.g., National

Hydrologic Warning Council, 2002). There are also non-monetary values associated with more efficient, equitable, and environmentally sustainable decisions related to water resources.

Droughts, floods, and increasing demands on available water supplies continue to create concern, and even crises, for water resources management. Many communities have faced multiple hydrologic events that were earlier thought to have low probabilities of occurrence (e.g., NRC, 1995), and long-term shifts in streamflows have been observed (Lettenmaier et al., 1994; Lins and Slack, 1999; Douglas et al., 2000), leading to questions about the relative impacts of shifts in river hydraulics, land use, and climate conditions.

Until the last two decades, climate was viewed largely as a collection of random processes, and this paradigm informed much of the water resource management practices developed over the past 50 years that persist today. However, climate is now recognized as a chaotic process, shifting among distinct regimes with statistically significant differences in average conditions and variability (Hansen et al., 1997). As instrumental records have grown longer and extremely long time-series of paleoclimatological indicators have been developed (Ekwurzal, 2005), they increasingly belie one of the fundamental assumptions behind most extant water resources management—stationarity. Stationary time series have time-invariant statistical characteristics (e.g., mean or variance), meaning that different parts of the historical record can be considered equally likely. Within the limits posed by sampling, statistics computed from stationary time series can be used to define a probability distribution that will also then faithfully represent expectations for the future (Salas, 1993).

Further, prospects for climate change due to global warming have moved from the realm of speculation to general acceptance (Intergovernmental Panel on Climate Change [IPCC] 1990, 1995a, 2001a, 2007). The potential impacts of climate on water resources, and their implications for management, have been central topics of concern in climate change assessments (e.g., EPA, 1989; IPCC, 1995b, 2001b; National Assessment Synthesis Team, 2000; Gleick and Adams, 2000; Barnett *et al.,* 2004). These studies are becoming increasingly confident in their conclusions that the future portends statistically significant changes in hydroclimatic averages and variability.

There has been persistent and broad disappointment in the extent to which improvements in hydroclimatic science from large-scale research programs have affected resource management practices in general (Pielke, 1995, 2001; NRC, 1998a, 1999a) and water resource management in particular (NRC, 1998b, 1999b,c). For example, seasonal climate outlooks have been slow to be entered into the water management decision processes, even though they have improved greatly over the past 20 years (Hartmann et al., 2002a, 2003). Water mangers have been even more resistant to incorporating notions of hydrologic non-stationarity in general and climate change in particular in decision processes. Until recently, hydrologic analysis techniques have been seen as generally sufficient (e.g., Matalas, 1997; Lins and Stakhiv, 1998), especially in the context of slow policy and institutional evolution (Stakhiv, 2003). However, an inescapable message for the water resource management community is the inappropriateness of the stationarity assumption in the face of climate change.

Several ongoing efforts are leading the way forward to establish more effective ways of incorporating climate understanding and earth observations into water resources management (Pulwarty, 2002; Office of Global Programs, 2004; NASA, 2005). While diverse in their details, these efforts seek to link hydroclimatological variability, analytical and predictive technologies, and water management decisions within an end-to-end context extending from observational data through large-scale analyses and predictions, uncertainty evaluation, impacts assessment, applications, and evaluations of applications (e.g., Young, 1995; Miles et al., 2000). Some end-to-end efforts focus on cultivating information and management networks; designing processes for recurrent interaction among research, operational product generation, management, and constituent communities; and developing adaptive strategies for accommodating climate variability, uncertainty, and change. Other end-to-end efforts focus on the development of decision support tools (DST) that embody unique resource management circumstances to enable formal and more objective linkages between meteorological, hydrologic, and institutional processes. Typically, end-to-end DST applications are developed for organizations making decisions with high-impact (e.g., state or national agencies) or high-economic value (e.g., hydropower production) and that possess the technical and managerial abilities to efficiently exploit research advances (e.g., Georgakakos et al, 1998, 2004, 2005; Georgakakos, 2006). If linked to socioeconomic models incorporating detailed information about the choices open to decision-makers and their tolerance for risk, these end-to-end tools could also enable explicit assessment of the impacts of scientific and technological research advances.

This chapter describes a river management DST, RiverWare, which facilitates coordinated efforts among the research, operational product generation, and water management communities. RiverWare emerged from an early and sustained effort by several federal agencies to develop generic tools to support the assessment of water resources management options in river basins with multiple reservoirs and multiple management objectives (Frevert et al., 2006). RiverWare was selected for use as a case study because it has been used in a variety of settings, by multiple agencies, over a longer period than many other water management DSTs. Furthermore, RiverWare can explicitly accommodate a broad range of resource management concerns (e.g., flood control, recreation, navigation, water supply, water quality, and power production). RiverWare can also consider perspectives ranging from day-to-day scheduling of operations to long-range planning and can accommodate a variety of climate observations, forecasts, and even climate change projections. RiverWare can incorporate hydrologic risk, whereby event consequences and their magnitudes are mediated by their probability of occurrence, in strategic planning applications and design studies, which can offer a way forward for decision makers reluctant to shift away from use of traditional, stationarity-based, statistical analysis of historical data (Lee, 1999; Davis and Pangburn, 1999).

