Multiobjective Optimization of the Colorado River

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Abstract

The Colorado River's 80-year history of treaties, compacts, laws, and court decisions are often referred to as the "Law of the River." The U.S. Bureau of Reclamation (USBR) has developed operating criteria to satisfy these legal requirements. Satisfaction of these complicated criteria is one important measure of the success of a basin model. USBR simulation models such as the Colorado River Simulation Study (CRSS) and the 24 Month Study have incorporated these criteria and are widely used for policy analysis. Both of these models have been reimplemented as rule-based simulations in RiverWare, a general river basin modelling tool. The application of optimization to policy analysis on the Colorado River has been limited by the ability of optimization models to similarly represent these mandated requirements for operations. Using the goal programming component of RiverWare, we have created a monthly optimization model of the Colorado River that replicated the 24 Month Study. Using this solution as a base, the hydropower value of selectively relaxing policies was found.

Introduction

Simulation models of the Colorado River have reached a mature state. The U.S. Bureau of Reclamation (USBR) has successfully applied rule-based simulation models of the river to monthly operations and long-term policy studies (Mohammadi et al. 1991, Stevens 1986). The Colorado River Simulation System (CRSS) and the 24 Month Study (Schuster 1989; Fulp et al. 1991) have been successful because they model the entire river at a monthly timestep while including the necessary elements of institutional policy. The policy involved in these models is a mixture of the Law of the River, which includes the international treaties, legislation, and court decrees and the operating criteria agreed to by the USBR and the stakeholders on the river. CRSS and the 24 Month Study are currently implemented using the rule-based simulation in the RiverWare (Zagona et al.) modeling tool.

These operating criteria do not completely determine the operations of the river. Other methods are used to specify the remaining degrees of freedom in the system. In CRSS (the long-term planning model) reservoir rule curves and rules to meet downstream demand are used. In the 24 Month Study, these decisions in the Upper Basin are made by experienced USBR personnel. Although the current models have the ability to simulate different operational choices in this realm (Zagona et al.), analysis of the trade-offs must be done manually after each model run. This decreases the likelihood that serious exploration of the costs of current and new policies will be considered. Optimization techniques are a natural choice for access to this information, as well as for quick selection of the optimal from many policies.

Operation policy analysis using optimization on the Colorado River has previously been limited to annual timesteps, because monthly operations policies are much more complex than the aggregated annual policies. Booker and Young created an annual optimization model that was used to suggest and analyze some drought coping measures (Booker 1995). However, to get a real picture of what occurred on a monthly timestep with these new policies, they were implemented by Sangoyomi and Harding (1995) in a previous simulation model.

Before comparing alternative policies, we first had to create an optimization model that reproduced the current policy. Preemptive goal programming is well suited to matching the priority structure of the current rules describing the operating policy on the Colorado River. RiverWare includes a preemptive goal programming approach integrated with an underlying linear program. RiverWare has been successfully applied to production models by the Tennessee Valley Authority (TVA) (Eschenbach et al.).

The remainder of the paper is organized as follows: First, we describe the 24 Month Study, a rule-based simulation of the Colorado River. Second, we present a goal programming formulation designed to closely match the simulation results. Third, we add a hydropower objective and evaluate the effect of introducing alternative types of policy flexibility: deviation from rule curves, varying the timing of flood control releases, and varying the timing of meeting demands.

The 24 Month Study

The 24 Month Study has previously been implemented in RiverWare using rule-based simulation and this model is currently used by USBR personnel in the development of the Annual Operating Plan (AOP). While the 24 Month Study does not explicitly contain all of the Colorado River policy, we were able to easily extend the model using rules taken from CRSS (for example, equalization of Lakes Powell and Mead).

For the 24 Month Study, the model representation is shown schematically in Figure 1.

