# MEETING THE NEEDS OF COLORADO RIVER STAKEHOLDERS: A NEW POLICY EVALUATION TOOL IN RIVERWARE & AN ANALYSIS OF COORDINATED RESERVOIR MANAGEMENT UNDER LOW RESERVOIR CONDITIONS

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**Abstract**
Reclamation and some of the major stakeholders on the Colorado River have expressed a need for a simpler and faster version of Reclamation's official long-term planning model, the Colorado River Support System (CRSS), implemented in RiverWare. The requested model would have an annual computational timestep and could be used to quickly and easily identify and screen potential alternatives. Although CRSS is flexible, it is quite large and complex with a run-time of up to two hours requiring intensive data management and is not well suited towards quickly reviewing and screening policies. CRSS-Lite, also implemented in RiverWare, was developed to meet these needs. Using the CRSS-Lite model, alternative operational policies during shortage conditions that involve the coordinated management of Lakes Powell and Mead are explored. Using RiverWare's Graphical Policy Analysis Tool (GPAT) the results and performance of the two strategies can be quantified in terms of reservoir elevation percentiles, magnitude and frequency of shortages and the protection of critical elevations for power generation and recreational use.

## INTRODUCTION

Water resource managers on the Colorado River are faced with the problem of meeting water demands for a body of stakeholders comprised of state agencies, Native American tribal groups, irrigation districts, municipalities and other non-governmental organizations with often conflicting interests such as municipal, industrial, and agricultural supply, hydropower production, recreation, endangered species and other environmental concerns. This problem is intensified by the extreme hydrologic variability that is characteristic of the Colorado River. While unregulated inflow to Powell was 105 percent of average for water year 2005, this was a dramatic change since 2000. Inflow volumes for the previous five water years were significantly below average. Total unregulated inflow in water years 2000, 2001, 2002, 2003, and 2004 was 62, 59, 25, 51, and 51 percent of average, respectively. Inflow in water year 2002 was the lowest ever observed since the completion of Glen Canyon Dam in 1963.

Controversy has been synonymous with the Colorado River since the signing of the Colorado River Compact in 1922, negotiated during a period of relatively high flows. Since then, the basin has continuously developed. A long history of litigation, increasing demands and hydrologic variability have driven Reclamation and the Colorado River stakeholders to enter negotiations with the intent of adopting official shortage guidelines for the Lower Basin. Computer modeling will play a central role in developing shortage policy alternatives.

Computer models that are capable of representing the complexities of the basin become critical and powerful tools to facilitate effective planning of reservoir operation throughout the system. Reclamation uses modeling extensively. Their official planning model, CRSS, is a necessary component of long-term planning and policy studies. The exploration of alternative reservoir operating polices and the assessment and review of existing policies using modeling is essential to ensure that operations can respond to the changing hydrologic conditions and management objectives on the river.

## MODELING

In addition to performing planning studies to inform decision-makers, a model facilitates communication and understanding of the policies between stakeholders and water managers. A variety of modeling systems are available to water management agencies and stakeholders although often they do not offer the flexibility required to mimic the changing multiple objectives of water projects and require significant effort and expense to maintain and update (Zagona et al., 2001).

### Official River Operations Model CRSS

Reclamation utilizes RiverWare that overcomes these shortcomings by its flexible policy expression and the extensive library of physical processes algorithms (Zagona et al., 2001). CRSS is Reclamation's designated monthly timestep model used to simulate reservoir and river operations in the Colorado River Basin. It was originally developed in the 1970's and 80's as a FORTRAN program. In the mid-1990's, Reclamation re-implemented CRSS in RiverWare, with involvement of interested stakeholders. The *Law of the River* and other operating criteria are expressed as logical rules in RiverWare's rule language that can be understood and modified to meet changing objectives in the basin and are isolated from the physical process model. The RiverWare version of CRSS is now the officially accepted version of the model. The process of implementing CRSS in RiverWare clarified many policies not documented in the FORTRAN version and was crucial in providing the foundation upon which new policies can be added. The flexibility of the RiverWare version of CRSS has made possible model studies for long-term planning, mid-term forecasting and short-term scheduling.