2. Description of RiverWare

RiverWare is a software framework used to develop detailed models of how water moves and is managed throughout complex river basin systems. RiverWare applications include physical processes (e.g., streamflow, bank storage, and solute transport), infrastructure (e.g., reservoirs, hydropower generating turbines, spillways, and diversion connections), and policies (e.g., minimum instream flow requirements and trades between water users) (Zagona et al., 2001, 2005). At a minimum, RiverWare applications require streamflow hydrographs as input for multiple locations throughout a river system. While hydrographs can be generated within the DST, they can also be input from other sources, with the latter approach being especially important in advanced end-to-end assessments. Detailed discussion of the role of observations and considerations of global change using RiverWare are discussed in later sections. RiverWare can be applied to address diverse water management concerns, including real-time operations, strategic planning for seasonal to interannual variability in water supplies and demands, and examining impacts of hydrologic non-stationarity. Because infrastructure, management rules, and policies can be easily changed, RiverWare also allows examination of alternative options for achieving management objectives over short-, medium-, and long-term planning horizons.

RiverWare was developed by the University of Colorado-Boulder's Center for Advanced Decision Support for Water and Environmental Systems (CADSWES) in collaboration with the BOR, Tennessee Valley Authority, and the Army Corps of Engineers (Frevert et al., 2006). CADSWES continues to develop and maintain the RiverWare software, as well as offer training and support for RiverWare users (see http://cadswes.colorado.edu). According to CADSWES, RiverWare is used by more than 75 federal and state agencies, private sector consultants, universities and research institutes, and water districts, among others.

Example Applications

Consistent with the intent of its original design, the use of RiverWare varies widely, depending on the specific application. An early application was its use for scheduling reservoir operations by the Tennessee Valley Authority (Eshenbach et al., 2001). In that application, RiverWare was used to define the physical and economic characteristics of the multi-reservoir system, including power production economics, to prioritize the policy goals that governed the reservoir operations and to specify parameters for linear optimization of system objectives. In another application, RiverWare was used to balance the competing priorities of minimum instream flows and consumptive water use in the operation of the Flaming Gorge Reservoir in Colorado (Wheeler et al., 2002).

While day-to-day scheduling of reservoir operations is more a function of weather than climate, the use of seasonal climate forecasts to optimize reservoir operations has long been a goal for water resources management. RiverWare is being implemented for the Truckee-Carson River basin in Nevada to investigate the impact of incorporating climate outlooks into an operational water management framework that prioritizes irrigation water supplies, interbasin diversions, and fish habitat (Grantz et al., 2007). Another example application to the Truckee-Carson River using a hypothetical operating policy indicated that fish populations could benefit from purchases of water rights for reservoir releases to mitigate warm summer stream temperatures resulting from low flows and high air temperatures (Neumann et al., 2006).

RiverWare has also been used to evaluate politically charged management strategies, including water transfers proposed in California's Quantification Settlement Agreement and the BOR's Inadvertant Overrun Policy, maintaining instream flows sufficient to restore biodiversity in the Colorado River delta, and conserving riparian habitat while accommodating future water and power development in the BOR Multiple Species Conservation Program (Wheeler et al., 2002). RiverWare also played a key role in negotiations by seven western states concerning how the Colorado River should be managed and the river flow should be distributed among the states during times of drought. The BOR implemented a special version of the RiverWare model of the Colorado River and its many reservoirs, diversions, and watersheds (Jerla, 2005). The model was used to provide support to the Basin States Modeling Work Group Committee over an 18-month period, as they assessed different operational strategies under different hydrologic scenarios, including extreme drought (U.S. Department of Interior, 2007).

Implementation

RiverWare requirements are multi-dimensional. A specific river system and its infrastructure operating policies are defined by data files supplied to RiverWare. This allows incorporation of new basin features (e.g., reservoirs), operating policies, and hydroclimatic conditions without users having to write software code. Utilities within RiverWare enable users to automatically execute many simulations, including accessing external data or exporting results of model runs. Users can also write new modules that CADSWES can integrate into RiverWare for use in other applications. For example, in an application for the Pecos River in New Mexico, engineers developed new methods and software code for realistic downstream routing of summer monsoon-related flood waves (Boroughs and Zagona, 2002). RiverWare is implemented for use on Windows or Unix Solaris systems, as described in the requirements document (http://cadswes.colorado.edu/PDF/RiverWare/RecommendedMinimumSystemsRequirements.pdf). An extensive manual is also available (http://cadswes.colorado.edu/PDF/ReleaseNotes/ RiverWareHelp.pdf).

