A Study of Optimization of Reservoir Operations of the Colorado River

by

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Gilmore, Andrew Fredrick (M.S. Civil Engineering)

A Study of Optimization of Reservoir Operations of the Colorado River

Thesis directed by Associate Professor Kenneth M. Strzepek

Abstract

This thesis has three objectives regarding the management of the water resources of the Colorado River basin. The first objective is to determine through an exhaustive literature review whether or not optimization models have been successfully used to support operational decision-making on the Colorado River. No review of the reservoir operations literature on the Colorado River has been published since the mid-1980s. This thesis lists the major attributes of 78 references to mathematical models in which reservoir storages or releases were a variable, and provides a summary of the capabilities of the underlying simulation and optimization models used by one or more of these references. While some simulation models accurately model the “Law of the River,” no optimization model to date has combined this ability with a prescriptive solution at a monthly timestep for use in reservoir operations and planning.

The application of optimization to policy analysis on the Colorado River has been limited by the ability of optimization models to fully represent the legally mandated requirements for operations. The second objective of this research is to create a monthly optimization model of the Colorado River that includes the operational policies. The difficult policies are flood control at Lake Mead and equalization of the storages of Lakes Powell and Mead. A comparison of the results of this optimization model with the results of the U.S. Bureau of Reclamation’s rulebased simulation model (using an extended version of the 24 Month Study) shows that the flood control policy has been exactly repro-

duced. The equalization policy has not been matched completely, but the difference is in the timing of releases, not whether or how much.

The third objective is to use the optimization model to determine if operational flexibility could be used to increase hydropower values. The analysis of operational policies currently contained in the 24 Month Study shows that gains on the order of 6% in forecasted hydropower generation value are possible using reasonable amounts of flexibility. Because the annual value from the three hydropower generation locations in the Lower Basin of the Colorado River is on the order of 200 million dollars, even small percentage gains can be worthwhile. This thesis did not explicitly consider the many other impacts of the operations of the Lower Basin, such as environmental impacts, water supply, and recreation. However, these and other issues could be addressed in further research with this model.

DEDICATION

To my long suffering wife and children, with many thanks for care along the journey.

ACKNOWLEDGEMENTS

Thanks are due to Ken Strzepek for his direction while working on this thesis, I must also thank Tim Magee for all his support and encouragement during this work, Janet Yowell for the copy-editing of some of the papers submitted as a result of this work, and Terry Fulp for his efforts in financial and data support, as well as direction. This has been a great work, and I am glad to have done it.

I also wish to thank the United States Bureau of Reclamation, Lower Colorado Region, Boulder Canyon Operations Office, for funding this research.

CONTENTS

TABLES

FIGURES

Chapter I: Introduction

The Colorado River basin is the major source of water for portions of seven southwestern states and Mexico. The river drains approximately 630,000 km^2 (243,000 mi^2), about 1/12th of the area of the lower 48 states. Since the southwest is a generally arid region, agriculture, industry, and municipalities all depend on the river as an economical source of water. The Colorado River rises out of the mountains of Colorado, Wyoming, Utah, and New Mexico to flow southwest through the deserts of Arizona, Nevada, and California. The river’s outlet is a delta in the Gulf of California.

Transbasin diversions are plentiful, taking water out of the basin and delivering it to the metropolises of Southern California, the Wasatch front, the Rio Grande Valley, and the Colorado Front Range. Large amounts of agriculture are also supported by the river, from livestock to alfalfa fields, fruit trees, and vegetables. The natural flow at Lee’s Ferry, AZ (below Lake Powell) averages around 15 million acre-feet (MAF) annually, with a high of 24, and a low of 5. To deal with the varying flow of the river, reservoirs have been built that can store 60 MAF combined, almost 4 times the annual flow. These reservoirs often have multiple purposes, flood control and water supply reliability being the two most often required. Hydropower generation capability has been installed at most of these reservoirs, and has proven a valuable resource, although of lower importance. Environmental concerns have now become important, and have changed the operations of the river. Two examples are limitations on the rate of change of outflow from Lake Powell to protect the Grand Canyon, and limitations on the rate of change of pool elevation at Lake Mohave to protect spawning endangered fish. Recreation is another large source of income for the population in the basin, with many national parks and other destinations dependent on the reservoirs and streams which make up the river.