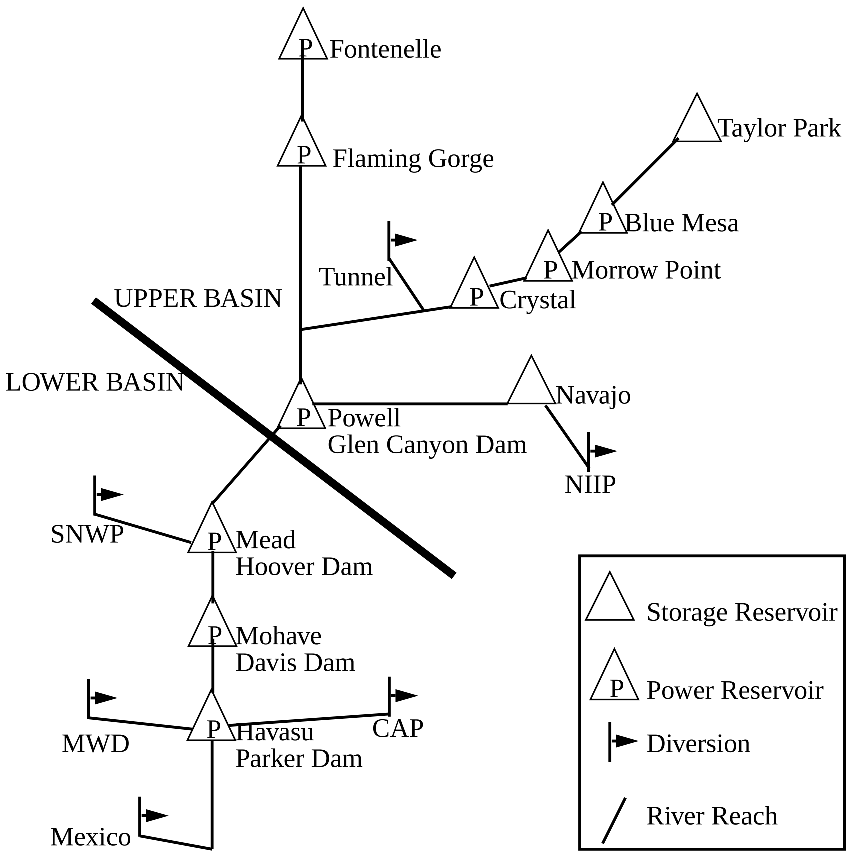

Figure 1: Schematic of the Reservoirs and Diversions in the 24 Month Study

Because the 24 Month Study is an operations model, it is driven by forecasts of inflows into the Upper Basin. These forecasts (termed unregulated inflow forecasts) are produced by the Colorado River Forecasting Center with the Upper Basin depletions already subtracted from the flows. This allows the model to use much less spatial detail with respect to diversions, while still modeling the effects of reservoir regulation.

The 24 Month Study model was run for the period October 1997 through September 1999. Because this time period is the immediate past, the actual historical inflows, diversions, and Upper Basin reservoir operations were used, instead of the hydrologic forecasts and operational decisions used in the planning process. At the beginning of the 1998 water year, the Colorado River system was fairly full, at about 90% of capacity. Lake Powell was at 94% capacity, and Lake Mead was at 87% capacity. Therefore, many of the rules that deal with flood control and high storage controlled the system. With this initial condition, water supply and diversion shortages were not a concern for the two year range of this model.

Operating Policy

Mead Flood Control

This set of procedures is mandated by an agreement between the U.S. Army Corps of Engineers and the USBR and effectively sets a minimum release from Lake Mead for each month. There are three procedures: a procedure for the spring runoff period (January through July), a procedure for the fall drawdown period (August through December), and a procedure to ensure a minimum space in Lake Mead at all times.

Procedure 1, Forecast Spring Runoff Release, January - July: This procedure determines Mead's minimum release for the current month, based primarily on a forecast of the volume of inflow for the entire runoff season (the current month through July), as well as the current space in Lakes Mead and Powell. Essentially, a mass balance is done over this time period to estimate the total volume of water that will need to be released, assuming that Lakes Powell and Mead will fill to specified target values (elevations 1128 and 372 meters respectively). The current month's minimum release is then determined based on this total volume to be released.

Procedure 2, Space Building, August - December: For August through December, an increasing amount of system storage space is required for flood control, in anticipation of the spring runoff. Some Upper Basin reservoir space, (termed "creditable space") is included, with limits varying by reservoir.Table 4. The outflow from Mead is then determined so that Mead supplies the necessary remaining space. This outflow is then a lower bound (it can be exceeded to meet demand), but is also not allowed to be greater than 793 cms.