RiverWare applications can be implemented by any group that can pay for access, both in terms of finances and educational effort. Development of RiverWare applications requires a site license from

CADSWES. Significant investment is required to learn to use RiverWare as well. CADSWES offers two 3-day RiverWare training courses, an initial class covering general simulation modeling, managing scenarios, and incorporating policy options through rule-based simulation, and a second class covering rule-based simulation in more detail, creating basin policies, and examining water policy options. Costs for the original license, annual renewals, technical support, and training require several thousand dollars. The costs of licensing and learning RiverWare mean that small communities and civic groups are unlikely to implement their own applications for assessing water management options. Rather, large agencies with technical staff or the financial means to fund university research or consultants are the most frequent users of RiverWare. The agencies then mediate the access of stakeholders to assessments of water management options through traditional public processes (e.g., U.S. Department of Interior, 2007). Conflicts may arise in having academic research groups conduct analyses funded by stakeholder groups, with inherent tensions between the open publication of research required by academia and the limited access to results required by strategic negotiations among interest groups.

3. Current and Future Use of Observations

The specific combination of observations used by a RiverWare application depends on both the decision context and the use of other models and DSTs to provide input to RiverWare that more comprehensively or accurately describes the character, conditions, and response of the river basin system. Figure 1 illustrates the information flow linking observations, RiverWare, other models and DSTs, and water management decisions; it shows that RiverWare has tremendous flexibility in the kinds of observations that could be useful in hydrologic modeling and river system assessment and management. The types of observations that may ultimately feed into RiverWare applications also depend on the timescale of the situation.

A detailed discussion of the role of satellite observations in RiverWare applications and selected input models and DSTs (e.g., the BOR's ET Toolbox and Precipitation Runoff Modeling System [PRMS]) is given by the "Evaluation Report for AWARDS ET Toolbox and RiverWare Decision Support Tools" (Hydrological Sciences Branch, 2007). Briefly, RiverWare can use a combination of observations from multiple sources, including satellites, products derived from land-atmosphere or hydrologic models, and combinations of both. Satellite observations can assist models in estimating evapotranspiration, precipitation, snow water equivalent, soil moisture, groundwater storage and aquifer volumes, reservoir storage, and water quality, among other variables. Measurements from sensors aboard a variety of satellites are being considered for their usefulness within DST contexts and their impacts on reducing water management uncertainty, including the MODIS (Moderate Resolution Imaging Spectroradiometer) sensor aboard the Earth Observing System (EOS) Terra and Aqua satellites, Landsat TM data, Advanced Spaceborne Thermal Emission and Reflection Radiometer (ASTER), Shuttle Radar Topography Mission (SRTM), Advanced Microwave Scanning Radiometer–EOS (AMSR-E), Gravity Recovery and Climate Experiment (GRACE), and Tropical Rainfall Mapping Mission (TRMM), among others. Future and planned satellites with hydrologically relevant sensors and measurements include CloudSAT, the Global Precipitation Mission (GPM), and the National Polar-Orbiting Operational Environmental Satellite (NPOESS). Use of these observations can be enhanced by assimilating them into land surface models to produce spatially-distributed estimates of snowpack, soil moisture, evapotranspiration, energy fluxes, and runff, which then provide inputs to RiverWare to base a more comprehensive assessment of river basin conditions. The land surface models include the Community Land Model (CLM), Mosaic, Noah, and VIC, among others, supported by NASA's Land Data Assimilation System (LDAS) and Land Information System (LIS) (NASA, 2006a).

NASA has several pilot projects specifically focused on assessing the impact of satellite observations in a variety of hydrologic models and DSTs as they feed into RiverWare applications (NASA, 2005, 2006b, 2007). For example, one project is comparing Terra and Aqua MODIS snow cover products for the Yakima-Columbia River basins with land-based snow telemetry measurements, testing their use for LIS simulations that also use the North American LDAS, connecting assimilated snow data with the Modular Modeling System (MMS) Precipitation-Runoff Modeling System (PRMS), and then supplying the simulated runoff as inputs to RiverWare. Another project on the Rio Grande River basin is assessing MODIS and Landsat data to improve evapotranspiration estimates generated by the BOR DST, the Agricultural Water Resources Decision Support (AWARDS) ET Toolbox, which then provides water demand time series to RiverWare. While application of specific hydrologic models and observations depend on the specific RiverWare application, significant processing of both model and observations are required and can be resource intensive (e.g., calibration and aggregation/disaggregation).