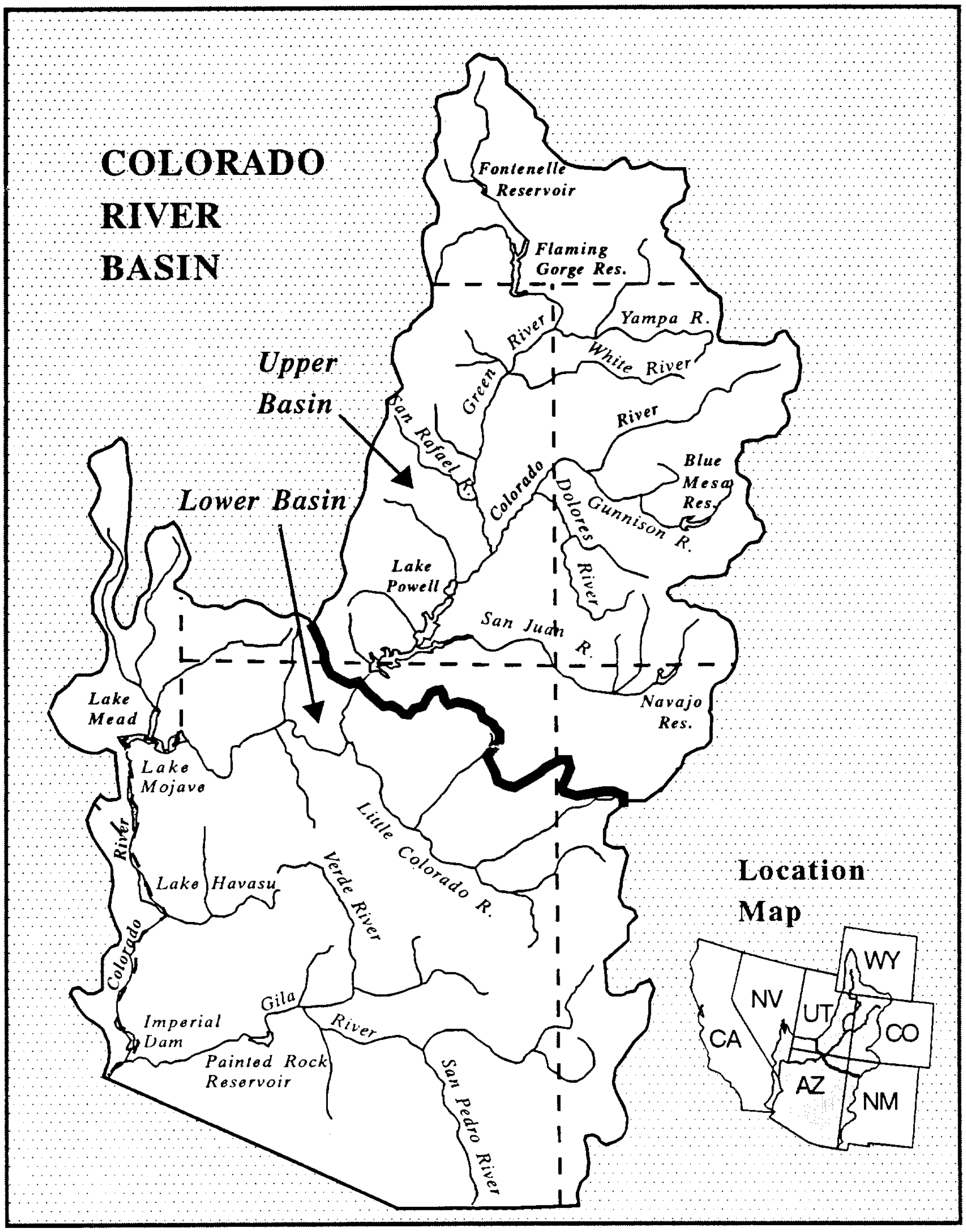

Figure 1: Map of the Colorado River Basin

(CADSWES, 1999)

The complexity due to multiple objectives is only enhanced by the river's 80-year history of laws, court decrees, international treaties, contracts, etc. These are often referred to as the "Law of the River," resulting in the Colorado River being called "the most litigated river in the world" (Nathanson 1978). One example of the legal framework is the separation of the drainage into the Upper and Lower

Basins, as shown in Figure 1. The U.S. Bureau of Reclamation (USBR), water managers of the Colorado River, has developed operating criteria to satistfy these legal requirements. Satisfaction of these complicated criteria is one important measure of the success of a basin model.

Management of such a complex and essential resource requires careful analysis and both short-term and long-term planning. Water resources systems analysis contains many rich and useful techniques for planning, operating, and scheduling of reservoirs and consumptive uses (Loucks et al. 1981; Mays and Tung 1996). Several computer models of the Colorado River basin based on these techniques have been developed since the late 1960s.

Models of the Colorado River can be broadly described as the Colorado River Simulation System (CRSS) and everything else. CRSS is a simulation model that is used by the USBR to do long term policy studies. The original CRSS model was developed in the late 1970s and used until the early 1990s. It was replaced in 1996 by a new model using the RiverWare™ modeling system (Fulp et al. 1996).

Previous work in optimization on the Colorado River stretches back to Heaney's (1968) work. Since then, optimization of facets of the Colorado River's operations and economy have been met with widely varied amounts of success.

This research focuses on applying optimization to the operations of the Lower Colorado River. The motivation for this effort has several sources. First, no optimization model has managed to replicate the Law of the River at a monthly timestep. Second, an optimization model would allow identification of potential flexibility in the system while still meeting the Law of the River. Finally, an optimization model allows one to selectively relax some of the policies to analyze the trade-offs between these policies and hydropower generation value.

This thesis is organized as follows: Chapter II is a review of the literature of reservoir operations models of the Colorado River. Chapter III describes the methodology involved in replicating the operating policy of the rule-based simulations, and shows the ability of the optimization model to reproduce the simulation model results. Chapter IV presents an analysis of the hydropower value of flexibility in the Lower Colorado River operating policy, and includes the derivation of a monthly wholesale value of peak power. Chapter V concludes the thesis, and looks at the many research directions made possible by this work.

Chapter II: A Review of Reservoir Operations Models of the Colorado River Basin

Introduction

Bishop et al. (1984) conducted a review of Colorado River basin models and concluded that while several models were useful and successful, there were still many outstanding needs such as the development of a definitive data set, models that are general enough to be used in many applications, better applications of optimization, and more stakeholder involvement. Although modeling of the Colorado River basin has advanced considerably in the 15 years since Bishop's review, no optimization models have been successfully applied to operational decision-making on the Colorado River.

The following section, Methodology, describes the literature search methodology and categorization of references. The next section offers an analysis of the state of simulation and optimization modeling of the Colorado River basin. Appendices A and B each contain descriptive summaries of the simulation and optimization models, respectively, used in one or more of the references.

Methodology

The initial search, intentionally broad, included any and all references to "Colorado River" in W*ater Resources Abstracts*, ASCE's index of publications, and the *National Technical Information Service Index*. In addition, the references cited in more than 20 of the most relevant papers were examined. This initial filter found approximately 2,000 Colorado River references. Other rivers in the state of Colorado, as well as the Colorado River in Texas, made up a large part of the references found. Subsequently, after removing these references to other rivers, and omitting geological, geomorphic, groundwater, precipitation enhancement, and other topics not of interest, nearly 400 references about surface water modeling of the Colorado River basin remained.

In 1984, Bishop et al. conducted a computerized literature search for “Colorado River Basin.” Of the 148 references found, 96 used a quantitative approach. The 96 references were classified by technique, geographical area, application, and subject. Due to a concentration on surface water, the 400 filtered references from 1999 are not directly comparable to Bishop et al.’s 148 references from 1984.