Procedure 3, Exclusive Space Requirement, January - December: During the entire year, available space in Mead is required to be at least 1.85 billion m^3. If the available space would be below 1.85 billion m^3, whatever release necessary to maintain that space is used, with no upper bound. On a monthly operations level, this is sufficient, since operational targets and planning does not make use of this space.

Powell

Equalization: Equalization refers to the policy of releasing water from Powell in excess of the minimum objective release to make the active storage contents of Powell and Mead equal at the end of the water year under certain conditions. These conditions depend on the calculation of total storage in the Upper Basin to assure future deliveries to the Lower Basin without impairing annual consumptive uses in the Upper Basin.

Minimum Objective Release: The Upper Basin is required to meet a 10 year delivery to the Lower Basin of 92.5 billion m^3, less water delivered into the Colorado River below Lee's Ferry to the credit of the Upper Basin. Additionally, the Upper Basin must fulfill half of the required 1.9 billion m^3 annual delivery to Mexico. These requirements have been translated to an operating criterion of an annual minimum release from Powell of 10.2 billion m^3, termed the "minimum objective release". This is divided up into 12 monthly releases, and serves as a minimum monthly outflow for Powell, until the annual sum has been satisfied.

Powell Rule Curve: In CRSS, Powell is operated with a single rule curve, which can be overridden by the minimum objective release or equalization rules. The rule curve is known to not be the best representation of the operations of Powell, and is only used in CRSS as a beginning point (Veselka et al. 1999). However, without implementing a new spring and fall forecasted operation in the rules, it was the only option available.

Normal Lower Basin Reservoir Operations

Lakes Havasu and Mohave Rule Curves: These two reservoirs are modeled along single rule curves based upon studies done by the USBR (Kaser and Diamond 1951). A recent addition to the rule curves for Mohave operations are limitations on pool elevation change during the spawning season for an endangered fish. For Lake Havasu, the requirements generally stem out of flood control concerns from summer thunderstorms, fall tropical systems, and hard winter rains, and the head requirements for the diversions on the Lake.

Meet Requested Diversion Demands: The 24 Month Study uses monthly diversion schedules from the stakeholders that are manually input for all diversions modeled.

Matching the 24 Month Study with Preemptive Goal Programming

The pre-emptive goal programming (GP) optimization solution technique as well as the automated physical modeling used in RiverWare is presented in detail in Eschenbach et al. The essential decision variables are reservoir releases and diversions from the river. Many other variables exist in the formulation to represent physical processes and constraints such as mass balance, turbine capacity, tailwater elevation, power generation, etc. For the purposes of replication of the rule-based simulation result, the Upper Basin reservoirs, except Powell, had their outflows constrained to be equal to their historical operations.

The priority levels in GP allow the policies stated above to be prioritized. Just as many of the policies above require multiple priorities to implement in a rule-based simulation, they also require multiple priorities in GP. For example, flood control requires different release schedules for different ranges of elevation. Roughly speaking, each of these release schedules and elevation ranges result in a priority level. A more detailed description of the actual priority levels can be found in Gilmore(1999).

The optimization has very closely matched the results of the rules for this scenario. In fact, the differences are only barely apparent during the fall of 1998. The worst point is during November, where the optimization released 4 million cubic meters less than the rules at Mead, an error of 0.4% in outflow. This error is due to the space building policy, and is primarily a result of the optimization using a value for evaporation that was slightly wrong at the four reservoirs in the system where evaporation is modeled (due to the inexactness of the linearization of surface area).

Hydropower and Alternative Policies

To analyze policy, one or more measures of value must be used. Although many costs or values could be applied for this analysis, the value of hydropower generated was selected because it is a major benefit of the operations of the Lower Basin. Since the USBR wholesales its energy to utilities, with the price based only on the operation and maintenance costs for each facility, (Fulp, 1999) another source for this data was needed. We used the closing prices for electricity futures contracts for delivery to the California Oregon border (COB), as traded on the New York Mercantile Exchange (NYMEX).

Lower Basin Reservoir Rule Curves

The historical results from the time period modeled show that the rule curves at Lake Mohave and Lake Havasu are not strictly followed. From communication with USBR employees, the historical operations were due to the high system content and the desire to maximize the water for consumptive use within the United States (Fulp 1999). We formulated several alternative policies by allowing the rule curve constraints to be relaxed by 0.3, 0.9, 1.5, 3, and 4.5 meters of monthly operating range around the Mohave rule curve. Since the rule curve for Havasu has only 1.2 meters of operating range, the Havasu requirement was relaxed by only 0.3 meters to see what that effect would be.