Operational scheduling of reservoir releases depend on orders of water from downstream users (e.g., irrigation districts) that are largely affected by day-to-day weather conditions as well as seasonally varying demands. In these cases, the important observations are the near real-time estimates of conditions within the river basin system (e.g., soil moisture or infiltration capacity), which affect the transformation of precipitation into runoff into the river system, relative to constraints on system operation (e.g., reservoir storage levels or water temperatures at specific river locations). Meteorological prospects are mediated by those placing the water orders or through short-term weather forecasts that may affect operations when the system is near some constraint (e.g., flood flows when reservoir levels are near peak storage capacity). In these situations, the important observations are recent extreme precipitation events and their location, which may be provided, separately or in some combination, by *in situ* monitoring networks, radar, or satellites.

For mid-range applications, such as strategic planning for operations over the next season or year, outlooks of total seasonal water supplies are routinely used in making commitments for water deliveries, determining industrial and agricultural water allocation, and carrying out reservoir operations. In these applications, it is also important for water managers to keep track of the current state of the watershed. Such observations are often used as input to one of the many independent hydrologic models that can provide input to a specific RiverWare application. In these situations, the important observations are those that provide boundary or forcing conditions for the independent hydrologic models, including snowpack moisture storage, soil moisture, precipitation (intensity, duration, and spatial distribution), air temperature, humidity, winds, and other meteorological conditions.

For long-term planning and design applications, observations are less important because the effects of recent conditions have less impact on long-term outcomes than future meteorological uncertainty, or even institutions at multi-decadal time scales. In these applications, accurate representation of anticipated natural hydroclimatological variability is important. In many western U.S. applications, observed streamflows are adjusted to remove the effects of reservoir management, interbasin diversions, and water withdrawals. The adjusted flows, termed “naturalized flows.” may be used as input to RiverWare applications to assess the impact of different management options. Use of naturalized flows is fraught with problems. A central issue is poor monitoring of actual human impacts, especially withdrawals, diversions, and return flows (e.g., from irrigation). Alternative approaches include the use of proxy streamflows (e.g., from paleoclimatological indicators) or output from hydrologic modeling studies (Hartmann, 2005). For example, Tarboton (1995) developed hydrologic scenarios for severe sustained drought in the Colorado River basin based on streamflows reconstructed from centuries of tree-ring records; the scenarios were used in an assessment of management options using a precursor to the current RiverWare application to the Colorado River system.

The usefulness of the observations used within RiverWare depends on the specific implementation, as well as the quality of the information itself. For example, one direct use of climate information for long-term planning includes hydrologic and hydraulic routing of "design storms" of various magnitudes and likelihoods, with the storms based on analyses of the available instrumental record (Urbanas and Roesner, 1993). However, those instrumental records have often been too short to adequately express climate variability and resulting impacts, regardless of the specific DSTs used to do the hydrologic or hydraulic routing. In short- and mid-range forecasting applications, the use of observations is mediated by the hydrologic model or DST that transforms weather and climate into streamflows, evaporative water demands, and other hydrologic processes. In these situations, from an operational perspective, the stream of observational inputs must be dependable, without downtime or large data gaps, and data processing, model simulation, and creation of forecast products must be fast and efficient. The usefulness of observations may be limited by other issues as well. The water resources management milieu is complex and diverse, and climate influences are only one factor among many affecting water management policies and practices. Factors limiting the use of observations or subsequent hydrologic model input to RiverWare for actual water management include lack of familiarity with the available information, disconnects between the specific information available (e.g., variables and spatiotemporal scales) and their relevance to decision makers, skepticism about the quality and applicability of information, conservative decision preferences due to accountability for poor consequences, and institutional impediments such as the inflexible nature of many multi-jurisdictional water management agreements (Changnon, 1990; Kenney, 1995; Pulwarty and Redmond, 1997; Pagano et al., 2001, 2002; Jacobs, 2002; Jacobs and Pulwarty, 2003; Rayner et al., 2005).

4. Uncertainty

The reliability of observations for driving hydrologic models that may provide input to RiverWare applications is the subject of much ongoing research. The hydrologic models, because they incompletely describe the physical relationships among important watershed components (e.g., vegetation processes that link the atmosphere and different levels of soil and surface and groundwater interactions), are themselves the subject of much research to determine their reliability. Streamflow and other hydrologic variables are intimately responsive to atmospheric factors, especially precipitation, that drive a watershed's behavior; however, errors in precipitation estimates are often amplified in the hydrologic response (Oudin et al., 2006).