The list of 400 references was further reduced to 78 references by allowing only models in which the storage or release of reservoirs was a variable. This criterion eliminated the following topics: capacity expansion, reservoir design, investment scheduling, conceptual models of salinity sources, salinity control, economic analyses, carrying capacity, and hydrologic sciences. This elimination was much more restrictive than that used by Bishop et al., but the review also includes references that post-date Bishop’s review. The Venn diagram presented in Figure 1 describes this relationship.

The 78 references were partitioned into four categories: simulation, optimization, water quality, and economics, based on the primary focus of the reported work. A few of the references touch on more than one category, but they are listed in their dominant category only. Papers from different categories may use the same model. For example, a reference describing a new simulation model would be in the simulation category, while references applying the same model to water quality would be in the water quality category.

The distinction between simulation and optimization models is not always clear. For example, some optimization models use operations research techniques to describe current policy rather than to prescribe “best” operations. The simulation definition includes models of the behavior of the system, that perhaps consider policies, but do not make any attempt to find an “optimal” operation. Optimization is used in the sense of systems analysis and operations research, where the system is modeled, and some objective function is used to find a “best” operation. The simulation and optimization references are sorted first by the model used, and second by the year of publication. These two categories are of central interest to this review. The water quality and economics categories were sorted by year of publication, newest first.

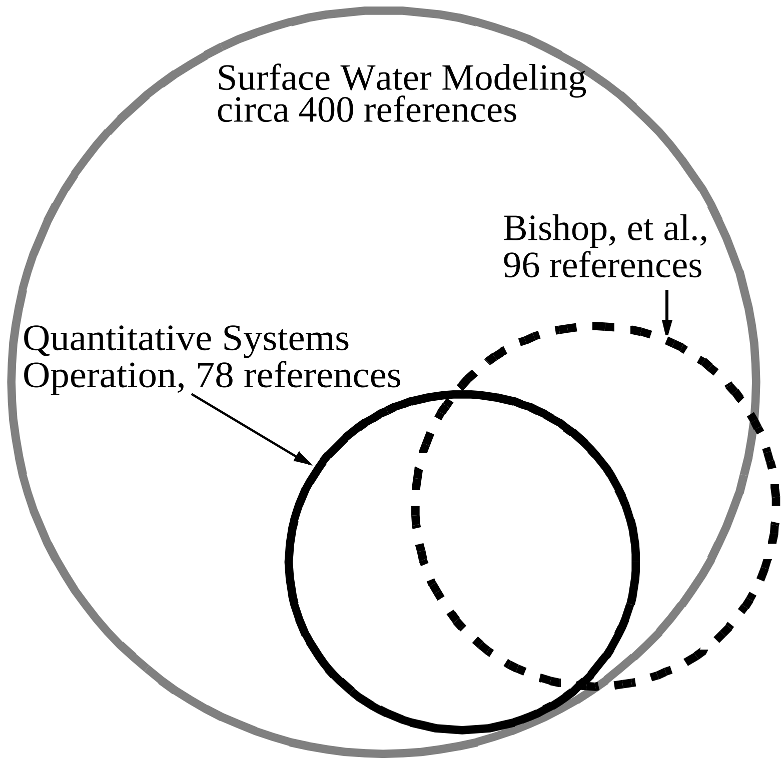

Figure 2: Venn Diagram of Literature Reviews

This diagram shows the set relationships among the 1999 set of about 400 references to surface water modeling, the 1999 set of 78 references to quantitative systems operation, and the set of 96 references to quantitative Colorado River models by Bishop et al. (1984). The new references present in the set of 78 consist of interesting models developed since the 1984 review and new applications of older models. Particularly of interest are the models developed to support the Severe Sustained Drought study in 1995 (Booker 1995; Henderson and Lord, 1995; Harding et al. 1995), and the development of RiverWare (Zagona et al. submitted 1999).

The 78 references are summarized using the attributes listed in Tables 1 and 2, and are separated by category: Simulation (Table 2), Optimization (Table 3), Water Quality (Table 4), and Economics (Table 5). While no list of attributes fully describes a modeling study, the attributes in Table 1 are intended to guide researchers to appropriate previous research. The numerical algorithms in Table 2 are not an exhaustive list, but are the algorithms that have been used by the references found.

Each modeling category characterizes its references according to the following attributes. The *spatial extent* of the model—the geographic region represented—directly affects the computational and data complexities, as well as the application of the model. Research varies considerably with which policies are incorporated and how they are modeled. I classified the policies based on their driving force: *institutional regulations*, *economics*, *hydropower*, and *water quality*. Finally, the *numerical modeling technique* employed was categorized.

For the simulation and optimization categories, additional attributes were used. These classifications are sorted by *model name* (or well-known acronym) and then by year of publication, newest first. The *timestep* and *time horizon* of the models—which have a great effect on the computational effort—were classified. The timestep is classified as annual, seasonal, monthly, daily, or subdaily. The duration is reported as short term (under one month), long term (more than one year), or as the number of years run, if known.

Each of the simulation and optimization models used in the references listed in Tables 2 and 3 is described in the Model Summary Sections, Appendices A and B, respectively. The summaries include a description of each model, a discussion of its intended use, a summary of the acceptance of the model by its intended audience, and its limitations. Limitations are stated relative to the current modeling needs of the USBR for the Colorado River basin: flexibility, ability to specify alternative policies, data-centered design, and a user-friendly graphical interface (Fulp et al. 1994). While in principle many of the more recent models considered by this search could have fulfilled these needs with additional work, only the reported application was discussed.

Table 1: Attributes Used to Characterize Modelling References[a]

TIME STEP	TIME HORIZON	GEOGRAPHIC EXTENT	POLICY	ECONOMY	HYDRO POWER	WATER QUALITY
mon = Monthly	LT = Long Term	UB = Upper Basin	yes = discussed or determined	yes = discussed or determined	yes = if used	yes = mentioned
ann = Annual	ST = Short Term (<1 Month)	LB = Lower Basin	law = “Law of the River”		peak = USBR power method	sal = salinity
hour = hourly	# = Number of Years	UT = Utah				sed = sediment
seas = seasonal	mult = more than one	GV = Grand Valley				temp = temperature
day = daily	ss = steady state	LV = Las Vegas				P = Phosphorus
		PM = Powell and Mead				
		P = Powell				
		CO = Colorado				

a. no = not used, N/A = not applicable. These symbols apply to all categories.