### RiverWare

RiverWare$^{TM}$ is a computer software package developed by the University of Colorado Center for Advanced Decision Support for Water and Environmental Systems (CU-CADSWES). It is a generalized river basin modeling tool than can be applied to a river basin of interest for operations and planning purposes (Zagona et al., 2001). RiverWare is visually oriented and displays and represents the physical river system using a series of predefined objects such as reservoirs, river reaches, canals, etc. These objects are linked together and information is propagated between them via the links when a simulation is performed.

A RiverWare model can be run in three different modes. These are pure simulation, rule-based simulation and optimization. CRSS is run in rulebased simulation mode in which the simulation is driven by a set of specified operating policies, i.e., a ruleset. The RiverWare Policy Language (RPL), viewed and modified outside of compiled code, allows the specification of logical "if-then-else" or "while" statements, and other customized functions to represent policy. The policy ruleset drives the simulation by setting values on variables within objects on the workspace. The objects then solve their hydrologic equations according to the values the stored values.

**Long-Term Planning Studies**

Long-term planning studies examine the effects of changes on the river system – new or modified structures, change in hydrology or climate, changes in water use and demands, and changes in operating procedures. Since the National Environmental Policy Act (NEPA) became a law in 1969, proposed federal actions that may significantly affect the river system must undergo analysis prior to implementation. These studies pursuant to NEPA require long-term planning model runs that compare several operating policy alternatives. At the initiation of a NEPA process, a public scoping process is conducted to inform the public and formulate potential policy alternatives. The selected policy alternatives are modeled in CRSS to assess potential impacts. Examples of long-term planning studies include the Interim Surplus Criteria EIS and the Lower Colorado Multi-Species Conservation Plan (Fulp and Harkins, 2001).

Due to the wide-ranging effects of these impacts, the time-horizon over which the model is run is on the order of decades. Different operating policies are implemented in separate rulesets, which are interpreted by RiverWare when the model is run. Model output is managed and presented using GPAT jointly developed by CU-CADSWES and Reclamation. GPAT presents the output from several RiverWare simulations in graphical comparative figures allowing the impacts of policy alternatives to be fully explored (Wheeler et al., 2002).

To represent hydrologic uncertainties during long-term policy studies, CRSS and CRSS-Lite use a technique known as the index sequential method (Ouarda et al., 1997). Under this technique cycling through the current historical natural flow record, dating 1906 through 1995, generates a future inflow scenario. The result is 90 different hydrologic sequences, referred to as “traces” for each policy alternative. Natural flows are the flows over time that would have been observed absent human development. These flows are computed from the gauged flows, adjusted for upstream reservoir regulation and consumptive uses. The natural flows through 2003 have recently been computed and are currently under review.

**CRSS-Lite - Policy Modeling Evaluation Tool**

CRSS-Lite (Lite) was designed to provide a faster, less complex alternative to CRSS for the purpose of screening policy alternatives, policy evaluation and comparing the results of different operations in the Lower Basin. Lite was developed at CU-CADSWES in collaboration with Reclamation using the modeling tool RiverWare. A group of stakeholders established the initial user-requirements and were kept actively engaged in the development process. The representation of the physical system and operational policies in Lite directly mimic those of the in CRSS from Lake Powell to Mexico. Although many computations and operations are made within Lite at a monthly time series, the model runs on an annual basis to reduce run times. In addition, the Upper Basin reservoirs above Powell are currently not represented in Lite. CRSS is used to model the Upper Basin and the resulting inflows into Lake Powell are then input into Lite. Future work may include the incorporation of the Upper Basin above Powell into Lite.