Obtaining quality precipitation estimates is a formidable challenge, especially in the western U.S. where orographic effects produce large spatial variability and where there is a scarcity of real-time precipitation gage data and radar beam blockage by mountains. In principal, outputs from atmospheric models can serve as surrogates for observations, as well as providing forecasts of meteorological variables that can be used to drive hydrologic models. One issue in integrating atmospheric model output into hydrologic models for small watersheds (<1000 km^2) is that the spatial resolution of atmospheric models is lower than the resolution of hydrologic models. For example, quantitative precipitation forecasts (QPF) produced by some atmospheric models may cover several thousand square kilometers, but the hydrologic models used for predicting daily streamflows require precipitation to be downscaled to precipitation fields for watersheds covering only tens or hundreds of square kilometers. One approach to produce output consistent with the needs of hydrologic models is to use nested atmospheric models, whereby outputs from large scale but coarse resolution models are used as boundary conditions for models operating over smaller domains with higher resolution. However, the error characteristics of atmospheric model products (e.g., bias in precipitation and air temperature) also can have significant effects on subsequent streamflow forecasts. Bias corrections require knowledge of the climatologies (i.e., long-term distributions) of both modeled and observed variables.

Although meteorological uncertainty may be high for the periods addressed by streamflow forecasts, accurate estimates of the state of watershed conditions prior to the forecast period are important because they are used to initialize hydrologic model states, with significant consequences for forecast results. However, watershed conditions can be difficult to measure, especially when streamflow forecasts must be made quickly, as in the case of flash flood forecasts. One option is to continuously update watershed states by running the hydrologic models continuously and by using inputs from recent meteorological observations and/or atmospheric models. Regardless of the source of inputs, Westrick et al. (2002) found it essential to obtain observational estimates of initial conditions to keep streamflow forecasts realistic; storm-by-storm corrections of model biases determined over extended simulation periods were insufficient. Recent experimental end-to-end forecasts of streamflow produced in a simulated operational setting (Wood et al., 2001) highlighted the critical role of quality estimates of spring and summer soil moisture used to initialize hydrologic model states for the eastern U.S.

Where streamflows may be largely comprised of snowmelt runoff, quality estimates of snow conditions are important. The importance of reducing errors in the timing and magnitude of snowmelt runoff are especially acute in regions where a large percentage of annual water supplies derive from snowmelt runoff, snowmelt impacts are highly non-linear with increasing deviation from long-term average supplies, and reservoir storage is smaller than interannual variation of water supplies. However, resources for on-site monitoring of snow conditions have diminished rather than grown, relative to the increasing costs of errors in hydrologic forecasts (Davis and Pangburn, 1999). Research activities of the NWS National Office of Hydrology Remote Sensing Center (NOHRSC) have long been directed at improving estimates of snowpack conditions through aerial and satellite remote sensing (Carroll, 1985). However, the cost of aerial flights prohibits routine use (T. Carroll, NOHRSC, personal communication, 1999), while satellite estimates have qualitative limitations (e.g., not considering fractional snow coverage over large regions) and have not found broad use operationally.

Multiple techniques exist to more accurately represent the uncertainty inherent in understanding and predicting potential hydroclimatic variability. Stochastic hydrology techniques use various forms of autoregressive models to generate multiple synthetic streamflow time series with statistical characteristics matching available observations. For example, in estimating the risk of low flows for the Sacramento River

Basin in California, the BOR (Frevert et al., 1989) generated 20 one-thousand-year streamflow time series matching selected statistics of observed flows (adjusted to compensate for water management impacts on natural flows); the non-exceedance probabilities of low flows were computed by counting the occurrences of low flows within 1- through 10-year intervals for all 20 one-thousand-year sequences. The U.S. Army Corps of Engineers (1992) used a similar approach to estimate flood magnitudes with return periods exceeding 1,000 years, using Monte Carlo sampling from within the 95% confidence limits of a Log Pearson III distribution developed by synthesizing multiple streamflow time series.

The ability to automatically execute many model runs within RiverWare, including accessing data from external sources and exporting model results, facilitates using stochastic hydrology approaches for representing uncertainty. For example, Carron et al. (2006) demonstrated RiverWare's capability to identify and quantify significant sources of uncertainty in projecting river and reservoir conditions, using a first-order, second-moment (FOSM) algorithm that is computationally more efficient than more traditional Monte Carlo approaches. The FOSM processes uncertainties in inputs and models to provide estimates of uncertainty in model results that can be used directly within a risk management decision framework. The case study presented by Carron et al. (2006) evaluated the uncertainties associated with meeting goals for reservoir water levels beneficial for recovering endangered fish species within the lower Colorado River.

