JOURNAL OF THE AMERICAN WATER RESOURCES ASSOCIATION

Vol. 44, No. 2 AMERICAN WATER RESOURCES ASSOCIATION April 2008

# MODELS, ASSUMPTIONS, AND STAKEHOLDERS: PLANNING FOR WATER SUPPLY VARIABILITY IN THE COLORADO RIVER BASIN[1]

*Dustin Garrick, Katharine Jacobs, and Gregg Garfin*[2]

ABSTRACT: Declining reservoir storage has raised the specter of the first water shortage on the Lower Colorado River since the completion of Glen Canyon and Hoover Dams. This focusing event spurred modeling efforts to frame alternatives for managing the reservoir system during prolonged droughts. This paper addresses the management challenges that arise when using modeling tools to manage water scarcity under variable hydroclimatology, shifting use patterns, and institutional complexity. Assumptions specified in modeling simulations are an integral feature of public processes. The policymaking and management implications of assumptions are examined by analyzing four interacting sources of physical and institutional uncertainty: inflow (runoff), depletion (water use), operating rules, and initial reservoir conditions. A review of planning documents and model reports generated during two recent processes to plan for surplus and shortage in the Colorado River demonstrates that modeling tools become useful to stakeholders by clarifying the impacts of modeling assumptions at several temporal and spatial scales. A high reservoir storage-to-runoff ratio elevates the importance of assumptions regarding initial reservoir conditions over the three-year outlook used to assess the likelihood of reaching surplus and shortage triggers. An ensemble of initial condition predictions can provide more robust initial conditions estimates. This paper concludes that water managers require model outputs that encompass a full range of future potential outcomes, including best and worst cases. Further research into methods of representing and communicating about hydrologic and institutional uncertainty in model outputs will help water managers and other stakeholders to assess tradeoffs when planning for water supply variability.

(KEY TERMS: drought; water supply variability; public planning; river system models; Colorado River; water management.)

Garrick, Dustin, Katharine Jacobs, and Gregg Garfin, 2008. Models, Assumptions, and Stakeholders: Planning for Water Supply Variability in the Colorado River Basin. *Journal of the American Water Resources Association* (JAWRA) 44(2):381-398. DOI: 10.1111/j.1752-1688.2007.00154.x

## INTRODUCTION

From 2001 to 2004, Colorado River Basin (Basin) water managers and users experienced a "focusing event" (Pulwarty and Melis 2001): unexpectedly rapid declines in reservoir storage because of prolonged drought conditions. By April 8, 2005, the Colorado River's second largest reservoir, Lake Powell, dropped to its lowest elevation since 1968 after five

[1]Paper No. J06041 of the *Journal of the American Water Resources Association* (JAWRA). Received March 18, 2006; accepted July 27, 2007.  **Discussions are open until August 1, 2008**.

[2]Respectively, PhD Candidate, Geography and Regional Development, University of Arizona, Harvill #2, Tucson, Arizona 85721; Executive Director, Arizona Water Institute, Marshall Building, 5th Floor, 845 N Park Ave, Tucson, Arizona 85721; and Program Manager, Climate Assessment for the Southwest, Institute for the Study of Planet Earth, University of Arizona, 715 N. Park Ave., 2nd Fl., Tucson, Arizona 85721-0156 (E-Mail/Garrick: dgarrick@email.arizona.edu).

successive years of below average inflow from 2000 to 2004 (USBR, 2005). Importantly, declines in Basin reservoir storage from 2001 to 2004 were not anticipated during the modeling simulations generated in December 2000 to formulate Interim Surplus Guidelines (ISG) for regulating water supplies during high reservoir conditions (USDOI, 2000). The divergence between actual and simulated conditions after the ISG planning process highlights the need to evaluate how decision makers incorporate and utilize model outputs during long-range planning processes.

Even though observed conditions from 2001 to 2004 were not encompassed within the range of simulated outcomes generated during the ISG planning process, U.S. Bureau of Reclamation (hereafter "Reclamation") and state water department managers within the Basin carefully note that this discrepancy should not be construed as a shortcoming of the Colorado River Simulations System (CRSS) – the river simulation model used for long-term planning analyses and policy evaluation in the Colorado River Basin (USDOI, 2000; Zagona *et al.*, 2001). Rather, this experience prompts several questions regarding the role of river system models in managing and planning for water supply variability and the ability of such models to predict outcomes that are outside the range of historic experience.

Which factors enable and constrain the effectiveness of river system models in public decision-making efforts conducted under climatic and institutional uncertainties? What are the water management implications of such uncertainty? While the answers to these questions are complex, the assumptions specified in river system simulations are a fundamental – and often poorly understood – component of public decision-making processes. The Colorado River provides an excellent arena for exploring these dynamics because of the integral role played by river system modeling in Basin water operations and planning.

This paper analyzes the role of modeling and uncertainty in water management by examining two public planning efforts. These processes involved formal rulemaking to devise (1) interim surplus guidelines (1996-2001) and (2) criteria for managing shortage conditions and coordinating basin-wide reservoir operations (2004-2007). The modeling assumptions and outputs used during the first process – surplus planning – have been revisited and scrutinized during the second process – drought planning – as Colorado River Basin managers devise shortage guidelines and criteria for coordinating management of Lakes Powell and Mead.

Simulation modeling for long-range planning in the Colorado River mirrors a Western US-wide trend in which river system modeling has emerged as one of the central components of public and technical water management decision-making processes. (For a comprehensive overview of river system modeling, see Wurbs, 2005.)

This paper analyzes the public planning implications of the Colorado River Simulation System (CRSS). This research also seeks to supplement the growing body of literature examining the role of scientific information and uncertainty in decision-making processes that involve varying degrees of public involvement (Carter and Morehouse, 2001; Jacobs and Pulwarty, 2003; Morss *et al.*, 2005; Pielke, 2003; Pulwarty and Redmond, 1997; Stewart *et al.*, 2004). The need for decision-support tools and applied interdisciplinary research on water management reflects growing recognition of the shortage risks associated with sustained dry conditions as well as changing demands on water resources. These trends have led to several partnerships between agencies and academic researchers seeking to integrate information on hydoclimatic variability into Basin water management (e.g., Hirshboeck and Meko, 2005; Woodhouse and Lukas, 2006). Several of the early efforts have analyzed the interactions among stakeholders, applied science, and uncertainty in various water management contexts, such as flood control (Morss *et al.*, 2005), climatic variability, and water quality (Jacobs and Pulwarty, 2003).

## OBJECTIVES

This paper addresses four objectives to understand the nexus of river system modeling and water management institutions in the multi-reservoir and multi-stakeholder Colorado River system: (1) clarifying water managers' needs and expectations of river system models; (2) evaluating how river system modeling has been used to manage water supply variability in the Colorado River Basin; (3) identifying the focal assumptions that drive the model outputs; and, (4) analyzing how these assumptions interact at different time scales and within different decision-making and planning contexts. Consequently, the paper is organized into four main parts and a conclusion section.

The first section describes the stakeholder-engagement process that was used to identify the needs and expectations of river system models in public planning processes for water supply under variable conditions. The next section traces the historical evolution of CRSS and its predecessors to understand how such modeling efforts have supported increasingly public decision-making efforts. The third section describes and analyzes the assumptions that drove the modeling environment in two recent efforts to cope with deviations from "normal" conditions within the Colorado River Basin. A fourth section explores how modeling assumptions and the uncertainties they engender can interact during complex and value-laden efforts to define and choose among management alternatives. The final section summarizes key management implications of assumptions, modeling and public planning across diverse stakeholder bodies. Throughout the course of the paper, this analysis will consider how experiences in the Colorado River Basin both inform and reflect wider trends in the United States (U.S.) and international water management contexts.

*Objective 1: Stakeholder Engagement and Observation – Clarifying Needs and Expectations of River System Modeling*

The authors pursued a two-part research design that involved direct and indirect stakeholder engagement at each stage of the research from issue identification and data collection through analysis and reporting. The goals of the stakeholder engagement process were to evaluate how water managers address the uncertainties inherent in river system models and to clarify the needs and expectations of different stakeholder groups when applying modeling resources to public planning efforts. In this study, stakeholders include a set of Lower Colorado River water managers and user groups involved in Basin-wide planning efforts to cope with water supply variability. The research design included (1) focus group sessions with Arizona water managers and user groups and (2) analysis of historic and current planning processes dedicated to choosing among management alternatives for operating reservoirs and allocating water supplies under variable conditions.

First, the authors conducted focus groups sessions with water managers and users in Arizona to identify issues important to decision makers grappling with management challenges associated with water supply variability. Stakeholder groups included the U.S. Bureau of Reclamation, Arizona Department of Water Resources (ADWR), Salt River Project, Central Arizona Project, and municipal water contractors in Central Arizona. Although these five groups were selected because of their focal role in basin-wide planning processes, other important actors (such as irrigation districts and conservation nonprofit organizations) also participated in the planning processes that we observed. Authors met with each focus group in two- to four-hour sessions, which involved a 20-min presentation to structure feedback on research priorities. The authors prioritized stakeholder concerns according to two criteria: (1) salience of the topic as measured by the fact that it was mentioned by two or more stakeholder groups, and (2) fit between stakeholder concerns and the research project's substantive focus on water supply reliability and decision-support in the Lower Colorado River Basin. This prioritization process yielded two overarching questions focusing on the relationship between water manager stakeholders and river system modeling, namely: (1) What are the key assumptions and sources of uncertainty underlying river system modeling in the Colorado River Basin, and what are the management implications of these assumptions? (2) How can river simulation models aid public decision-making processes in the context of water supply variability and shortage conditions? This paper addresses the first question in full and responds to the second question in part before outlining future research directions.