Lite was also developed to replace CRSSez, a simplified Visual Basic model that was developed by Reclamation in the early 1990’s, based on the old FORTRAN version of CRSS. The greatest benefit of CRSSez is its speed; it is capable of performing a 90-trace simulation on the order of minutes. It does, however, have the same limitation as the old FORTRAN model: the operating policies cannot be explicitly seen (they are hidden in the code) nor can the policies be modified by the user to investigate new alternatives. Thus, its use is limited to investigating only previously developed polices, alternative demands, or hydrologic inputs. One reason for the fast run-time of CRSSez is that the reservoirs in the Upper Basin above Powell are aggregated and represented as a single virtual reservoir. This virtual reservoir is modeled by applying linear regression equations that predict the inflow to Powell based on historical hydrology, Upper Basin demands, and a shortage coefficient derived from CRSS data (Reclamation, 1998). Also, in CRSSez the operation of the Upper Basin virtual reservoir is dependent on Powell's capacity, which is consistent with the FORTRAN version of CRSS but is not consistent with the current version of CRSS or real operational procedures.

CRSSez does not meet the current need for investigating new alternative policies for re-allocation of water or reservoir operations. CRSS-Lite, developed in RiverWare meets this need. RiverWare was developed with the intention of meeting the needs of water management agencies in replacing obsolete site-specific models. RiverWare provides a RiverWare-specific rule language, a rich programming language kept separate from the compiled code that is easily modified and viewed by the user (Zagona et al., 2001). The ability of this language to capture significant detail is demonstrated by its ability to capture the complexity of the operational policies in CRSS.

From the perspective that the primary purpose of Lite is the investigation and evaluation of policy alternatives, a language that presents a clear representation of the policy that can be viewed explicitly, and communicated to and shared with various bodies of stakeholders is absolutely essential. Lite provides a replacement to CRSSez, built with the modeling paradigm of the prior-generation of hard-wired models and allows users to view and understand the details of the policies participate in the exploring of new alternatives.

Although testing of Lite indicates that the results are within $10^{-4}$ percent of CRSS, the detailed monthly timestep model would still be used to provide the final model results for the final evaluation of selected alternatives used for subsequent resource analyses (i.e., analyses for EIS). Studies of this sort require analyses of monthly data such as flows in reaches for environmental considerations of which Lite does not provide. Lite requires a run-time of approximately twelve minutes for 90 traces. The coordinated management strategies presented in this paper were modeled in Lite.

## COORDINATED RESERVOIR OPERATIONS

The political boundary at Lee Ferry that divides the basin also serves as the division point for the operation of Lakes Powell and Mead. Powell is currently operated according to the Long Range Operating Criteria (Reclamation, 2004). Under these operations, Powell releases a minimum objective release of 8.23 MAF/year unless equalization or spill avoidance is in effect (both of which require relatively high storage levels at Lake Powell). The equalization provision states that if the end-of-water-year (September 30 of each year) storage in Lake Powell is forecasted to be greater than the forecasted end-of-water-year storage in Lake Mead, Lake Powell will release more than the minimum objective release in order to equalize the storage. Equalization occurs, however, only if there is sufficient storage in the Upper Basin, known as the "602a storage requirement" (Reclamation, 2004). Mead operations are governed by downstream demands or flood control.

The net effect of equalization is a coordinated operation between Lake Powell and Lake Mead at relatively high reservoir levels. However, when one or both of the reservoirs are relatively low, current operations do not provide for a similar coordinated operation, resulting in quite different behavior of the two reservoirs during the onset and offset of drought. This relationship is depicted in Figure 1, which plots the end of the water year (EOWY) storages of Powell and Mead from 1988 – 2005. The hydrology of this period includes periods of below average runoff from 1988 – 1994 (excluding 1993), above average from about 1995 – 1999 (excluding 1996) and average or below from 2000 – 2005.