With regard to RiverWare applications concerned with mid-range planning and use of hydrologic forecasts, at the core of any forecasting system is the predictive model, whether a simple statistical relationship or a complex dynamic numerical model. Advances in hydrologic modeling have been notable, especially those associated with the proper identification of a model's parameters (e.g., Duan et al., 2002) and the development of models that consider the spatially distributed characteristics of watersheds, rather than treating entire basins as a single point (Grayson and Bloschl, 2000). Conceptual rainfall-runoff models offer some advantages over statistical techniques in support of long-range planning for water resources management. These models represent, with varying levels of complexity, the transformation of precipitation and other meteorological forcing variables (e.g., air temperature and humidity) to watershed runoff and streamflow, including accounting for hydrologic storage conditions (e.g., snowpack, soil moisture, and groundwater). These models can be used to assess the impacts and implications of various climate scenarios by using historic meteorological time series as input, generating hydrologic time series, and then using those hydrologic scenarios as input to RiverWare. This approach enables consideration of current landscape and river channel conditions, which may be quite different than recorded in early instrumental records and which can dramatically alter a watershed's hydrologic behavior (Vorosmarty et al., 2004). Furthermore, the use of multiple input time series, system parameterizations, or multiple models, enables a probabilistic assessment of an ensemble of scenarios. The Hydrological Ensemble Prediction Experiment (HEPEX) (Schaake et al., 2007) aims to address the unique challenges of expressing uncertainty associated with ensemble forecasts for water resources management.

An additional concern for mid- and long-range planning is that, as instrumental records have grown longer, they often show trends (e.g., Baldwin and Lall, 1999; Olsen et al., 1999; Andreadis and Lettenmaier, 2006) or persistent regimes (i.e., periods characterized by distinctly different statistics) (e.g., Angel and Huff, 1995; Quinn, 1981, 2002), with consequences for estimation of hydrologic risk (Olsen et al., 1998). Observed regimes and trends can have multiple causes, including climatic changes, watershed and river transformations, and management impacts (e.g., irrigation return flows and trans-basin water diversions). These issues enter into RiverWare applications directly through the use of naturalized flows, which are notoriously unreliable. For example, in assessments of water management options on the San Juan River in Colorado and New Mexico, the reliability of naturalized flows was considered to be affected by the inconsistent accounting of consumptive uses between irrigation and non-irrigation data, use of reservoir evaporation rates with no year-to-year variation, neglecting time lags in the accounting of return flows from irrigation to the river, errors in river gage readings that underestimated flows in critical months, and the lack of documentation of diversions that reduce river flows as well as subsequent adjustments to data used to compute naturalized flows.

5. Global Change Information and RiverWare

Climate Variability

Decision makers increasingly recognize that climate is an important source of uncertainty and potential vulnerability in long-term planning for the sustainability of water resources (Hartmann, 2005). With the appropriate investment in site licenses, training of personnel, implementation for a specific river system, and assessment efforts, RiverWare is capable of supporting climate-related water resources management decisions by U.S. agencies. However, technology alone is insufficient to resolve conflicts among competing water uses. Early in the development of RiverWare, Reitsma et al. (1996) investigated its potential role as a DST within complex negotiations between hydroelectric, agricultural, and flood control interests. Results indicated that while DSTs can help identify policies that can satisfy specific management requirements and constraints, as well as expand the range of policy options considered, they are of limited value in helping decision makers understand interactions within the river system. Furthermore, the burdens of direct use by decision makers of a DST that embodies a complex system are significant; a more useful approach is to have specialists support decision makers by making model runs and presenting the results in an iterative manner. This is the approach used by the Bureau of Reclamation in the application of RiverWare to support interstate negotiations concerning the sharing of Colorado River water supply shortages during times of drought (Jerla, 2005; U.S. Department of Interior, 2007).

From the perspective of mid-range water management issues, the use of forecasts within RiverWare applications constitutes an important pathway for supporting climate-related decision making. Each time a prediction is made, science has an opportunity to address and communicate the strengths and limitations of current understanding. Each time a decision is made, managers have an opportunity to confront their understanding of scientific information and forecast products. Furthermore, each prediction and decision provides opportunities for interaction between scientists and decision makers and for making clear the importance of investments in scientific research. Perceptions of poor forecast quality are a significant barrier to more effective use of hydroclimatic forecasts (Changnon, 1990; Pagano et al., 2001, 2002; Rayner et al., 2005); however, recent advances in modeling and predictive capabilities naturally lead to speculation that hydroclimatic forecasts can be used to improve the operation of water resource systems.