In the second part of the research method, the authors reviewed and analyzed archival documents and reports associated with current and previous Basin planning efforts, particularly the Interim Surplus Guidelines public planning process and the initial phases of shortage criteria development. The importance of examining these archival sources, policy documents, and model reports is to provide a benchmark for understanding the role of assumptions in past planning processes to manage water supply variability. As outlined below, the Colorado River Basin resembles many other water management contexts because of the need to optimize management decisions in light of changes in demand and variable supply conditions. The modeling assumptions and scientific uncertainties that become encoded into water management institutions are not usually well articulated or analyzed until they are re-evaluated with the knowledge of hindsight. The records of these prior planning processes yielded numerous insights about stakeholder expectations and the role of experts in framing the analysis. These archival sources were obtained from files at the Arizona Department of Water Resources (ADWR) in Phoenix, Arizona and the Bureau of Reclamation Lower Colorado Regional Office.

The authors also tracked shortage planning meetings within Arizona and the Lower Colorado River Basin. These meetings provided a venue for monitoring stakeholder experiences with river system modeling and uncertainty and also offered the opportunity to glean insights from groups, such as irrigation districts and conservation nongovernmental organizations, that were not engaged during the focus group sessions. In particular, authors attended and documented Arizona's intrastate shortage planning stakeholder process, which proceeded in two stages. First, ADWR held six informal meetings that reviewed background concepts, legal interpretations, and preliminary model simulations regarding shortage management (ADWR 2005). ADWR then initiated a second stage of formal stakeholder discussions in July 2005 by convening the "Arizona Shortage Sharing Stakeholder Workgroup" (hereafter "the Workgroup"). The Workgroup was comprised of municipal water contractors, irrigation districts, conservation nonprofit groups, and other water users and managers (ADWR 2006a) with varying experience integrating model results into their decision-making processes. The Workgroup met on eight occasions to examine shortage impacts for Arizona water users dependent on Colorado River water supplies (ADWR 2006b). The authors observed all meetings during both stages of Arizona's intrastate process and transcribed notes of meeting discussions regarding model outputs and shortage. Stakeholder perspectives discussed herein are therefore based on (1) focus groups discussions and (2) transcribed notes from both stages of ADWR's shortage planning process.

*Objective 2: Colorado River Management and the Rise of Modeling in Planning Processes*

This section examines the historical evolution of the CRSS and other river system modeling efforts. This historical analysis serves the important functions of (1) documenting the growing role of modeling in Basin-wide management and planning and (2) highlighting the impacts and implications of model assumptions and uncertainties in previous water allocation decisions and water supply management criteria.

The Colorado River Reservoir System (see Figure 1, map) supplies water to approximately 30 million people, providing a substantial proportion of the water supply for Los Angeles and Phoenix residents. The Basin supports irrigated agriculture on over two million acres in addition to hydropower generation, recreation opportunities, and ecosystem services (ADWR 2006c); however, the Basin's water supplies are overallocated. The best estimate of average annual runoff in 1922 when the Colorado River Compact was negotiated was at least 16.5 million acre-ft (maf) per year (Figure 2). Water supply allocations of 16.5 maf were made between the Upper and Lower Basins and to Mexico on the basis of this estimate. A century of instrumental streamflow records shows an average of approximately 15 maf of runoff per year, and tree-ring reconstructions of the paleohydrologic record include estimates of long-term average annual runoff from 13.5 to 14.7 maf (Stockton and Jacoby, 1976; Woodhouse *et al.*, 2006; Meko *et al.*, 2007). The overallocation of Colorado River supplies elevates the importance of vast reservoir storage in the Basin. The Colorado River Reservoir System has a storage-to-annual runoff ratio of four to one (i.e., a storage capacity of roughly 60 maf of water, or approximately four years of average annual runoff). Overallocation in the Basin has reinforced the importance of river system modeling to regulate the River's vast reservoir storage infrastructure to provide water supply, hydropower, and environmental benefits.

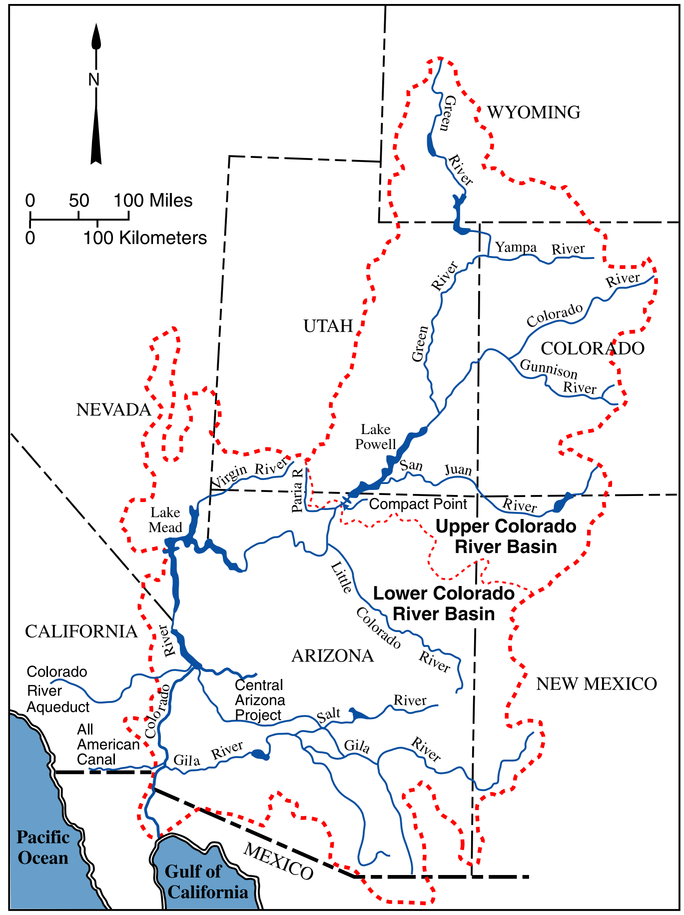


FIGURE 1. Map of the Colorado River Basin.

Though federal agencies conducted extensive river characterizations prior to the negotiation of the 1922 Colorado River Compact (e.g., La Rue 1916), complex river system modeling for planning purposes and policy evaluation began in earnest in the Basin in 1969 with the development of the Long Range Operating Criteria (USBR 2006a) – a set of river management rules designed to implement key Colorado River water allocation decisions finalized by the 1963 Supreme Court decree (373 U.S. 546 [1963]) and 1968

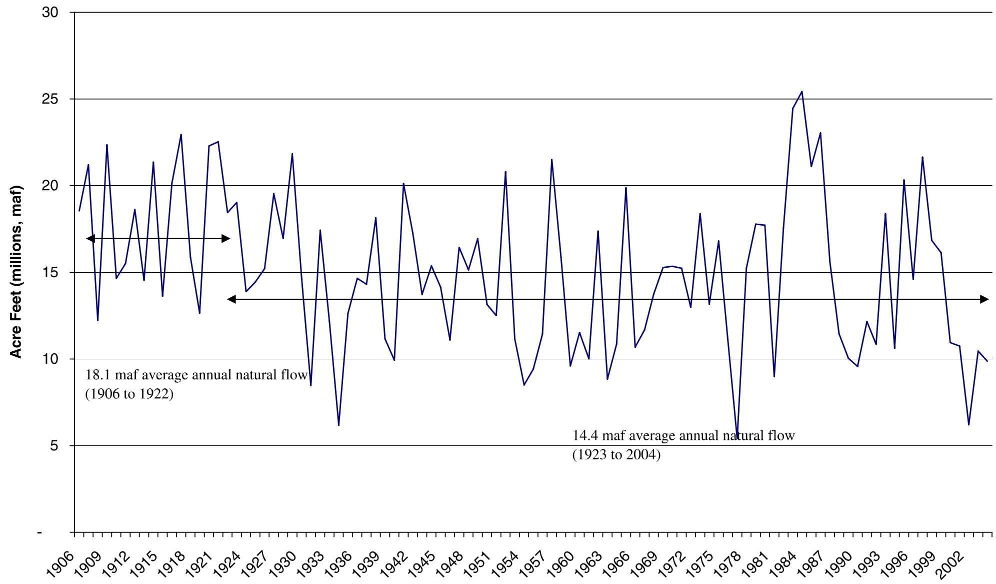


FIGURE 2. Observed Colorado River Natural Flows at Lees Ferry, Arizona. Arrowed lines represent averages.

Colorado River Basin Project Act (Public Law 90-537 [1968]). The Bureau of Reclamation's 1969 report for the Task Force on Operating Criteria for the Colorado River marked one of the first times computer-aided river system simulations were used to guide operations decisions and planning efforts in the Basin (USBR 1969). Moreover, the adoption of Long Range Operating Criteria reflected a shift in water management paradigms from dam *building* to dam *operation* to optimize multiple goals served by a single dam or, in the case of the Colorado River, a system of dams (Sabatier *et al.*, 2005).

**Modeling and the "Law of the River".** Before outlining the assumptions embedded in CRSS, it is necessary to identify the key legal aspects of the River's governance that are encoded in the model. The Colorado River is governed by a combination of over 100 court case decisions, statutes, regulations, international treaties and interstate agreements that together comprise what is known as the "Law of the River" (MacDonnell *et al.*, 1995; Carter and Morehouse, 2001; Getches, 2003). The foundation of the Law of the River is the 1922 Colorado River Compact, which divided Colorado River water supplies among four Upper Basin states (Wyoming, Colorado, Utah and New Mexico) and three Lower Basin states (California, Nevada and Arizona), providing 7.5 maf to each group of states. An international treaty between the U.S. and Mexico was signed in 1944 and provided a 1.5 maf allocation for Mexico (all referenced documents associated with the Law of the River are available at USBR 2006a). Under the Law of the River, the burden of shortage is disproportionately borne by different states and water user groups. For example, Central Arizona Project water users and other post-1968 water rights holders in Arizona hold junior priority water rights during times of shortage under the terms of the 1968 Colorado River Basin Project Act (Public Law 90-537 [1968]) and the 1963 U.S. Supreme Court decree (373 U.S. 546 [1963]). While this paper cannot adequately cover the intricacies of the River's legal and regulatory framework, certain elements are considered below in the discussion of modeling assumptions that are specified in CRSS to approximate the constraints and entitlements under the Law of the River.