Flood Control Flexibility

The two seasons of flood control at Mead are candidates for timing and flexibility studies. Of these two, the spring runoff season carries a greater risk, and was therefore not studied in a flexibility analysis. Flexibility in space building policy has historically been used, has a smaller risk associated with it, and was included in the flexibility analysis. The amount of water released from Lake Mead was not changed. Specifically, the timing of the releases for space building could be released earlier in the space building season by the optimization.

Flexibility in Water Demand

The water demands below Mead in the 24 Month Study are two diversion points and an aggregated outflow demand from Lake Havasu. Because these demands are the sole controlling factor in water release from Mead (other than flood control), and these diversions have single values at each timestep, flexibility in the timing of the demands here may have a impact on the value of hydropower generated. Flexibility in water delivery was implemented by allowing water delivery to be as much as 10% different from demand in any given time period, but requiring the total delivery to remain unchanged.

Combined Flexibility

A run was also made that combined the flexibility described in the Water Demand Flex, Space building Flex, and Rule Curve Flex scenarios. This scenario included all the flexibility discussed in the previous sections: 4.5 meters of latitude in Lake Mohave’s pool elevation, 0.3 meters of latitude at Lake Havasu, 10% flexibility in meeting water demands, and the space building relaxation.

Maximize Hydropower

Finally, a scenario was made that removed most of the constraints from the system.This scenario included all the changes of the Combined Flex scenario, and also removed the flood control minimum release requirement, the space building storage requirements, and the spring flood control constraint. While this scenario clearly would never be implemented, it does provide a useful comparison to the other scenarios.

Results and Discussion

The economic value of hydropower for all of the alternative policies is reported in Table 1.

Table 1: Annual Energy Values

Scenario	Simulated Average Annual Energy Value, (millions of US dollars)	Percent Increase Over Rules
Actual Operations[a]	203.1	6.14%
Baseline	191.4	--
Rule Curve Flex, Havasu 0.3 m	192.2	0.4%
Rule Curve Flex, Mohave 0.3 m	192.6	0.6%
Rule Curve Flex, Mohave 0.9 m	194.2	1.4%
Rule Curve Flex, Mohave 1.5 m	195.8	2.3%
Rule Curve Flex, Mohave 3 m	198.9	3.9%
Rule Curve Flex, Mohave 4.5 m.	200.1	4.6%
Water Demand Flex, 10%	195.6	2.2%
Space Building Flex	193.7	1.2%
Combined Flex	203.3	6.2%
Max HP	219.9	14.9%

a. The actual operations releases 3.46% more water from Mead than the rules operation, but only 2.16% from Havasu.

It is interesting to note the difference between the simulated value using actual operations, and the value derived from the rules, as shown in Table 1. A marginal analysis was conducted with the rule-based simulation out-flows of Mead, Mohave, and Havasu. An estimated marginal value of water for hydropower was made at the baseline scenario values for the outflow from the Lower Basin. Applying this value (0.015 $/m^3), an estimate of the value for the additional water released was found (8.8 million dollars per year), which is 4.3% of the value of the baseline scenario. This value represents 70% of the increase in the value for historical operations. This may confirm that some of the potential gain in value is achievable in practice.

For the Space building Flex scenario, the valuation gain is interesting, because it is all due to a single shift in flow allocation. This scenario is the most likely to be applied to actual operations, because it is not very controversial.

For the Max HP scenario, it should be noted that a 15% increase in value with the same amount of flow is a large increase, even if that operation is very unlikely.

Conclusion

The current policy has been recreated in an optimization model based on the 24 Month Study, which will allow for straightforward analysis of the Colorado River operating criteria. Model results for both the rule based simulation and the optimization show that these policies have been matched. The optimization model was successfully applied to analyze the value in flexibility of several of the rules currently applied to Lower Basin operations in the 24 Month Study. Given that the annual average energy value for the Lower Basin is on the order of 200 million dollars, even a one percent change in that value is significant. The perfect foreknowledge of the energy price and hydrologies is a bit unrealistic, but the analysis does yield results worth considering when evaluating reservoir and diversion operations on the Lower Basin.

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