Table 2: Numerical Algorithms Characterized in Modelling Reference Tables

NUMERICAL ALGORITHM
ANA = analog computer
IO = Input-Output and others
STAT = Statistical
SIM = Deterministic Simulation
SSIM = Stochastic Simulation
2D = 2-dimensional model
HEUR = Heuristic and Rulebased models
OPT = Optimization
LP = Linear Programming
DP = Dynamic Programming
SDP = Stochastic Dynamic Programming
SO = Stochastic Optimization
NOPT = Nonlinear Optimization
TRANS = Transportation and network flow

Table 3: Simulation Model References

REFERENCE	MODEL NAME	TIME-STEP	TIME HOR	GEO	POL	ECON	POWER	WQ	ALG
Fulp et al. 1991	24MO	mon	2	all	law	no	peak	sal	SIM
Stevens 1986	BHOPS	daily	ST	LB	no	no	yes	no	SIM
Harding et al. 1995	CRM	mon	LT	all	yes	no	yes	sal	SIM
Sangoyomi and Harding 1995	CRM	mon	LT	all	yes	no	yes	sal	SIM
Brown et al. 1988	CRM	seas	LT	all	yes	yes	yes	no	TRANS
Mohammadi 1989	CRMM	mon	LT	all	yes	no	yes	no	SIM
Ouarda et al. 1997	CRSS	mon	LT	all	law	no	yes	no	SIM
Nash and Gle-ick 1993	CRSS	mon	LT	all	law	no	peak	sal	SIM
Kendall and Dracup 1991	CRSS	mon	32	all	law	no	yes	sal	SIM
Mohammadi et al. 1991	CRSS	mon	LT	all	law	no	peak	sal	SIM

Table 3: Simulation Model References

REFERENCE	MODEL NAME	TIME-STEP	TIME HOR	GEO	POL	ECON	POWER	WQ	ALG
Schuster 1989	CRSS	mon	LT	all	law	no	peak	sal	SIM
Oamek 1988	CRSS	mon	LT	all	yes	yes	yes	sal	SIM
Cowan et al. 1981	CRSS	mon	LT	all	law	no	peak	sal	SIM
Eggleston et al. 1974	CRSS	mon	LT	all	yes	no	yes	sal	SIM
USBR 1998	CRSSez	ann	LT	all	law	no	peak	no	SIM
Neff 1987	MITSIM	mon	LT	UB	yes	no	yes	no	SIM
Weiss et al. 1997	MODSIM	mon	LT	CO	yes	yes	yes	no	TRANS
Michel, and Oliger 1975	RIVER I	mon	LT	CO	yes	yes	no	no	SIM
Zagona et al. unpublished paper	RIVER-WARE	mult	LT	all	law	no	yes	sal	HEUR/ SIM
Reitsma and Carron 1997	RSS	day	ST	PM	yes	no	yes	no	HEUR
Brazil and Bethel 1994	STATE-MOD	mon	LT	CO	yes	no	no	no	SIM
Hyatt 1970	NONE	mon	2	UB	yes	no	no	sal	ANA
Hyatt et al. 1970	NONE	mon	2	UB	yes	no	no	sal	ANA

Table 4: Optimization Model References

REFERENCE	MODEL NAME	TIME-STEP	TIME HOR	GEO	POL	ECON	POWER	WQ	ALG
Henderson and Lord 1995	AZCOL	ann	LT	all	yes	yes	yes	sal	OPT
Hardy 1995	AZCOL	ann	LT	all	yes	yes	yes	sal	OPT
Sheer et al. 1992	COL-GAM	hour	ST	LB	yes	no	peak	no	SIM
Over and Horsey 1990	COL-GAM	hour	ST	LB	yes	no	peak	no	SIM
Booker 1995	CRIM	ann	LT	all	yes	yes	yes	sal	NOPT
Booker and Young 1994	CRIM	ann	LT	all	yes	yes	yes	sal	NOPT
Booker and Young 1991	CRIM	ann	LT	all	yes	yes	yes	sal	NOPT
Fontane et al. 1986	CSUDP	mon	3	all	law	no	peak	no	DP
Liang et al. 1996a	NONE	mon	LT	UB	yes	yes	yes	no	SDP
Liang et al. 1996b	NONE	mon	LT	UB	yes	yes	yes	no	SDP
Yi 1996	NONE	hour	ST	LB	no	yes	yes	no	DP
Stillwater 1993	NONE	mon	LT	UB	yes	no	yes	no	DP
Behrens 1991	NONE	mon	1	UB	yes	no	yes	no	HEUR/ SDP
Behrens et al. 1991	NONE	mon	1	UB	yes	no	yes	no	HEUR/ SDP
Cummings and McFarland 1977	NONE	ann	LT	UB	yes	yes	no	no	DP
Jensen 1976	NONE	mon	LT	PM	yes	no	yes	sal	SIM
Myers 1975	NONE	mon	ss	UB	yes	yes	yes	no	SDP
Heaney 1968a	NONE	seas	ss	all	yes	yes	no	yes	LP
Heaney 1968b	NONE	seas	ss	all	yes	yes	no	yes	LP
Heaney et al. 1967	NONE	seas	ss	all	yes	yes	no	yes	LP