**Current Planning Context: Water Supply Variability.** Two recent long-range planning processes for surplus and shortage conditions have exposed the important nexus between stakeholders and river system modeling in managing water supply variability. The ISG planning process spanned from 1996 to 2001. It established operating criteria for managing reservoir storage at Lake Mead in a way that would provide California a temporary incentive, in the form of surplus water deliveries, to encourage the state to comply with its legal entitlement of 4.4 maf per year over the long term [USDOI, 2000]. This arrangement was deemed an "interim" management guideline because these surplus criteria expire in 2016. California was expected to have developed in-state water resources and transfer agreements that would allow it to live within its Colorado River allocation before 2016.

By 2004, a second long-range planning process was initiated to confront the suddenly pressing specter of shortage in the Basin. Although above average inflow into Lake Powell in water year 2005 (105% of average) mitigated the short-term risk of shortage impacts, under her authority as "rivermaster" in the Lower Colorado River Basin, former Secretary of Interior Gale Norton issued a Federal Register notice to begin shortage planning (Federal Register 2005). As with the ISG planning process that culminated in January 2001, the shortage planning process falls within the purview of the National Environmental Policy Act (hereafter "NEPA"; see 42 USC 4331). In accordance with NEPA procedural requirements, Reclamation provided notice of its intent to prepare an environmental impact statement (EIS) in September 2005 and solicited public comments on the proposed project. As a result of extensive stakeholder input and analysis of comments, the proposed regulatory action was refined to include four operational elements, including

(1) shortage guidelines for the Lower Basin;
(2) coordinated operations of Lakes Powell and Mead throughout a full range of reservoir conditions;
(3) storage and delivery of conserved system and nonsystem water in Lake Mead;
(4) modification and/or extension of the Interim Surplus Guidelines (USBR, 2006b).

The preferred alternative for coordinating reservoir operations during shortage conditions will be in effect through 2026 (USDOI, 2007). Reclamation published the draft EIS in February 2007 and released the final EIS in November 2007. On December 13, 2007, a record of decision was signed by Secretary of Interior Dirk Kempthorne, in which he approved the new rules for reservoir management and shortage conditions stipulated in the preferred alternative developed with input from the seven U.S. basin states. As was the case during the Interim Surplus Guidelines process, development of the EIS for shortage operations relied on CRSS to evaluate the water supply impacts associated with operating criteria alternatives. CRSS has supported the early phase of the EIS by helping water managers and stakeholders to formulate the operating criteria alternatives that have undergone comparative analysis. For example, the seven U.S. states in the Basin met in a technical workgroup supported by CRSS simulations to generate the tentative, consensus "Basin States" proposal for shortage criteria and coordinated operations of Lakes Powell and Mead (University of Colorado 2006). This paper does not contain a comprehensive or systematic analysis of the assumptions and modeling exercises conducted through the course of the shortage planning process. Instead, it emphasizes modeling efforts conducted during the early stages of planning as operational alternatives were being defined.

**An Abbreviated History of the Colorado River Simulation System.** The Colorado River Simulation System (CRSS), initially a FORTRAN-encoded river planning and operations model, was developed in the 1970s and 80s to address the Basin's increasing complexity and water resource demands (Zagona *et al.*, 2001). Key inputs to the model include historical inflow data, projected depletion (or demand), operating criteria, and initial conditions. Reliance on river system modeling for Basin operations and planning increased when Reclamation and the Tennessee Valley Authority partnered with the Center for Advanced Decision Support for Water and Environmental Systems (CADSWES) in the early 1990s to produce a new operations and planning modeling framework called RiverWare, encoded in a more flexible, object-oriented format. Riverware provided a general modeling framework which could be tailored to basin-specific processes and operating policies (Zagona *et al.*, 2001). Reclamation used physical process algorithms and operation rule functions available in Riverware to implement a new CRSS that officially replaced the FORTRAN-based CRSS model in 1996. Riverware tools have enabled water managers to simulate and optimize multiple planning and operations objectives at varying time horizons ranging from daily optimization to long-term projections over 90 years (Zagona *et al.*, 2001; see Table 1). While stakeholder input guided the development of the RiverWare version of CRSS, two recent incarnations of models implemented within RiverWare – CRSS-EZ and CRSS-Lite – have been developed specifically for direct use by stakeholders other than Reclamation. These versions of CRSS have enabled state agencies and water users to compare and evaluate policy alternatives (Jerla and Fulp, 2005), and this broadened set of users has also underscored the need to define assumptions and evaluate the uncertainty associated with river system simulations.

TABLE 1. Long-Range Planning Processes in the Colorado River Basin by Model Type.

| Selected Planning Processes | Long-Range Operating Criteria (1970) | Hydrologic Determination (1988) | Interim Surplus Guidelines (2001) | Shortage Criteria and Coordinated Management (2004) |
|---|---|---|---|---|
| Model Type | Hydrologic Studies<br>Proto-CRSS<br>Rule Curves | Fortran-encoded CRSS | CRSS in RiverWare (1996) | |
| STAKEHOLDER-BASED VERSIONS OF CRSS→ | | | CRSS-EZ (1994) | CRSS-Lite (2005) |

1970 1975 1980 1985 1990 1995 2000 2005

The most widely heralded improvement in the Riverware version of CRSS has been its departure from hard-coded operations and policy rules. These changes have provided stakeholder groups with the capacity to evaluate policy alternatives by specifying 'what-if' scenarios (Zagona *et al.*, 2001; University of Colorado 2006). The development of stakeholder-oriented modeling and decision support tools in the early 1990s coincided with the Basin's first attempts to designate management criteria to deal explicitly with water supply variability in the form of surplus and shortage conditions (beginning with surplus criteria development in 1996). The ISG planning process was one of the first major Colorado River planning processes to extensively apply new policy comparison and evaluation tools available in the CRSS version implemented in Riverware. As such, the ISG process provides a valuable case study for understanding the role of modeling assumptions in Basin water management.

Since the ISG planning process commenced in 1996, Basin managers have increasingly relied on river system models to devise criteria for managing the river under conditions that deviate from "normal." Although CRSS is not able to adequately reflect all aspects of the Law of the River, river system modeling is becoming increasingly flexible in the RiverWare framework to address the water management challenges stemming from complicated operational and hydroclimatic assumptions and processes. These modeling tools have incorporated stakeholder-oriented elements, such as graphical, object-oriented interfaces, to accommodate the decision-making needs of a widening set of water users and interest groups.

### *Objective 3: Assumptions in the Colorado River System Modeling and Planning*

This section builds on the previous objective's historical exploration of modeling efforts by outlining the focal assumptions in contemporary public planning contexts for surplus and shortage conditions. Articulating and scrutinizing these assumptions proves important because historical decisions based on modeling assumptions and scientific analyses have demonstrated that transparency in model assumptions can have significant implications for water management by framing the legitimacy and credibility of water allocations that rely on the modeling efforts used in public planning processes.

Three important caveats are warranted. First, this section does not provide an exhaustive survey of the assumptions defined in the RiverWare version of CRSS, which contains over 50 operations-based rules (Zagona *et al.*, 2001); instead, the analysis highlights the focal assumptions discussed during long-range planning processes, especially during Arizona Shortage Sharing Stakeholder Workgroup meetings. Second, the assumptions featured in this section are relevant because they have substantial impacts on simulated water supply conditions, such as reservoir storage. Importantly, the assumptions analyzed herein were explicitly evaluated through sensitivity analyses and river system simulations prepared for the Workgroup. These simulations frequently isolated the water supply impacts of different operational criteria, demand projections, and/or inflow conditions. Finally, Reclamation utilizes three different models implemented in Riverware, and each model functions at different temporal scales from long-range planning to day-to-day operations. CRSS is the long-term planning and policy evaluation model for the Basin, and it has an outlook of over 90 years. CRSS is used in conjunction with two other models that function over shorter time scales. The mid-term, or annual operating, model is called the 24-month study model, and it generates initial reservoir starting conditions that later feed into the long-term CRSS model. The 24-month study model is used to project end of the water year reservoir storage conditions, and these projections help to the identify trigger points used to designate whether annual operations are governed by normal, surplus, or shortage conditions. The third model operates at the daily time scale to schedule water deliveries and implement the reservoir operations targets established in the 24-month study model. Careful attention must be paid to the interactions and distinctions between these three models because their assumptions about inflow and depletions often differ. This analysis refers to long-term planning simulations within CRSS unless otherwise noted.

To understand the role and importance of modeling assumptions in public planning, it is necessary to outline the three basic functions performed by RiverWare: (1) simple simulations of river operations; (2) rule-based simulations ('if, then' statements), and (3) optimization of multiple management objectives (Zagona *et al.*, 2001). Each of these functions requires the establishment of a focal set of assumptions and algorithms that represent physical processes, operational complexity, and legal requirements. For the purposes of this analysis, these assumptions can be divided into four major categories: (1) physical processes, such as river runoff (inflow); (2) projections of future water use (depletion); (3) initial reservoir conditions (initial conditions); and (4) operating criteria. In general terms, the outputs of river system model simulations are a function of these four categories of assumptions:

Outputs (reservoir levels and derived parameters, such as shortage probability) = *f* (inflow, depletion, initial conditions, operating criteria).

This section outlines key assumption(s) in each major category and assesses the water management implications associated with uncertainty regarding assumption parameter values. This analysis links to the succeeding section which examines configurations of these assumptions associated with different future water supply management criteria and scenarios, including the best-case and worst-case conditions.

Six sample assumptions are examined below. These assumptions are distributed across the four categories introduced above, namely: (1) physical processes, such as runoff; (2) depletion, such as water allocation and demand; (3) operating criteria; and (4) initial reservoir conditions. Notably, these focal assumption categories can lead to future inter-basin comparative analyses regarding the role of assumptions and modeling in stakeholder processes to cope with a mixture of physical (hydroclimatic) and institutional (allocation and demand) sources of uncertainty.