Great strides have been made in monitoring, understanding, and predicting interannual climate phenomena such as the El Nino-Southern Oscillation (ENSO). This improved understanding has resulted in long-lead (up to about a year) climate forecast capabilities that can be exploited in streamflow forecasting. Techniques have been developed to directly incorporate variable climate states into probabilistic streamflow forecast models based on linear discriminant analysis (LDA) with various ENSO indicators, (e.g., the Southern Oscillation Index [SOI]) (Peichota and Dracup, 1999; Piechota et al., 2001). Recent improved understanding of decadal-scale climate variability also has contributed to improved interannual hydroclimatic forecast capabilities. For example, the Pacific Decadal Oscillation (PDO) (Mantua et al., 1997) has been shown to modulate ENSO-related climate signals in the West. Experimental streamflow forecasting systems for the Pacific Northwest have been developed based on long-range forecasts of both PDO and ENSO (Hamlet and Lettenmaier, 1999). In the U.S., the Pacific Northwest, California, and the Southwest are strong candidates for the use of long-lead forecasts because ENSO and PDO signals are particularly strong in these regions and each region's water supplies are closely tied to accumulation of winter snowfall, amplifying the impacts of climatic variability.

While many current water management decision processes use single-value deterministic approaches, probabilistic forecasts enable quantitative estimation of the inevitable uncertainties associated with weather and climate systems. From a decision maker's perspective, probabilistic forecasts are more informative because they explicitly communicate uncertainty and are more useful because they can be directly incorporated into risk-based calculations. Probabilistic forecasts of water supplies can be created by overlaying a single prediction with a normal distribution of estimation error determined at the time of calibration of the forecast equations (Garen, 1992). However, to account for future meteorological uncertainty, new developments have focused on ensembles, whereby multiple possible futures (each termed an ensemble trace) are generated; statistical analysis of the ensemble distribution then provides the basis for a probabilistic forecast.

Changnon (2000), Rayner et al. (2005), and Pagano et al. (2002) found that improved climate prediction capabilities are initially incorporated into water management decisions informally, using subjective, ad hoc procedures on the initiative of individual water managers. While improvised, those decisions are not necessarily insignificant. For example, the Salt River Project, among the largest water management agencies in the Colorado River Basin and primary supplier to the Phoenix metropolitan area, decided in August 1997 to substitute groundwater withdrawals with reservoir releases, expecting increased surface runoff during a wet winter related to El Nino. With that decision, they risked losses exceeding $4 million in an attempt to realize benefits of $1 million (Pagano et al., 2002). Because these informal processes are based in part on confidence in the predictions, overconfidence in forecasts can be even more problematic than lack of confidence, as a single incorrect forecast that provokes costly shifts in operations can devastate user confidence in subsequent forecasts (e.g., Glantz, 1982).

The lack of verification of hydroclimatic forecasts is a significant barrier to their application in water management, but it is not easy to resolve with traditional research efforts, because the level of acceptable skill varies widely depending on the intended use (Hartmann et al., 2002a; Pagano et al., 2002). Information on forecast performance has rarely been available to, and framed for, decision makers, although hydrologic forecasts are reviewed annually by the issuing agencies in the U.S (Hartmann et al., 2002b). Hydrologic forecast verification is an expanding area of research (Franz et al., 2003; Hartmann et al., 2003; Bradley et al, 2004; Pagano et al., 2004; Kruger et al., 2007), but much work remains and could benefit from approaches developed within the meteorological community (Welles et al., 2007). Because uncertainty exists in all phases of the forecast process, forecast systems designed to support risk-based decision making need to explicitly quantify and communicate uncertainties from the entire forecast system and from each component source, including model parameterization and initialization, meteorological forecast uncertainty at the multiple spatial and temporal scales at which they are issued, adjustment of meteorological forecasts (e.g., through downscaling) to make them usable for hydrologic models, implementation of ensemble techniques, and verification of hydrologic forecasts.

Climate Change

From the perspective of long-range water management issues, the potential impacts of climate change on water resources, and their implications for management, are central topics of concern. Estimates of prospective impacts of climate change on precipitation have been mixed, leading, in many cases, to increasing uncertainty about the reliability of future water supplies. However, where snow provides a large fraction of annual water supplies, prospective temperature increases dominate hydrologic impacts, leading to stresses on water resources and increased hydrologic risk. Higher temperatures effectively shift the timing of the release of water stored in the snowpack “reservoir” to earlier in the year, reducing supplies in summer when demands are greatest, while also increasing the risk of floods due to rain-on-snow events. While not using RiverWare, several river basin studies have assessed the risks of higher temperatures on water supplies and management challenges. The near universal analytical approach has been one of sensitivity analysis (Lettenmaier, 2003):

1) downscaling outputs from a dynamic general circulation model of the global land-atmosphere-ocean system to generate regional- or local-scale meteorological time series over many decades,
2) using the meteorological time series as input to rainfall-runoff models to generate hydrologic time series,
3) using the hydrologic scenarios as input to water management models, and
4) assessing differences among baseline and change scenarios using a variety of metrics.