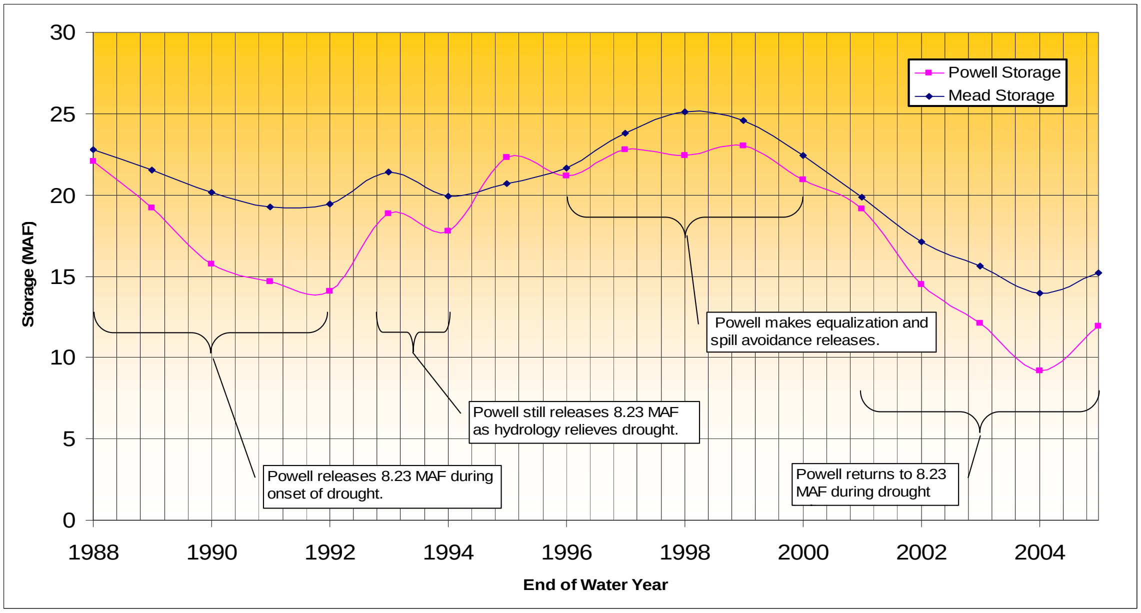


Figure 1 Actual EOWY Storage Capacity at Powell & Mead 1988 – 2005

Note that at the EOWY in 1988 both reservoirs are at approximately the same capacity. During the drought of 1988-1992, Powell's inflow is less than its 8.23 MAF annual release into Mead, and thus Powell is drawn down at a rapid rate. Under this scenario, Mead declines, but at a slower rate than Powell. This is illustrated in Figure 1 by the steepness of the slope at which Powell declines compared to that of Mead through 1992. As hydrologic conditions start to improve in 1993, the reservoir levels in the Upper Basin recover earlier than in the Lower Basin. Because the Upper Basin storage is below the 602(a) requirement and the storage at Powell is less than that at Mead, Powell continues to release the minimum objective release through 1994. As Powell's inflow exceeds its release, Powell recovers faster than Mead (indicated by the steepness of the slope) as Mead continues to release to meet downstream delivery requirements. Increased consumptive use in the Upper Basin in the future will exacerbate this imbalance. Equalization releases that increase the storage at Mead to the same capacity at Powell do not occur until 1996 when the 602(a) storage level has been met. Powell makes large releases due to equalization and spill avoidance during 1997 – 2000 further increasing the storage at Mead. As hydrology declines after 2000, Powell returns to the 8.23 MAF release resulting in an increasing differential between the reservoir storages.

Coordinated management aims to maintain a more consistent balance of the contents between Powell and Mead under low reservoir conditions. Under coordinated operation, the objective of Powell's release during low flow times might be to more evenly distribute risk to both basins. This can be accomplished by incorporating the storage capacity of Mead into the release decision of Powell at all times (rather than only during equalization as under the current policy). As a management strategy for low reservoir conditions, coordinated management is an appealing approach as it aims to balance the contents of Lakes Powell and Mead as the system enters and recovers from drought conditions.