**Assumption #1: Runoff and Hydroclimatic Variability – Does History Repeat Itself?** Water managers have long attempted to characterize the Colorado River's 'normal' runoff. As noted above, the River is renowned both for its highly variable flows and for its overallocation because of streamflow estimates based on the anomalous wet period that preceded the 1922 Colorado River Compact negotiations (Reisner, 1986; MacDonnell *et al.*, 1995; see Figure 1). The water supply, or runoff, data used in CRSS provides one of the most useful entry points to understand the importance of model assumptions in planning and policy contexts. Fulp and Harkins (2001) have concluded that the greatest source of uncertainty in Colorado River modeling is future inflows. Reclamation modelers have acknowledged the role of assumptions regarding historic streamflow data and initial reservoir conditions when explaining why simulations conducted for the ISG did not encompass observed declines in reservoir storage from 2001 and 2004 within the range of projected future conditions (Callejo and Fulp, 2005).. CRSS currently simulates future inflow scenarios based on historical monthly streamflow data using a technique referred to as the Index Sequential Method (ISM), which generates a series of inflow sequences derived by cycling through the historical record (Ouarda *et al.*, 1997; Jerla, 2005; see Table 2). Under the ISM, Reclamation uses streamflow data collected at monthly time steps from 1906 to 2004 (a 99-year record) as the basis of future inflows (Fulp and Harkins 2001). Each year of the historical record provides the starting point for a sequence of inflows that spans the full length of the historical record. For example, the first trace would establish initial reservoir conditions and then simulate future conditions by using the actual inflow data starting in 1906 and ending with the inflow in 2004. The second trace begins in 1907 and cycles through each year of the historic record for a total of 99 years, wrapping back to 1906 after reaching 2004 (i.e., 1907-2004, then start again with 1906).

TABLE 2. 99-Year (1906-2004) Traces Using the Index Sequential Method (wrap-around concept).

| Trace | Initial Year (year 1) | Second Year (year 2) | Second to Last Year (year 98) | Last Year (year 99) |
|---|---|---|---|---|
| 1 | 1906 | 1907 | 2003 | 2004 |
| 2 | 1907 | 1908 | 2004 | 1906 |
| … | … | | … | … |
| 99 | 2004 | 1906 | 2002 | 2003 |

Note: Adapted from USBR 1988.

Historic streamflow records are used in two ways. First, these records are used to generate *percentile* "traces" of likely future inflows. In this application, all traces are deemed equally probable, and CRSS projects reservoir conditions based on the least (10th percentile), most (50th percentile), and maximum probable (90th percentile) inflows at monthly time steps. The second use of the streamflow records follows an individual trace to assess how a particular sequence of inflow variability (usually prolonged drought or flood) will impact projected reservoir levels. A common example is to select the trace beginning in 1953 (known as "trace 47") to assess the impact of the historic drought of record if it were imposed on current reservoir conditions. This second form of inflow sensitivity analysis is used to determine the time horizon before shortage or surplus probability crosses a given threshold (e.g., to identify the first year shortage probability exceeds 20% based on the historic drought of record starting today).

Reliance on historical observed records entails two implicit assumptions about future inflows, namely that (1) flows will behave within the bounds of variability demonstrated in the instrumental record, and, (2) in the cases involving the use of a representative trace, that inflows will follow historical sequences of variability. The use of historic streamflow data to assess future variability is common in Western U.S. water management beyond the Colorado River context (Lettenmaier, 2003). In short, past streamflow data dictate the range of potential future inflow scenarios. The EIS prepared for the ISG planning process (ISG EIS), therefore, did not encompass 2004-5 observed reservoir conditions because the period of streamflow from 1996-2005 introduced a novel sequence of runoff data not previously encountered in the historical record (Callejo and Fulp, 2005). Thus, just as negotiators of the Colorado River Compact-based allocation decisions on an historical record that overestimated the long-term average streamflow, current analyses rely on historical streamflow data that may not capture the full range of possible inflow conditions. A longer historical record or other streamflow assumptions might not have led to changes in policy or management decisions during the ISG process. Nevertheless, the instrumental record provides only a partial basis for assessing future flows. For example, it has been long noted that tree-ring analysis and other paleoclimate proxies suggest that past streamflow exhibited variability and extremes that are not encompassed by the 99-year instrumental stream gauge record in the Basin (Stockton and Jacoby, 1976; Meko *et al.*, 1995; Woodhouse *et al.*, 2006). In turn, water supply projections based on downscaled global circulation model results suggest that future Basin inflows could be diminished and hydrologic regimes of winter precipitation and spring snowmelt could be altered under anticipated carbon emission scenarios (Christensen *et al.*, 2004; Christensen and Lettenmaier, 2007). Reclamation has attempted to temper the potential for biases caused by reliance on historic data by conducting analyses outside of CRSS during the shortage EIS process. These efforts have incorporated studies of the paleoclimate record (i.e., long-term streamflow records derived from non-instrumented proxies such as tree rings) to provide a longer historical context of streamflow variability and potential for prolonged drought conditions (USDOI, 2007).

This analysis emphasizes a recurrent theme: uncertainties inherent in modeling assumptions can have significant unanticipated consequences. In particular, model results that stem from such sources of uncertainty have the potential to constrain analyses of management alternatives in a manner that could undermine the rules that are ultimately adopted to manage water supply variability. The classic example of this complaint arose in the aftermath of the 1922 Colorado River Compact once it was recognized that river runoff calculations based on historical records overestimated the long-range average runoff, leading some members of the Compact to resent the unanticipated inequalities in water entitlements between the Upper and Lower Basin. Similarly, the new reality of more frequent shortages means that the junior priority of the Central Arizona Project is a more serious problem than anticipated.

**Assumption #2: Validating Historic Depletions and Water Uses.** Under current operating conditions, an administrative lag occurs before historical streamflow data and depletion (or demand) schedules are adopted by Reclamation. This lag stems in part from the process of collecting, analyzing, and validating depletion data in the Upper Basin (Colorado, New Mexico, Utah, and Wyoming), where individual state agencies report depletion information. Reclamation has begun to work with the Upper Basin states to streamline this process with the goal of producing preliminary accounts of Upper Basin depletion that can feed into modeling efforts. Conversely, in the Lower Basin states of Arizona, California, and Nevada, Reclamation's Lower Colorado office monitors depletion centrally. Depletion data in the Lower Colorado River states are published each year according to a procedure known as "Decree accounting."

What are the management implications of this lag and other data availability considerations. Although recognition of the lag problem resulted in a change in procedure so that the ongoing shortage planning efforts now use near real-time updated historical inflow records that end in 2004, during the ISG planning process, validated historical inflow records were limited to the 85-year period from 1906 to 1990. Because of the relatively short historical record, the lag limited the ability of the model to simulate the full range of reservoir system outcomes, including extreme declines. The average annual inflow after 1990 has been below the instrumental average for the previous 85-year period. This lag partially explains why the ISG CRSS simulations did not capture the actual observed conditions after 2001. As with the hydroclimatic assumptions examined above, this lag has parallels in other basins. Any diminishment in the accuracy of projections caused by the lag can undermine confidence in modeling results if actual outcomes are outside the range of projected outcomes.

**Assumption #3: Demand, Water Allocation and Infrastructure – Upper Basin Depletion.** The five-year period spanning from water year 2000 through 2004 exhibited the lowest inflow into Lake Powell during the instrumental record. These drought conditions become even more important because consumptive water use of Colorado River water has also reached historic highs and continues to grow (see Figure 3). For example, Arizona diverted its full allocation for the first time in 2002, although, in previous years, Arizona's unused allocation was used by California to supplement its basic allocation of 4.4 maf. Consumptive use projections are a fundamental source of uncertainty and variability in future river conditions projected by CRSS simulations.

Unlike the Lower Basin states that divert their entire entitlement to the Colorado River, Upper Basin states are still developing the capacity to divert their

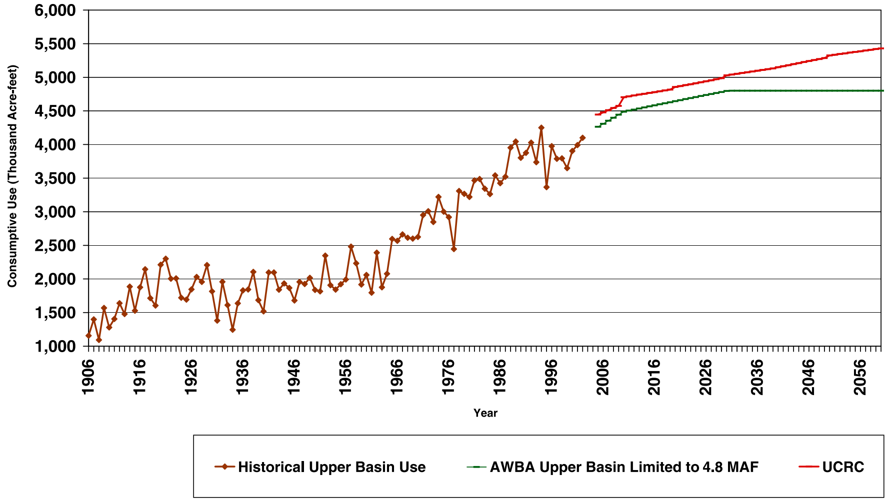


FIGURE 3. Upper Colorado River Basin – Historical and Projected Use. Data sources: USBR; UCRC; AWBA.

legal allocation from the River. Upper Basin states were using approximately 3.9 maf of their 7.5 maf allocation as of 2000, and a study by Reclamation (USBR 1988) concluded that only approximately 6.0 maf are actually available for Upper Basin development. Due to uncertainty surrounding future Upper Basin depletions, CRSS simulations often compare the impact of different Upper Basin consumptive use projections on future water supply conditions.