Early assessments of warming impacts on large river basins generally showed extant water management systems to be effective for all but the most severe scenarios (Hamlet and Lettenmaier, 1999; Lettenmaier et al., 1999), with a notable exception being the Great Lakes system where increased lake heat storage was tied to loss of ice cover, increased winter lake evaporation, lower lake levels, and potential failure to meet Lake Ontario regulation objectives under extant operating rules (Croley, 1990; Hartmann, 1990; Lee et al., 1994; Lee et al., 1997; Sousounis et al., 2000; Lofgren et al., 2002).

Extensive detailed studies of the ability of existing reservoir systems and operational regulation rules to meet water management goals under changed climates are fairly recent (e.g., Saunders and Lewis, 2003; Christensen, et. al, 2004; Payne et. al, 2004; VanRheenan et. al, 2004; Maurer, 2007). However, there is a rapidly growing literature on broad considerations of climate change in water resources management (Frederick et al., 1997; Gamble et al., 2003; Lettenmaier, 2003; Loomis et al., 2003; Snover et al., 2003; Stakhiv, 2003; Ward et al., 2003; Vicuna et al., 2007). Some (Matalas, 1997) that contend that existing approaches are sufficient for water resource management planning and risk assessment because they contain safety factors; however, an inescapable message for the water resource management community is the inappropriateness of the stationarity assumption in the face of climate change. While precipitation changes may remain too uncertain for consideration in the near term, temperature increases are more certain and can have strong hydrologic consequences.

Cognitively, climate change information is difficult to integrate into water resources management. First, within the water resources engineering community, the stationarity assumption is a fundamental element of professional training. Second, the century timescales of climate change exceed typical planning and infrastructure design horizons and are remote from human experience. Third, even individuals trying to stay up-to-date can face confusion in conceptually melding the burgeoning climate change impacts literature. Assessments are often repeated as general circulation and hydrologic model formulations advance or as new models become available throughout the research community. Furthermore, assessments can employ a variety of techniques for downscaling. Transposition techniques (e.g., Croley et al., 1998) are more intuitive than the often mathematically complex statistical and dynamical downscaling techniques (e.g., Clark et al., 1999; Westrick and Mass, 2001; Wood et al., 2002; Benestad, 2004).

GCMs and their downscaled corollaries provide one unique perspective on long-term trends related to global change. Another unique perspective is provided by tree-ring reconstructions of paleo-streamflows, which, for example, indicate that in the U.S. Southwest droughts over the past several hundred years have been more intense, regionally extensive, and persistent than those reflected in the instrumental record (Woodhouse and Lukas, 2006). Decision makers have expressed interest in combining the perspectives of paleoclimatological information and GCMs. While some studies have linked instrumental records to paleoclimatological information (e.g., Prairie, 2006) and others with GCMs (e.g., Christensen and Lettenmaier, 2006), few link all three (an exception is Smith et al., 2007).

Conceptual integration of climate change impacts assessment results in a practical water management context is complicated by the multiplicity of scenarios and vague attribution of their prospects for occurrence, which depend so strongly on feedbacks among social, economic, political, technological, and physical processes. For decision makers, a critical issue concerns the extent to which the various scenarios reflect the actual uncertainty of the relevant risks versus the uncertainty due to methodological approaches and biases in underlying models. The difficulties facing decision makers in reconciling disparate climate change impact assessments are exemplified by the Upper Colorado River Basin, where reductions in naturalized flow by the mid-21st century have been estimated to range from about 45% by Hoerling and Eischeid (2007), 10 to 25% by Milly et al (2005), about 18% by Christensen et al. (2004), and about 6% by Christensen and Lettenmaier (2006). Furthermore, using the difference between precipitation and evapotranspiration as a proxy for runoff, Seager et al. (2007) suggest an “imminent transition to a more arid climate in southwestern North America.”

However, in the face of circumstances nearing or exceeding the effectiveness of existing management paradigms, individuals can become more cognizant of the need to consider climate change. In the U.S. Southwest, over 1999–2004, Lake Powell levels declined faster than previously considered in scenarios of extreme sustained drought (e.g., Harding et al., 1995; Tarboton, 1995), from full to only 38% capacity in November 2004 (BOR, 2004). Resource managers, policymakers, and the general public are now actively seeking scientific guidance in exploring how management practices can be more responsive to the uncertainties associated with a changing climate.