Table 5: Water Quality References

REFERENCE	GEO	POL	ECON	POWER	WQ	ALG
LaBounty and Horn 1997	LV	no	no	no	yes	IO
Korn and Eckhardt 1994	P	no	no	no	yes	STAT
Winter and Chapra 1994	all	no	no	no	sal	SIM
Lee et al. 1993	all	yes	yes	no	sal	SSIM
Merritt 1993	all	yes	no	yes	sal	SIM
Lieberman, and Burke 1993	LB	no	no	no	yes	IO
Lee 1989	all	yes	yes	no	sal	SSIM
Mueller and Moody 1984	all	no	no	no	all	STAT
Edinger et al. 1984	PM	no	no	no	all	2D
Theurer et al. 1983	UB	no	no	no	temp	IO
Flug et al. 1982	UB	yes	yes	no	sal	MP
Miller et al. 1981	all	no	no	no	Ph	IO
Ward and Eckhardt 1981	UB	no	no	no	sed	IO
Boles 1980	all	yes	yes	yes	sal	TRANS
Flug et al. 1979	UB	yes	yes	no	sal	LP
Malone et al. 1979	all	no	no	no	sal	SSIM
Flug 1977	UB	yes	yes	no	sal	OPT
Holcomb Research Institute 1976	all	yes	no	no	sal	SIM
Bessler and Maletic 1975	all	yes	yes	no	sal	SIM
Evans et al. 1973	LB	no	no	no	yes	STAT
Slawson 1972	LB	no	no	no	sal	STAT
Hyatt et al. 1968	UB	yes	no	no	sal	ANA

Table 6: Economics References

REFERENCE	GEO	POL	ECON	POWER	WQ	ALG
Hughes 1991	P	yes	yes	yes	no	SIM
Brown et al. 1990	all	yes	yes	yes	sal	TRANS
Narayanan et al. 1981	UT	yes	yes	no	no	SO
Pandungchai 1980	all	yes	yes	no	sal	LP
Keith et al. 1978	UT	yes	yes	no	no	LP
Diemer, and Wengert 1977	all	yes	yes	no	no	HEUR
Erlenkotter and Scherer 1977	all	no	yes	no	sal	DP
Jacoby 1975	all	yes	yes	no	yes	STAT
Clyde and King 1973	UT	no	yes	no	no	LP
Keith et al. 1973	UT	no	yes	no	no	MP
Udis et al. 1973	UB	no	no	no	sal	IO
Howe et al. 1972	UB	no	yes	yes	yes	IO
King et al. 1972	UT	yes	yes	no	no	LP

Analysis: State of Modeling of the Colorado River Basin

Based on the model summaries in Appendix A, and the tables just presented, it is clear that simulation of the Colorado River basin has reached a mature state. In general, simulation models are now able to reflect the Law of the River, as well as simulate the effects of changes to legislation and policy. This is an important accomplishment because representing the complex Law of the River is a requirement for any model to be of practical use. The Colorado River Simulation System (CRSS) is a good example of the success of these models (Mohammadi et al. 1991). It is directly used in 8 of the 23 simulation modeling references, and 7 other references are to models which attempt to reproduce it. One major problem with CRSS and most of the older simulation models has been the extent to which policy is part of the program code and is, therefore, difficult to change and verify (Nash and Glieck 1993).

With the use of RiverWare (Zagona et al. unpublished paper), the USBR has translated CRSS operating policy from FORTRAN code to a user-alterable language. This change has made the details and consequences of CRSS operating policy accessible to a wider audience, including the major stake-holders on the river. The new modeling system allows for study of the effects of alternate policies and new operating criteria development. However, the new models still do not attempt to specify the optimal operating policy for the river.

The Law of the River constrains river operations but does not specify a single solution; some operating flexibility remains (Sangoyomi and Harding 1995; Fontane et al. 1986). Hence, the shortcoming of simulation models is that they are unable to prescribe the “best” use of this remaining flexibility. Since the advent of systems analysis applications to water resources in the mid 1960s, attempts have been made to apply optimization to the Colorado River basin to fill this gap. The literature review results summarized in Appendix B indicate that no model of the Colorado River basin has applied system-wide optimization to the monthly operations realm, while encompassing the entire Law of the River.

From the few optimization models of the Colorado River that are monthly, none have attempted to reproduce the Law of the River. Fontane et al. (1986) used dynamic programming (DP) to develop monthly operations models with varying amounts of detail (two, four and six reservoirs). They avoided the problem of matching the Law of the River by calibrating their results to the CRSS model. By fixing the reservoir storages to those from CRSS, they were satisfied when their discrete storage model produced energy results that were close enough to CRSS.

Upper Basin monthly models include a stochastic DP/knowledge based model by Behrens (1991), a simulation/DP model by Stillwater (1993), and a comparison between two stochastic DP methods by Liang (1996a). All of these Upper Basin models included only the minimum objective release from Powell requirement, and ignored the rest of the policy. Booker (1995) and Booker and Young (1991, 1994) wrote an annual model of the river for study of the economics of water allocation and costs of drought. Henderson and Lord (1995) wrote a closely related annual gaming model to study reactions to severe sustained drought. Yi (1996) looked at the hourly unit commitment problem on the dams on the Lower Basin. Sheer et al. (1992) wrote a gaming model that also looked at hourly unit commitment of the Lower Basin generators.

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The reasons behind the lack of monthly operational optimization models are three-fold. First, the methodological limits of operations research have prevented the simultaneous capture of the important elements of a practical model: complex policies, multiple reservoirs and objectives, hydropower, and stochasticity (Liang et al. 1996b). Since more demands are being placed on the system, particularly from the environmental side, it is imperative that future models provide multi-objective solutions within the current constraints. Second, the computational burden of multiple reservoirs, long planning horizons, and complex policies has been too great for the computer hardware available (Loucks et al 1981; Fontane et al. 1986; Mays and Tung 1996). Third, acceptance of new methodologies and models is difficult to achieve. The litigious nature of Colorado River water decisions (Nathanson 1978) led to the justifiable perception that a complex mathematical solution would be impossible to defend, even if optimal. For these reasons, the USBR has not invested the time and/or money to improve or adapt operations research techniques.

Fortunately, the obstacles listed above are now eroding, due to methodology advancements, computer hardware and software improvements, and increased stakeholder involvement. First, the computational limits of operations research are continually expanding. Specifically, new breakthroughs in optimization methodology can now describe multi-objective systems (Eschenbach et al. unpublished paper), perhaps even reproducing the simulation model's results. A new method of including and satisfying constraints called the "shrinking envelope" (Magee, unpublished paper) has been implemented into a pre-emptive goal programming optimization solution in RiverWare. This technique has been used to successfully and directly represent complex policies by the Tennessee Valley Authority (TVA) (Eschenbach et al. unpublished paper).