Planning discussions in the Arizona Workgroup process have compared three projections of Upper Basin depletion, which depend critically on two factors: volume of build-out development and rate of development. The ISG EIS analysis performed by Reclamation used the Upper Basin depletion schedule proposed by the Upper Colorado River Commission (UCRC) in 1999, as modified by various Upper Basin tribes (USDOI, 2000). This projection rises to approximately 5.4 maf by 2060. The UCRC is the institution representing the four Upper Basin states (Wyoming, Colorado, Utah, and New Mexico). The Arizona Water Banking Authority (AWBA), however, has developed a different projection. AWBA was formed in 1996 and "safeguards [Arizona's] municipal water supplies against future shortages on the CAP system, assists in meeting the goals of the Groundwater Code, and aids neighboring states without harming Arizona" (AWBA 2005, emphasis added). AWBA assessed the feasibility of proposed Upper Basin water development projects and concluded that 4.8 maf provides a more realistic estimate of maximum future use in the Upper Basin. The UCRC and AWBA projections also differ in their rates of increase. The AWBA projection for Upper Basin depletion increases at a slower rate than the UCRC projections. The Arizona Department of Water Resources has formulated a third projection by using the faster build up rate of the UCRC projection but capping it at the AWBA limit of 4.8 maf.

Holding all other assumptions equal, Upper Basin depletion projections lead to pronounced divergence in the probability of incurring lower basin shortages (see Figure 4). The UCRC projection – with its higher limit and faster increase – results in a probability of shortage in the Lower Basin that is as much as 20% higher than under the AWBA projection. As part of the shortage planning process, Upper Basin depletion projections are receiving increased scrutiny because of uncertainty concerning water rights issues, legal interpretations, and hydroclimatic variability. Debates regarding model assumptions can therefore transcend the technical arena and involve alternate interpretations of legal water entitlements and the potential to develop water supply infrastructure. Clearly, demand assumptions reflect institutional and political uncertainties that may not be reducible through model simulations and improvements in data availability alone.

**Assumption #4: Operations Criteria I – 602a Storage Algorithm and Layers of Uncertainty.** As noted above, in response to the 1968 Colorado River Basin Project Act (CRBPA), Reclamation adopted Long Range Operating Criteria in 1970 that govern annual reservoir operational decisions (USBR 2006a). Among the most important of these criteria are two related operational rules: (1) equalization of reservoir storage in Lakes Powell and Mead and (2) the 602 (a) Upper Basin reservoir storage requirements. Equalization refers to the practice of maintaining equal volumes of storage in Lakes Powell and Mead at the end of each water year subject to conditions specified in Section 602 (a) of the CRBPA.

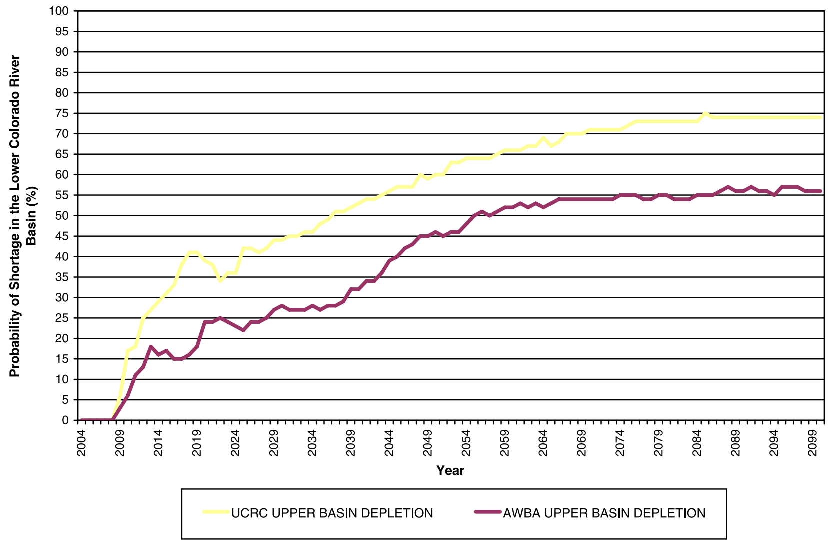


FIGURE 4. Impact of Upper Basin Depletion Projections on Shortage Probability in the Lower Colorado River Basin. Data source: Arizona Shortage Sharing Stakeholder Workgroup.

"602 (a) storage" also complies with Section 602a of the CRBPA by establishing the minimum Upper Basin storage levels needed to satisfy water delivery obligations to the Lower Basin while maintaining the Upper Basin's capacity to continue developing its water supply infrastructure.

Equalization and 602 (a) storage criteria are conceptually straightforward as written rules (see USBR 2006a); however, for operational purposes and planning simulations, 602 (a) storage is implemented through an algorithm that integrates several important variables, including focal assumptions detailed in this paper: projected Upper Basin depletions, minimum storage requirements for hydropower generation, evaporation loss in Upper Basin reservoirs, and runoff data from a period of critical low inflow (to simulate prolonged drought impacts). The algorithm formalizes the relationship between inflows, diversions, reservoir levels, and operating criteria. The 602 (a) parameters are summarized and described in Table 3. The algorithm incorporates and integrates several layers of uncertainty.

In the Shortage EIS, operational rules for coordinating resevoir management during shortage conditions dwarf the complexity exhibited by the 602(a) storage criteria. By comparison, the set of trigger points and contingencies embedded in new operational rules for coordinating management of Lakes Powell and Mead may render the 602(a) algorithm relatively straightforward; however, it is precisely because future operating criteria for coping with water variability are becoming more complicated that it is valuable to analyze previous debates regarding the parameter values used in the 602 (a) storage criteria. These historic debates regarding the 602(a) assumptions underscore the wider political and institutional context of the modeling assumptions that become layered in complex operating criteria. Even more than the physical process assumptions, such as runoff, and uncertainties regarding demand, the

TABLE 3. Key Parameters of the 602 (a) Storage Calculation

| 602 (a) parameter | Description | Current Model Input Assumption |
|---|---|---|
| UB depletion | Average of next 12 years of projected demand | UCRC projection, as modified by tribes. |
| UB evaporation | Average annual evaporation | 560,000 acre-ft |
| % Shortage | Percent shortage applied to UB | 0% |
| Minimum objective release | Annual minimum release from Lake Powell to Mead | 8.23 maf |
| Critical period inflow | Average annual natural inflow into the Upper Basin from 1953 to 1964, which is considered the critical low inflow period. | 12.18 maf |
| Minimum power pool | Amount preserved for power pool in Upper Basin | 5.19 maf |

Source – Final Environmental Assessment (March 2004) – Adoption of Interim 602 (a) Storage Guideline.

evaluation of operational criteria using river system models transcends the technical arena by involving stakeholder interests and political uncertainties stemming from legal interpretations or implementation efforts. Modeling effectiveness for long-range water supply planning and operation therefore involves multiple disciplines at the science-policy interface as well as transparently organized public outreach and participation processes among Reclamation, state agencies, and water user groups.

**Assumption #5: Operations Criteria II – Managing Surplus, Inducing Shortage?** The Interim Surplus Guidelines are another operating policy assumption that highlights the sources and management implications of uncertainty in CRSS. The interim period for the previous surplus guidelines under the ISG ended in 2016, but the planning time horizon for the recently concluded shortage sharing negotiations and other policy analyses extends beyond that timeframe through at least 2026. In other words, studies that extend beyond 2016 must confront the uncertainty surrounding surplus operating policies after the interim period concludes. The interim status of the surplus guidelines creates a source of uncertainty in future simulations, and consequently, to characterize this uncertainty, CRSS simulations often project future water supply conditions by varying the surplus criteria while leaving all other parameters consistent (e.g., depletion rates and inflow).

Simulations have compared the surplus criteria stipulated by the ISG of 2001 with the previous surplus operations criteria, known as the "70R strategy" (which was in effect from 1986 to 2000). These comparisons demonstrate that the ISG leads to a relative increase in the probability of shortage holding all other assumptions equal (see USDOI, 2000 for an overview of the 70R strategy, which was the "baseline" alternative for the ISG EIS). This conclusion follows intuitively from the fact that the ISG allow surplus deliveries to the Lower Basin under a wider range of reservoir storage states in Lake Mead than under the 70R strategy.

Under the 70R strategy, decisions to release flows under high reservoir storage conditions were based on spill avoidance and flood control objectives. On the other hand, the ISG were explicitly designed to provide a more permissive operating policy than the previous management framework by allowing surplus deliveries to the Lower Basin until Lake Mead reaches 1125 feet above sea level (the 70R strategy suspended excess deliveries below 1200 feet above sea level). In addition to allowing for temporary increases in California water deliveries, another clear benefit of the ISG is the enhanced predictability of water flows based on a reservoir elevation-based water release trigger rather than the probabilistic threshold used in the 70R strategy. The 70R strategy was devised in response to flood conditions in 1983 and 1984 and is designed to release additional water supplies to Lower Basin (primarily California) water users while maintaining a storage capacity buffer to accommodate a 70Pth$^{P}$ percentile water year, hence the name 70R.

Holding all other depletion and inflow projections equal, shortage risk is unambiguously higher under the ISG. The ISG allow reservoir depletion to occur far more rapidly during low reservoir conditions than under the 70R strategy. Nevertheless, these more permissive surplus criteria have achieved their primary goal by spurring California to set up intrastate agreements and conservation programs that led to a rapid reduction of its consumptive water uses, allowing the state to stay within its 4.4 maf allocation since 2003. It should be noted that California actually achieved the reduction in diversions well in advance of the deadline associated with the end of the ISG period in 2016, as a response to the serious drought conditions since the 2001 ISG record of decision.

**Assumption #6: Initial Reservoir Conditions – Where to Start?**

> "The change in initial conditions affects the results of the first few years of the simulations, and then is negligible." Chapter 3.03 Final Environmental Impact Statement USDOI, 2000; in 2005, actual reservoir conditions dipped below the lowest projected conditions generated for the ISG EIS.

CRSS simulations must specify a starting reservoir elevation, and it is against the backdrop of these initial conditions that physical process algorithms, depletion projections, and operational criteria shape future water supply conditions. If starting reservoir levels inaccurately represent initial system storage, simulations will provide scant, or even misleading, characterizations of the impacts associated with the different policy alternatives – particularly during the first years of the simulation (USDOI, 2000).