The Severe Sustained Drought (SSD) study first examined coordinated management of Powell and Mead as an alternative operation during severe shortage, and demonstrated that restoration of a balanced reservoir system reduces risk incurred from low reservoir conditions by providing protection of minimum power pools and potentially reducing shortage levels. Coordinated management was shown to be successful in mitigating the impacts of drought and was thought to be within the legal context of the *Law of the River* (Young, 1995).

## MODELING RESULTS

Two coordinated management strategies were examined and both explored reducing the release from Powell below the 8.23 MAF minimum objective release when certain conditions are met. The first strategy, C1, allows this to happen when Powell is below a specified trigger elevation and Mead is above a specified trigger elevation. The objective of the second strategy, C2, is to keep Powell and Mead at equal capacity, essentially operating them as a single reservoir. Releases are reduced as necessary from Powell if the storage at Mead is higher. Conversely, if the storage at Mead is lower, larger releases will be made from Powell. In both strategies there is no constraint in place that protects the minimum power pool at Powell.

Each simulation begins in 2005 and ends in 2025; runs are performed with each strategy in place through 2016 (end of interim period as defined by the Interim Surplus Guidelines (ISG) EIS), returning to baseline or normal operating policies for the remainder of the simulation. The interim period is viewed as a transitional period and alternative operating policies are frequently modeled by Reclamation as being in effect only during this period. Initial reservoir conditions reflect actual levels at April 2005 when Lakes Powell and Mead stood at 33 and 60 percent capacity, respectively. The Lower Basin shortage policy is the same policy used in the ISG EIS. In two-tiered policy first level shortages are triggered to protect Mead at 1050 ft (minimum power pool) with an 80 percent assurance probability. Second level shortages of a higher magnitude are administered to prevent Mead from falling below 1000 ft, the level of Southern Nevada Water Authority's lower intake structure (Reclamation, 2000).

GPAT was used to generate the statistics used to quantify the outcome of each strategy. Percentile analysis is a statistical method used to view the results of the hydrologic traces in a compact manner yet maintain the fluctuations at high and low reservoir levels that would be lost by averaging the results of the 90 traces. Figure 2 shows the probabilistic projected reservoir elevations for the end of the calendar year and demonstrates the potential impacts on the Upper Basin. A clear benefit is seen through 2013 as Powell's low initial conditions warrant a release below the minimum objective release of 8.23 MAF. Past 2016, however, Powell declines under these strategies compared to the baseline.