Second, with the continuing exponential growth of computing power and advances in optimization software, the computational burden classically associated with optimization of complex river systems is rapidly decreasing. The supercomputer used by Fontane et al. in 1986 to do their study had roughly the capability of a new desktop computer in 1998. While many optimization applications still must deal with the classic "curse of dimensionality" when adding new state variables like reservoirs, an increase of orders of magnitude in computing power has changed previously impossible problems into solvable problems. Further, improvements in commercially available optimization solvers have resulted in further reductions in the computational burden.

Finally, acceptance of new models is now easier to gain because the stakeholders are much more involved in the modeling process. This is indicated by the ability of the USBR was replace the old CRSS and 24 Month Study FORTRAN models with models implemented in RiverWare.

Conclusion

The literature review found that no optimization model has successfully been used in operations on the Colorado River. Three factors contributed to this situation. First, the complex policy and multiple objectives required were not able to be represented. Second, the models which were built required excessive amounts of computer power. Third, the stakeholders in the river resisted new methodologies and models. However, these obstacles are now being overcome. The algorithmic development in RiverWare can now be applied to the replication of the Law of the River in an optimization model. Faster computers make the development and application of an optimization model much more useful. Guarded openness to the use of new methodologies and models is new to the Colorado River, and suggests that an optimization model of the river may be acceptable to the USBR and stakeholders.

Because of these developments, an opportunity now exists for the use of optimization on the Colorado River. An obvious first use of this opportunity is the development of an optimization model that replicates exactly the results of a pre-existing model of the river. Once that is accomplished, the model can be used to selectively relax certain policies and quantify the costs of those policies

Chapter III: Replication of Complex Colorado River Rules Using Pre-emptive Goal Programming

Introduction

Simulation models of the Colorado River have reached a mature state. The U.S. Bureau of Reclamation (USBR) has successfully applied rulebased simulation models of the river to monthly operations and long-term policy studies (Mohammadi et al. 1997, 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 (USBR 1985).

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. unpublished paper), 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.

To allow an optimization model to be accepted in the operational environment, it must be able to replicate the results of the simulation models using current policies. Further, it must allow for selective relaxation of the operating decisions without sacrificing compliance with those policies which are binding. This goal has been fulfilled by producing the first monthly operations optimization model that matches the results of an extended version of the 24 Month Study, a rulebased simulation of the Colorado River. Preemptive goal programming offers the ability to allow for multiple priorities and policies to be met. The technique uses a linear programming solver for speed, although nonlinearities must be approximated, and has been successfully applied to production models by the Tennessee Valley Authority (TVA) (Eschenbach et al. unpublished paper).

This chapter is organized as follows: First, the 24 Month Study rulebased simulation and included policy are reviewed, then the formulation of the goal programming optimization is discussed. Results from rule based and optimization runs for the same dataset are used to demonstrate that the policies of the Lower Basin and interactions with Lake Powell have been reproduced. Further, some issues which arise from the transition from rulebased policy to optimization are presented.

Review of Rulebased Simulation and Policy

Model Selection

The 24 Month Study was selected as a representative model of the system for several reasons. First, the 24 month time span is long enough to insure that policies are implemented correctly without extremely large data requirements. Second, the 24 Month Study has already been already implemented in RiverWare, where the optimization solver is also available. Third, it is currently used by USBR personnel, and therefore is a credible model. Finally, although it currently does not explicitly contain all of the Colorado River policy, it can be easily extended using rules taken from CRSS (for example, equalization of Lakes Powell and Mead).

RiverWare: a General River Basin Modeling Tool.

RiverWare was developed as a software tool to allow non-computer and non-optimization experts to build, run, and analyze river basin models. A user builds a representation of the river basin to be modelled via a graphical interface. For the 24 Month Study, the model representation is shown schematically in Figure 3.

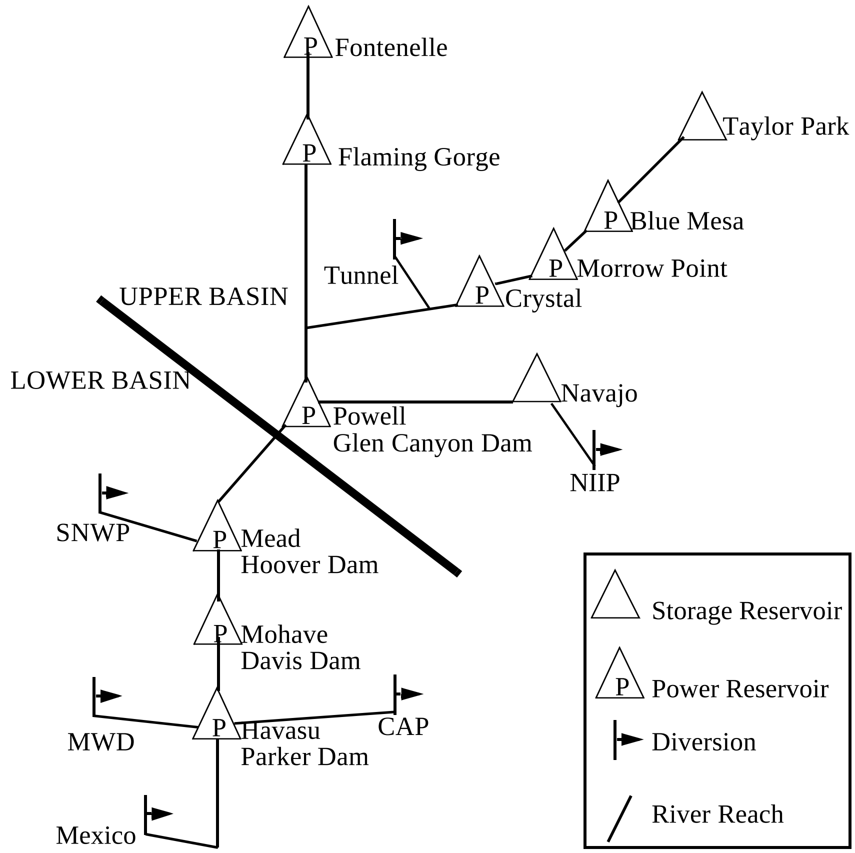


Figure 3: Schematic of the Reservoirs and Diversions in the 24 Month Study

The user also selects methods on each of the objects to simulate processes like evaporation, spill, bank storage, diversion, power generation, reach routing, local inflow, etc. Functional relationships between variables, e.g. the elevation-volume relationship, are expressed in tables that are interpolated linearly.