Reclamation follows an operational protocol when establishing the starting conditions for annual operation planning, although this protocol has shifted between the ISG EIS and shortage planning. Prior to 2005, simulations conducted for annual operating purposes utilized observed reservoir levels from January of any given water year if conducted prior to June of the same water year (e.g., in March 2004, the Bureau would have adopted the January 1, 2004 reservoir conditions in annual operations planning). After June, Reclamation incorporated inflow forecasts generated by the mid-term, 24-month study model to project reservoir levels for January 1 of the following water year. The most probable – or 50th percentile – inflow forecast is frequently used to establish initial reservoir conditions for such planning simulations.

For long-range planning, Reclamation typically follows the same protocol to define initial reservoir conditions as that used for the annual operations. It is important to note the interplay of the long-term CRSS model with the mid-term 24-month model, as the latter model generates the initial reservoir conditions and evaluates the likelihood of crossing reservoir storage levels that could trigger operational changes (such as 602(a) storage releases or shortage conditions). The model runs generated for the ISG EIS illustrate the impact of (a) initial reservoir levels and (b) the role of projected inflow in the establishment of those conditions. For the ISG EIS, starting conditions relied on a forecast of January 2001 storage generated using the 24-month study model in August 2000 (the 24-month study model is Reclamation's mid-term, annual operations model, which, like CRSS, is implemented in the RiverWare software framework). This forecast assumed inflows from August to December 2000 would mirror the "most probable" inflow scenario (50th percentile inflow). The most probable inflow projection did not materialize, however, and actual January 2001 storage conditions were lower than the forecasted levels. The ISG EIS overestimated initial reservoir conditions, and this assumption helps to explain CRSS' inability to account for the subsequent reservoir storage impact wrought by continued drought conditions. It is important to note that the ISG planning process did not examine an ensemble of initial starting conditions and neither did the more recent EIS to develop shortage criteria. However, Reclamation has modified its protocol for establishing initial conditions during shortage planning efforts, replacing the 50th percentile inflow with an average of the preceding five years of the instrumental record. Adopting the five-year average ensures that initial condition assumptions are more sensitive to deviations from observed streamflow records during prolonged dry conditions.

Sensitivity analyses have isolated the effects of initial conditions assumptions. A Colorado River modeling meeting in 2003 focused on the impact of initial reservoir conditions on the risk of incurring shortage or surplus conditions (USBR, 2003). The modeling group assessed the sensitivity of simulation outcomes to initial reservoir conditions by comparing two different starting points, one taken from the Surplus EIS and the other starting a year later. During the intervening year (January to December 2002) deepening drought conditions induced continued reservoir depletion. As Figure 5 demonstrates, reservoir storage decreased markedly over this timeframe from roughly 88 percent to 61 percent as an unprecedented low flow

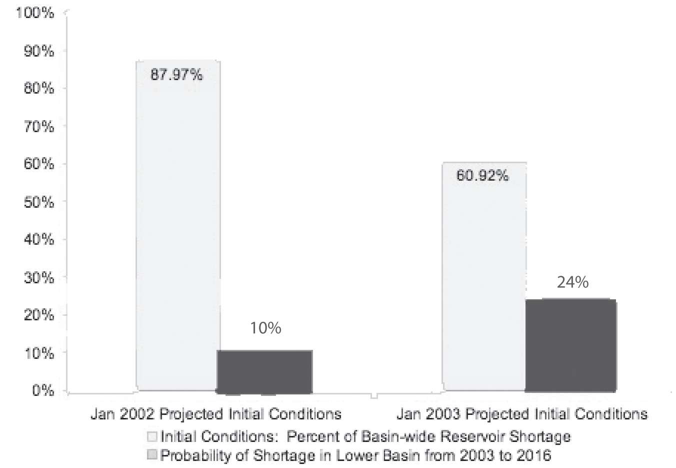


FIGURE 5. Impact of Initial Reservoir Conditions on Lower Basin Shortage Probability. Data source: USBR 2003.

year occurred during water year 2002. Therefore, initial conditions were substantially lower than those used for the ISG EIS. Examining the risk of shortage and surplus over the fixed period from 2003 to 2016, diminished initial reservoir conditions in the latter option entailed a decreased probability of surplus (from 87 to 65% average annual probability from 2003 to 2016), while shortage risk increased notably (from 10 to 24% average annual probability) (USBR, 2003).

The foregoing analysis examines a suite of assumptions across four primary categories: physical processes, depletion, operating criteria, and initial conditions. Careful scrutiny of these assumptions reveals that the success of modeling efforts is impacted by inputs that cannot be reduced to strictly technical considerations. As river system models have become increasingly prevalent in natural and water resource management applications, individual model assumptions serve as proxies for wider policy and institutional uncertainties involving diverse stakeholder constituencies. Therefore, the specification of model parameters values and assumptions needs to be handled explicitly to build public confidence in the credibility of model results, which can have the extended effect of legitimizing the management alternatives that such model results devise and evaluate. The cross-section of model assumptions evaluated above is partial in the sense that river systems contain several variables that interact in complex, and potentially nonlinear, ways. Such interactions underlie the formation of the management scenarios compiled during public planning processes for surplus and shortage, such as the specification of management alternatives, identification of impacts to stakeholder constituencies, and consideration of the best- and worst-case conditions that may ensue. These interactions and complexity are the subject of the next section.

*Objective 4: Complexity and Assumptions – Interactions, Operating Alternatives, and Management Implications*

The foregoing analysis of CRSS' basic assumptions elaborates several of the key sources of uncertainty embedded in the model; however, these assumptions also interact in ways that enable or constrain the effectiveness of models in planning contexts. This section briefly examines such interactions because the complex suite of assumptions used to specify and compare management alternatives using river system models can have different impacts across stakeholder groups; can legitimize or undermine decision-making processes; and can affect the confidence in modeling as a tool for consensus-driven public planning efforts.

CRSS synthesizes 50 operating policy-based rules and 120 functions to simulate the Colorado River system's physical and operational complexity (Zagona *et al.*, 2001). Uncertainty associated with individual assumptions becomes dispersed through the simulations as physical process and operating rule algorithms are executed. Because 50 operating policy rules are encoded in CRSS, the consequences of different *combinations*, or configurations of assumption parameters, are difficult to systematically compare, but such comparisons of scenarios and management alternatives are at the heart of formal rulemaking processes under federal NEPA requirements (DOI 2001; DOI 2007).

Participants in Workgroup sessions in the early stages of shortage planning in 2004 and 2005 expressed important perspectives on the role of river system planning. to manage water supply variability. On the one hand, some participants expressed a need to simplify model outputs by isolating key factors and examining their impacts on reservoir conditions; on the other hand, participants also requested best- and worst-case scenarios that would require changes to multiple factors simultaneously. Outcomes generated using these opposing approaches were frequently confusing to stakeholders. A "perfect storm," or worst-case scenario would align the extreme parameter values for the full complement of inflow, depletion, operating criteria, and initial condition assumptions (see Table 4). During Workgroup discussions, simulations that were presented often combined worst-case values of some parameters with normal or best-case values for other critical parameters. For example, in calculating risk, even those cases labeled "worst case" used the AWBA's Upper Basin depletion (the projection with the lowest shortage probability holding other assumptions equal) and excluding the UCRC depletion projections, which would depict a higher risk of shortage for Lower Basin water users.

Second, the evaluation of the impact of complexly interacting assumptions depends on the time horizon over which such alternatives are analyzed. Over the immediate (seasonal to inter-annual) to mid-term outlook (three- to five-year), initial reservoir conditions assumptions can predominate in river systems with high reservoir-to-runoff ratios (USDOI 2000). Over the longer time horizons (decadal or longer) that typically characterize public planning processes for water supply variability, runoff variability, demand projections, such as Upper Basin depletion, and uncertainties stemming from potential changes to existing operational rules can become increasingly important for understanding and comparing management alternatives for coping with variable water supply conditions.

Clearly, understanding the relationships between input variables in modeling activities is critical to developing outcomes that are useful. Some variables are independent of others, and some covary in complex ways. Ensuring that modeling outputs are useful in public processes requires a very high level of sophistication among the participants to ensure that they understand why and how outcomes of alternative modeling exercises differ. Exploring sensitivities of individual variables as well as explicitly developing scenarios and "story lines" that combine different assumptions were observed to be useful in assisting stakeholders to provide meaningful input to this process.

Developing key modeling assumptions in the context of public processes may benefit from a framework that emphasizes different types of uncertainty (Wood, 2005). In this framework, key assumptions fall into categories of "known knowns," "known unknowns," or "unknown unknowns." In the Colorado

TABLE 4. Configuring Assumptions to Form Best- and Worst-Case Scenarios

| | **Relative Shortage Probability** | |
|---|---|---|
| **Key Assumptions** | **Higher** | **Lower** |
| Inflow | Prolonged drought (e.g., 2000-2004) | Extended high flows (e.g., 1983-1984) |
| Demand – Upper Basin | Limit: 5.4 maf<br>Rate: UCRC | Limit: 4.8 maf<br>Rate: AWBA |
| Operating policy—surplus criteria | Interim Surplus Guidelines | 70R Strategy |
| Initial conditions | January 2005 (i.e., 50% storage capacity) | January 2000 (i.e., over 90% storage capacity) |

River context, some legal allocations may comprise "known knowns" while future inflows are "known unknowns." The potential for catastrophic damage to infrastructure could constitute an "unknown unknown." For "known unknowns," probabilistic information provides one of the chief tools for framing uncertainty. As revealed during focus group discussions, such probabilistic information can cause consternation for stakeholders who prefer more deterministic outcomes for decision-making purposes. For example, the "known unknown" of future inflow has been addressed through probabilistic analyses, and the "most probable" moniker applied to the 50Pth$^{P}$ percentile inflow trace has the potential to overstate the model's ability to accurately project future reservoir conditions (see section on *Initial Starting Conditions* above). The proliferation of river system modeling in diverse management contexts and stakeholder audiences reinforces the need to communicate the nature of probabilistic information in an effective way (Hartmann, 2003). Applied to CRSS, this 'knowing' framework may enable stakeholders to calibrate expectations about model projections and incorporate these model runs into decision-making processes while recognizing the uncertainty intrinsic to the different assumptions discussed above. For the EIS process initiated in 2005 (Federal Register 2005), Reclamation has expanded its efforts to integrate and communicate uncertainty associated with CRSS simulations.