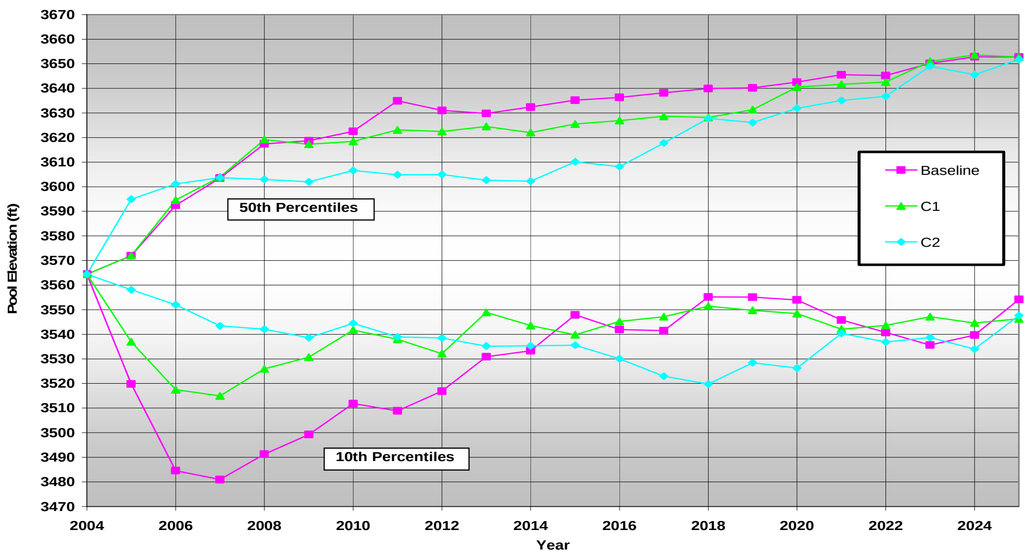


Figure 2 Powell Percentile Elevations

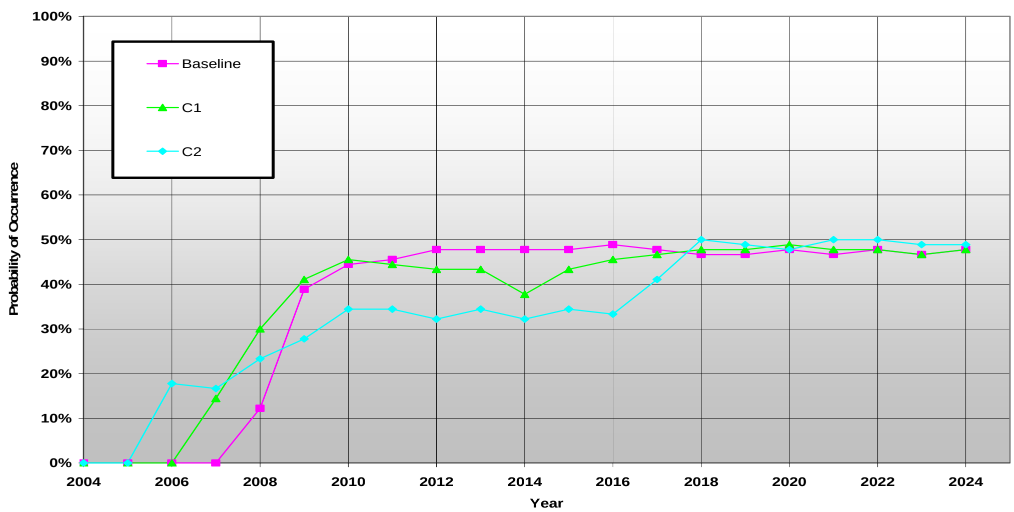


Figure 3 Probability of Lower Basin & Mexico Shortage

GPAT also generates exceedance and non-exceedance probabilities. This capability was used to generate Figure 3, which illustrates the probability that the Lower Basin and Mexico will be in shortage and demonstrates consumptive use impacts on the Lower Basin. This probability increases with time for all strategies, a result of increasing Upper Basin depletions and the deficit at Mead as releases to meet downstream demands exceed the minimum objective release from Powell. A reduction in shortage is seen while coordinated management is in place through 2016.

## CONCLUSION

CRSS-Lite is a policy screening model designed to provide a simplified and fast alternative to CRSS, Reclamation's official monthly timestep planning model. Several Colorado River stakeholders were involved in the development and testing phases of Lite resulting in a successful finished product. Lite preserves the flexibility and accuracy of CRSS but reduces the simulation run-time by two-thirds. CRSSez, the Reclamation screening model of which Lite has replaced, is limited in that policies are hard-coded and can be neither viewed nor changed by a user. In Lite, operational policies are expressed via rule sets that are easily understood, easily modified and can be viewed explicitly by all. This capability allows the exploration of innovative management strategies for reservoir operation under low levels, such as coordinated management.

RiverWare's rule language provides the ability to view the policies representing diverse objectives central to different bodies of stakeholders and promotes and encourages an understanding of the difficulty of the managing dams and reservoirs in a multi-objective environment. RiverWare's Graphical Policy Analysis Tool conveys hydrologic uncertainty and is used for tradeoff analysis to effectively analyze alternatives, express and quantify preferences and communicate results.

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