During simulation, each objects acts on what it “knows,” simulates its physical processes, and propagates the results to the objects that are connected to it. In an exactly specified solution, every variable is either input or solved for by the various objects. In a rulebased simulation, timestep-by timestep, one or more values is not input, and is set by one of a prioritized series of if-then type rules. These could include flood control, demand fulfillment, reservoir rule curves, iterative reservoir “equalization” rules, or others.

Therefore, a RiverWare “model” can be viewed as a collection of data describing what objects exist in the workspace, what methods and data exist on those objects, and what policy to apply to those objects. For this thesis, an existing 24 Month Study model was altered to use the optimization solution method available in RiverWare, as well as the rulebased simulation.

USBR Use

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 is also used to assist the Annual Operating Plan (AOP) process. Three sets of hydrologies, representing maximum, minimum, and most probable inflows are used for the AOP. The AOP is generated for the water year, October to September, agreed upon by the stakeholders in the river, and signed by the Secretary of the Department of Interior.

For this work, the time period corresponding to the AOP for the water year 1998 was used. Therefore, 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. Use of the historical data allows for the comparison of hydropower value from the generated optimization policy in the next section with actual results.

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.

Current and Extended Policy

The 24 Month Study as it is currently implemented determines the Lower Basin operations by rules. The Upper Basin is solved in simulation mode, where the operators have set the reservoir operations manually, including diversions and equalization releases. These Upper Basin decisions and reservoirs must be included in the 24 Month Study because several of the Lower Basin rules are dependent on the amount of storage available in the Upper Basin. The model was extended to determine Powell operations by adding rules taken from CRSS. Therefore, the operating rules that were implemented in this extended version of the 24 Month Study are Lower Basin operations (Mead flood control, rule curves for Lakes Mohave and Havasu, and meeting diversion demands below Havasu) and Powell operations (equalization, rule curve, and minimum objective release). These rules are explained in more detail below.

Two other sections of policy from CRSS were considered for inclusion in this work, but were rejected. First, the remaining Upper Basin reservoir operations were not included, primarily because the rules from CRSS do not reflect current operational practices (Fulp 1999). Second, the Lower Basin diversion schedule decisions (shortage/normal/surplus) were not included as these decisions are currently made on a yearly basis via the AOP process, and the schedules are then manually set in the 24 Month Study model. A possible method of including these diversion decisions into the optimization was explored, but was not included in the model. This methodology is documented, however, in Appendix D.

Rulebased Policy Description

Mead Flood Control

This set of procedures is mandated by an agreement between the U.S. Army Corps of Engineers and the USBR (Corps of Engineers 1982) and effectively sets a minimum release from Lake Mead for each month. The release from Mead can be greater, however, if necessary to meet downstream demand.

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. Each of these procedures is briefly described.

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 3700 and 1219.61 feet respectively). The current month's minimum release is then determined based on this total volume to be released.

In the 24 Month Study, the inflow forecast to Lake Powell is based on the unregulated forecasts for each subbasin provided by the Colorado River Forecasting Center. Per the Flood Control procedure, the inflow into Lake Mead is then estimated by including in that forecast the estimated gains between Powell and Mead, and an additional amount of water to ensure that the inflow forecast to Mead is a 5% exceedence value (i.e., there is only 1 chance in 20 that the inflow will be greater than the forecast). The magnitude of this additional amount of water depends upon the month as shown in Table 7.

Table 7: Total Additional Inflow for 5% Exceedence Value

Month	Additional Inflow (millions of acre-feet)
January	4.980
February	4.260
March	3.600
April	2.970
May	2.525
June	2.130
July	0.750

To allow description of the policies of the Colorado River, the following expressions are defined:

t = current month of simulation

i = a particular month in the range from t through July

$Q_{M,i}$ = outflow (in volume/time) from Lake Mead during time i.

T = set of months, from t through July

$O_{M,T}$ = total volumetric outflow from Lake Mead during time T.

$I_{M,T}$ = total forecasted volumetric inflow into Lake Mead during time T.

$S_{M,JUL}$ = target storage of Lake Mead at the end of July.

$S_{P,JUL}$ = target storage of Lake Powell at the end of July.

$S_{M,t-1}$ = storage of Lake Mead at the beginning of the current month.

$S_{P,t-1}$ = storage of Lake Powell at the beginning of the current month.

$E_{M,T}$ = estimated evaporation loss from Lake Mead during time T.

$E_{P,T}$ = estimated evaporation loss from Lake Powell during time T.

$B_{M,T}$ = estimated loss to bank storage from Lake Mead during time T.

$B_{P,T}$ = estimated loss to bank storage from Lake Powell during time T.

$D_{M,T}$ = total volumetric diversion from Lake Mead by SNWP during time T.

With these definitions, the mass balance can be written as:

$$\begin{aligned} O_{M,T} = I_{M,T} - (S_{M,JUL} - S_{M,t-1}) - (S_{P,JUL} - S_{P,t-1}) \\ - E_{M,T} - E_{P,T} - B_{M,T} - B_{P,T} - D_{M,T} \end{aligned} \quad \textbf{(III-1)}$$

Again, $O_{M,T}$ represents the total amount of water that should be released from Lake Mead during time period T (the current month through July). Further documentation of the meaning of these terms is contained in Appendix C.

The procedure then breaks this total amount of water into two parts: the amount of water to be released in the current month, and the amount of water to be released in the future months through July.

$$O_{M,T} = \frac{Q_{M,t}}{(\Delta t)_t} + \sum_{i=t+1}^{JUL} [QW_t \cdot (\Delta t)_i] \qquad \textbf{(III-2)}$$

where $(\Delta t)_i$ represents the amount of time in each month i, and is used for the volume to flow conversion, and QW_t represents the forecasted future outflow level, assuming all future outflows through July are equal.