## CONCLUSIONS

This paper addressed four objectives to understand the nexus of river system modeling and water management institutions for the multi-reservoir and multi-stakeholder Colorado River system: (1) clarifying water managers' needs and expectations of river system models; (2) evaluating how river system modeling has been used to manage water supply variability in the Colorado River Basin; (3) identifying the focal assumptions that drive the model outputs; and (4) analyzing how these assumptions interact at different time scales and within different decision-making and planning contexts. The broader implications of these objectives are discussed below (see Table 5). In brief, through our discussions with water managers and observations of Colorado River Basin shortage planning meetings (Objective #1), we determined that water managers most need information on the key assumptions and sources of uncertainty in river system models; they expect models to address a full range of future conditions and scenarios (including best- and worst-cases), and they require clarity on how variations in individual parameters affect forecasts, as well as how complex interactions between parameters affect forecasts. Our section on Colorado River Modeling (Objective #2) documented the interplay between improved understanding of hydrology, and changing operational rules and policies; the section also noted the increasing need for modeling flexibility and interfaces that allow a widening set of water users and interest groups to evaluate forecasts. Our analysis of Colorado River System Modeling assumptions (Objective #3) showed that key assumptions about the representativeness of historical streamflow variability and total runoff, lags in recent data incorporation into the model, institutional and political uncertainties about water supply depletions and demand, managing separately for surplus and shortage, and initial reservoir storage have large impacts on forecast outcomes, and require explicit and transparent communication to decision makers using the models for planning. Finally, our analysis of managers' reactions to the complex interactions between parameters and the variations over different time scales showed that it is necessary for modelers to work with stakeholders to establish a framework that explicitly states the known and unknown aspects of forecasts, expressed in vocabulary that matches stakeholder experience (e.g., the 50th percentile forecast has been termed "most probable," which can overstate forecast confidence).

This analysis of modeling, assumptions, and stakeholders in the Colorado River Basin evaluates the relationships between water management objectives and river system modeling assumptions using two case studies involving stakeholder participation. The two cases examine the Interim Surplus Guideline planning process from 1996 to 2001, and the more recent development of shortage sharing criteria and alternative management modes for Lakes Mead and Powell. The simulations generated by CRSS reflect alternative assumptions regarding future inflows, depletion projections, operating rules, and initial reservoir conditions. Supply assumptions rely on observed inflows that may not capture the full range of conditions possible in the future. The need to understand underlying sources of variability is increasing as the Colorado River Basin enters what is likely to be a period of chronic shortage, given increasing demands, overallocation, and the potential impacts of global warming. With the stakes rising and a trend towards more sophistication regarding hydroclimatic variability among water managers, use of models to support decision-making is expanding to a broader audience. It is increasingly important that the implications of modeling assumptions, both individually and in combination,

TABLE 5. The Role of Modeling Assumptions in Planning for Water Supply Variability: Research Objectives, Findings, and Implications.

| Objective | Finding | Broader Implications |
|---|---|---|
| Clarify needs and expectations of river system modeling through stakeholder engagement and observation | Water managers' greatest needs: information on the key assumptions and sources of uncertainty in river system models; clarity on how variations in individual parameters affect forecasts, as well as how complex interactions between parameters affect forecasts; forecasts of a full range of future conditions and scenarios (including best- and worst-cases) | It is essential that modelers (or their representatives) communicate with the full spectrum of model users, in order to identify key questions, express interactions between parameters, convey the impact of assumptions on outcomes, and develop a common vocabulary for expressing outcomes. |
| Evaluate how river system modeling has been used to manage water supply variability in the Colorado River Basin | The convergence of growing demands, hydroclimatic variability, and institutional complexity have caused increasing reliance on river system models, such as CRSS, in Colorado River management. CRSS has become increasingly flexible to accommodate the decision-making needs of a widening set of water users and interest groups. | Increasing demands on river system models and an increasing number of diverse stakeholder groups has resulted in a need for transparency and clear explanation of the modeling assumptions used to manage complex systems, which requires assessment and explanations of both physical and institutional sources of uncertainty. |
| Identify the focal assumptions that drive the model outputs | The focal assumptions in CRSS span hydroclimatic, technical, and institutional sources, such that modeling outputs reflect the integration of assumptions regarding inflow, demand, operational rules, and initial conditions. Examples from each of these categories demonstrate the sources of uncertainty attached to key assumptions as well as the way these uncertainties frame public decision-making using model outputs. | Documenting core assumptions that drive river system modeling efforts has proven important in bolstering the legitimacy and credibility of management decisions that rely on the modeling efforts used in public planning processes. |
| Analyze how these assumptions interact at different time scales and within different decision-making and planning contexts | Examining individual assumptions in isolation masks important interactions among the 50 operation-based rules and 125 physical process algorithms that drive CRSS. These interactions introduce complexity and uncertainties that operate at different time scales. Stakeholder groups with experiences using river system modeling in public planning processes have emphasized the tradeoffs between isolating the impacts of individual assumptions and representing their interactions through scenario building efforts. | Interactions among the assumptions used to specify and compare management alternatives deserve careful delineation because these interactions become represented by summary model outputs. These outputs support public planning decisions that have different impacts across stakeholder groups; can legitimize or undermine decision-making processes; and can affect the confidence in modeling as a tool for consensus-driven public planning efforts. |

are well articulated. Building scenarios that encompass the full range of possible future water supply conditions, including best- and worst-case conditions, will become increasingly important to guide adaptation decisions.

An example of how basic modeling assumptions can inadvertently constrain outcomes is the divergence between the AWBA and UCRC build-out projections as expressed in modeled reservoir conditions and characterizations of Lower Basin shortage risk; using the more aggressive Upper Basin build out projection provided by UCRC can increase the annual probability of incurring shortages in the Lower Basin by up to 20%. Using the AWBA projection for Upper Basin demand instead of the UCRC projection appeared to reflect policy considerations rather than technical uncertainties regarding water entitlements and future infrastructure development. Operating criteria, including 602 (a) storage and surplus management, integrate several sources of uncertainty, including inflow records, future depletion, and initial reservoir conditions. Operating criteria can change due to evolving management objectives and political resolutions, and therefore, one of CRSS' primary functions is to evaluate the impacts of changes on future water supply variability.

Subsequent to the ISG EIS simulations the impact of initial reservoir condition on modeling outcomes became much more apparent. Understanding that the "worst case" scenario modeled in the ISG effort did not actually predict the declines that occurred over the ensuing three years following underscored these issues with initial conditions and historic inflow records. Understanding the full range of variability allows managers and stakeholders to more accurately reflect on the degree of risk that they are facing when making operating decisions. The impact of modifying initial reservoir conditions is limited to a relatively short period, the first three to five years, but this is a critical time frame from an operations perspective during shortage conditions. An approach using an ensemble of initial conditions may remedy this shortcoming. A range of values could then be assessed rather than selecting a single starting point.

The additive nature of several sources of uncertainty, as well as the potential for nonlinear effects, underscores the need to configure parameter values into scenarios that generate a range of outcomes, including the best- and worst-case, over different time horizons. This is especially important in the context of global change, because many variables could simultaneously exceed their historic ranges, so alternative futures need to be explored.

Stakeholder focus groups posed a related, more process-oriented question, namely: How can public processes to plan for water supply variability and shortage conditions incorporate river system simulations to best meet the needs of diverse stakeholder audiences? This topic provides a fertile area for future research, especially because river system modeling has become a fixture of planning efforts in the Colorado River Basin. An emergent research focus would examine the tension between the need to simplify model outputs by isolating the impact of different assumptions and the countervailing need to express complex interactions among different assumptions and sources of uncertainty. A corollary to this future research direction is the challenge of communicating with diverse stakeholders groups regarding uncertainty and river system modeling. There are decision support tools that allow decision makers to explore the sensitivities of variables using stakeholder driven frameworks (e.g., Sumer *et al.*, 2006; Kimaite *et al.*, 2007). However, these approaches require substantial investments in building a robust database and must be updated regularly to be useful. Even these tools require significant training to aid and empower stakeholders. Clearly, more work is required to build capacity among water managers and other stakeholders to know enough to ask the right questions without providing an overwhelming level of technical details about the underlying modeling framework. Further research into new approaches for framing discussions regarding of modeling assumptions and successfully engaging water managers in public processes would prove useful in a variety of applications across the U.S. and internationally.

## ACKNOWLEDGMENTS

The authors thank the US Bureau of Reclamation – Lower Colorado River Operations office and the Arizona Department of Water Resources, particularly Sandy Whitney, Perri Benemelis and Donald Gross for sharing modeling data and outputs. Comments from Terry Fulp, Kenneth Seasholes, and three anonymous reviewers improved the paper. Authors remain solely responsible for the paper's accuracy. This work was supported by the University of Arizona, Technology and Research Initiative Fund (TRIF), Water Sustainability Program. Funding support from the Bureau of Reclamation also made this research possible.

## LITERATURE CITED

ADWR (Arizona Department of Water Resources), 2005. Arizona Colorado River Shortage Workshops Archive. http://www.azwater.gov/dwr/Content/Find_by_Program/Colorado_River_Management/AZ_CO_files/default.htm, *accessed* November 2006.

ADWR (Arizona Department of Water Resources), 2006a. Shortage Sharing Stakeholder Workshops. http://www.azwater.gov/dwr/Content/Find_by_Program/Colorado_River_Management/AZ_CO_Sharing_Stakeholder_2005/default.htm, *accessed* March 2006.

ADWR (Arizona Department of Water Resources), 2006b. Arizona Colorado River Shortagoe Sharing Stakeholder Committee. http://www.azwater.gov/dwr/Content/Find_by_Program/Colorado_River_Management/AZ_CO_Sharing_Stakeholder_2005/meeting1/AZ_COLORADO_RIVER_SHORTAGE_SHARING_STAKEHOLDER_COMMITTEE.pdf, *accessed* November 2006.

ADWR (Arizona Department of Water Resources), 2006c. Colorado River Management Section. http://www.azwater.gov/dwr/Content/Find_by_Program/Colorado_River_Management/, *accessed* November 2006.

AWBA (Arizona Water Banking Authority), 2005. Background. http://www.awba.state.az.us/default.htm, *accessed* October 2005.

Callejo, R. and T. Fulp, 2005. Using CRSS to Explore Shortage Studies on the Lower Colorado. http://cadswes.colorado.edu/riverware/ugm/2005/presentations/guest/2005_RussCallejo.pdf, *accessed* October 2005.

Carter, Rebecca.H. and Barbara.J. Morehouse, 2001. An Examination of Arizona Water Law and Policy from the Perspective of Climate Impacts. CLIMAS Report Series No. CL2-01. Institute for the Study of Planet Earth, University of Arizona, Tucson, Arizona, 37 pp.

Christensen, N. and D.P. Lettenmaier, 2007. A multimodel ensemble approach to assessment of climate change impacts on the hydrology and water resources of the Colorado River basin. Hydrology and Earth System Sciences 3:1-44.

Christensen, Niklas.S., Andrew.W. Wood, Nathalie. Voisin, Dennis.P. Lettenmaier, and Richard.N. Palmer, 2004. The Effects of Climate Change on the Hydrology and Water Resources of the Colorado River Basin. Climatic Change 62:337-363.

Federal Register, 2005. "Notices", Vol. 70, No. 189, Friday, September 30, 2005

Fulp, T. and J. Harkins2001. Policy Analysis Using RiverWare: Colorado River Interim Surplus Guidelines. Proceedings of ASCE World Water & Environmental Resource Congress. http://cadswes.colorado.edu/riverware/abstracts/FulpOrlando2001.html, *accessed* in September 2005.

Getches, D., 2003. Constraints of Law and Policy on the Management of Western Water. *In:* Water and Climate in the Western US. University Press of Colorado, Boulder, Colorado.

Hartmann, H., 2003. Stakeholder Driven Research in a Hydroclimatic Context, PhD Dissertation, Deprtment of Hydrology and Water Resources, University of Arizona.

Hirshboeck, 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: A Collaborative Project between The University of Arizona's Laboratory of Tree-Ring Research & The Salt River Project". http://fpnew.ccit.arizona.edu/kkh/srp.htm, *accessed* March 2006.

Jacobs, K. and R. Pulwarty, 2003. "Water Resource Management: Science, Planning, and Decision-Making." *In:* Water: Science, Policy, and Management: challenges and opportunities, Richard G. Lawford, Denise D. Fort, Holly C. Hartmann, and Susanna Eden (Editors). American Geophysical Union, Washington, D.C pp. 177-204.

Jerla, Carly., 2005. "An Analysis of Coordinated Operation of Lakes Powell and Mead Under Lower Reservoir Conditions". MS Thesis, University of Colorado, Boulder, Colorado.

Jerla, C. and T. Fulp, 2005. "CRSS Lite: An Annual Time Step Model for the Colorado River Stakeholders". http://cadsweb.colorado.edu/riverware/ugm/2005/presentations/cw/CRSS_Lite_Carly.pdf, *accessed* November 2005.

Kimaite, F., A. Tidwell, C. Braneon, M. Kistenmacher, H. Yao, and A. Georgakakos, 2007. "Decision Support Tools for River Basin Planning and Management". Georgia Water Resources Conference, Athens, Georgia, March 27 to 29, 2007.

Lettenmaier, D., 2003. The Role of Climate in Water Resources Planning and Management. *In:* Water: Science, Policy, and Management: challenges and opportunities, Richard.G. Lawford, Denise.D. Fort, Holly.C. Hartman, and Susanna. Eden (Editors). American Geophysical Union, Washington, D.C. pp. 247-266.

MacDonnell, L.J., D.H. Getches, and W.C. Hugenberg, Jr, 1995. Law of the River: Coping with Severe Sustained Drought. Water Resources Bulletin 31(5):825-836.

Meko, D., C.S. Stockton, and W.R. Boggess, 1995. Tree-ring Record of Severe Sustained Drought. Water Resources Bulletin 31(5):789-801.

Meko, D.M., C.A. Woodhouse, C.A. 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):10705-10709.

Morss, R., O. Wilhelmi, M. Downton, and E. Gruntfest, 2005. Flood risk, uncertainty, and scientific information for decision making. Bulletin of the American Meteorological Society 86(11):1593-1601.

Ouarda, T., J.W. Labadie, and D.G. Fontane, 1997. Index Sequential Hydrologic Modeling for Hydropower Capacity Estimation. Journal of the American Water Resources Association, 33(6):1337-1349.

Pielke, Jr., R.A., 2003. The role of models in prediction for decision. In: Understanding Ecosystems: The Role of Quantitative Models in Observations, Synthesis, and Prediction, C. Canham, and W. Lauenroth (Editors). Princeton University Press, Princeton, New Jersey, pp. 113-137.

Pulwarty, R.S. and T.S. Melis, 2001. Climate extremes and adaptive management on the Colorado River: Lessons from the 1997-1998 ENSO event. Journal of Environmental Management, 63:307-324.

Pulwarty, R.S. and K. Redmond, 1997. Climate and Salmon Restoration in the Columbia River Basin: the Role and Usability of Seasonal Forecasts. Bulletin of American Meteorological Society 78(3):381-397.

Reisner, Marc., 1986. Cadillac Desert: The American West and Its Disappearing Water. Penguin Books.

Sabatier, P.A., C. Weible, and J. Ficker, 2005. Eras of Water Management in the United States: Implications for Collaborative Watershed Approaches. *In:* Swimming Upstream. P.A. Sabatier, W. Focht, M. Lubell, Z. Trachtenberg, A. Vedlitz, and M. Matlock (Editors). MIT Press, Cambridge, Massachusetts. pp. 23-52.

Stewart, T.S., R.A. Pielke, Jr., and R. Nath, 2004. Understanding User Decision Making and the Value of Improved Precipitation Forecasts: Lessons from a Case Study. Bulletin of the American Meteorological Society 85(2):223-235.

Stockton, C.W. and G.C. Jacoby, 1976. Long-Term Surface-Water Supply and Streamflow Trends in the Upper Colorado River Basin. Lake Powell Research Project Bulletin No. 18, Report NSF/RA-760410, March 1976.

Sumer, D., G. Chung, H. Richter, and K. Lansey, 2006. Decision Support System for Managing Conflict in the Upper San Pedro Subwatershed, AZ. Proceedings of Operations Management 2006 Conference.

University of Colorado, 2006. CU-Boulder's RiverWare Modeling Tool Played Key Role in Colorado River Negotiations. http://www.colorado.edu/news/releases/2006/66.html, *accessed* November 2006.

USBR (U.S. Bureau of Reclamation), , 1969. Report of the Committee on Probabilities and Test Studies to the Task Force on Operating Criteria for the Colorado River. http://wwa.colorado.edu/in_focus/colorado_river/USBR%20Operating%20Criteria%20Task%20Force%20report%201969.pdf, *accessed* October 2005.

USBR (U.S. Bureau of Reclamation), 1988. Hydrologic Determination. http://wwa.colorado.edu, *accessed* November 2005.

USBR (U.S. Bureau of Reclamation), 2003. Meeting Minutes, Colorado River Modeling Group, May 15, 2003. Arizona Department of Water Resources Data Archive, Phoenix, Arizona. *Accessed* June 2005.

USBR (U.S. Bureau of Reclamation), 2005. Upper Colorado Region Reservoir Operations. http://www.usbr.gov/uc/crsp/GetSiteInfo, *accessed* November 2005

USBR (U.S. Bureau of Reclamation), 2006a. Law of the River Homepage. http://www.usbr.gov/lc/region/pao/lawofrvr.html, *accessed* November 2006.

USBR (U.S. Bureau of Reclamation), 2006b. Managing Strategies for Lakes Powell and Mead. http://www.usbr.gov/lc/region/programs/strategies.html, *accessed* November 2006.

USDOI (U.S. Department of Interior), 2000. Final Environmental Impact Statement. Colorado River Interim Surplus Criteria. http://www.usbr.gov/lc/region/g4000/surplus/SURPLUS_FEIS.HTML#, *accessed* November 2005.

USDOI (U.S. Department of Interior), 2007. Draft Environmental Impact Statement. Colorado River Interim Guidelines for Lower Basin Shortages and Coordinated Operations for Lake Powell and Lake Mead. http://www.usbr.gov/lc/region/programs/strategies/draftEIS/index.html, *accessed* June 2007.

Wood, A.W., 2005. Invited Seminar, Department of Hydrology (Tucson, AZ). Experimental Real-time Seasonal Hydrologic Nowcasting and Forecasting for the Western U.S.. http://www.hydro.washington.edu/Lettenmaier/Presentations/2005/a_wood_AZseminar_apr05_talk.ppt, *accessed* November 2005.

Woodhouse, C., S. Gray, and D. Meko, 2006. Updated Streamflow Reconstructions for the Upper Colorado River Basin. Water Resources Research 42:5415-5430.

Woodhouse, C.A. and J.J. Lukas, 2006. Multi-century tree-ring reconstructions of Colorado streamflow for water resource planning. Climatic Change 78(2-4):293-315.

Wurbs, R.A., 2005. Comparative Evaluation of Reservoir/River Simulation Models. Texas Water Resources Institute. Technical Report-282. http://twri.tamu.edu/reports/2005/tr282.pdf. *Accessed* November 2006.

Zagona, E.A., T.J. Fulp, R. Shane, T. Magee, and H.M. Goranflo, 2001. RiverWare: A Generalized Tool for Complex Reservoir Systems Modeling. Journal of American Water Resources Association 37(4):913-929.