From the discrete levels of outflow, listed in Table 8, the policy uses Equation III-2 to find the QW_t for which the current outflow ($Q_{M,t}$) is less than that value, starting from 0. If the current outflow value calculated is less than the next lower step for future outflow, that step is used. These values correspond to very specific levels of damage and control downstream. These values are specified in the Water Control Manual (1982), and are included in the current operating policy.

Table 8: Discharge Levels for Mead Flood Control

Reason for Value	Outflow, (cfs)
Default	0
Parker Dam Powerplant Limit	19,000
Non-damaging Release	28,000
Hoover Powerplant Limit	35,000
Historic Floodway Capacity	40,000
Maximum Controlled Release	73,000

The end result is a value for the release from Lake Mead for the current month that assumes that if the 5% exceedence inflow actually occurs, the remaining months through July will be constant at the current or next higher discharge level. Because this inflow rarely occurs in practice, the usual effect is that in January, the highest flood control flow is required, and as the 5% exceedence case is not realized in the next months, the required flood control release decreases. The path along which the rules travel is represented schematically in Figure 4, and is explained below.

In this figure, the squares represent the values that the rules will use for the current month's required flood control release even if Equation III-1 results in a lower (even negative) value (represented by the dashed lines). An example is useful. First, assume that in January, 19,000 cfs is tried as value for QW_t. If Equation III-2 results in a current flood control release ($Q_{M,t}$) value that is greater than 19,000 cfs, then we must try a 28,000 cfs value for QW_t (i.e. we cannot have $Q_{M,t} > QW_t$). With QW_t = 28,000 cfs, suppose Equation III-2 yields any value for $Q_{M,t} < 28{,}000$. Then $Q_{M,t}$ can be anywhere between 19,000 and 28,000 cfs (the solid line in Figure 4 for QW_t = 28,000 cfs), but will not be allowed to be less than 19,000 cfs (the dashed line and square along QW_t = 28,000 in Figure 4).

The discrete nature of this policy is clearly visible. As shown later, pre-emptive goal programming as implemented in RiverWare can reproduce the outflow results ($Q_{M,t}$) of this policy.

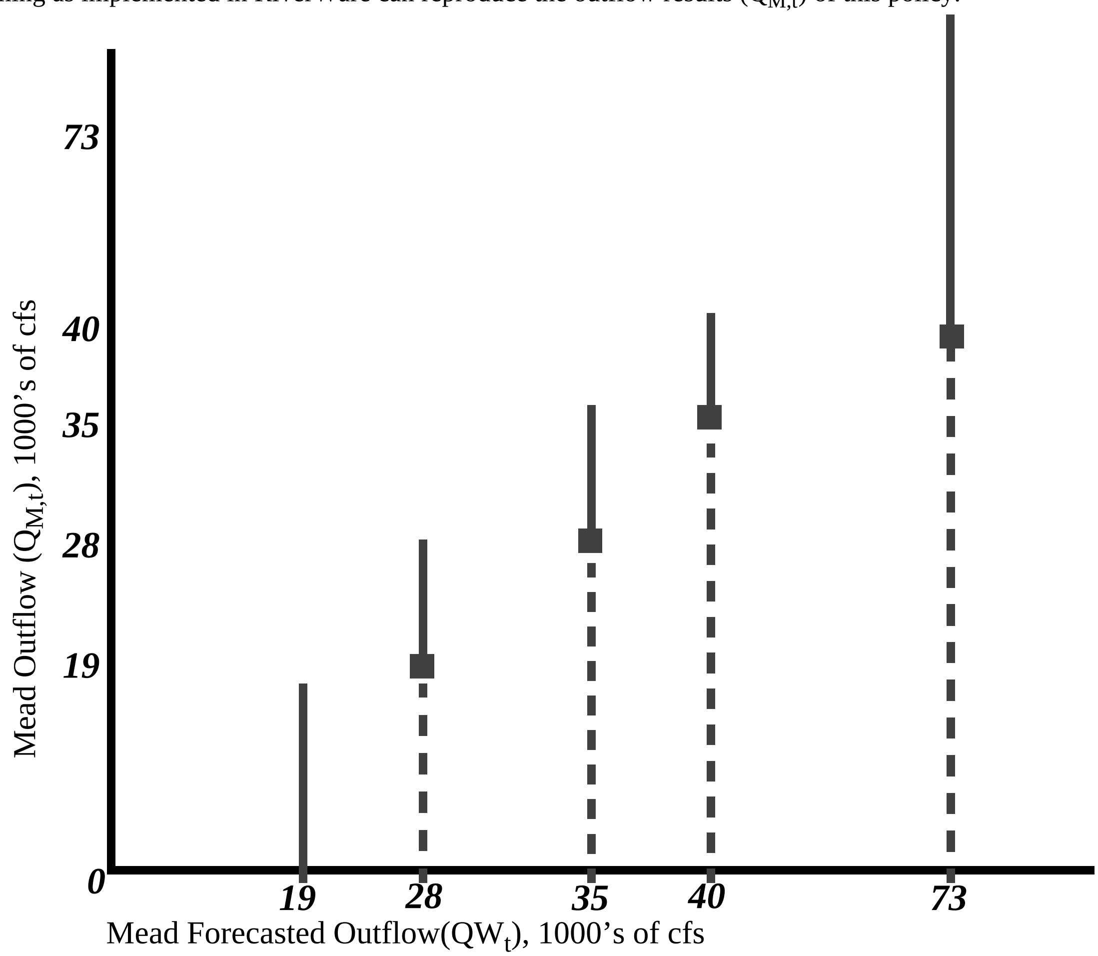


Figure 4: Mead Flood Control in Rules

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. That required space is given in Table 9. Some Upper Basin reservoir space, (termed "creditable space") is included, with limits varying by reservoir as shown in Table 10. 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 28,000 cfs.

Table 9: Monthly Required System Space

Month	Required System Space (MAF)
August	2.270
September	3.040
October	3.810
November	4.580
December	5.350

Table 10: Creditable Space Limits for Upper Basin Flood Control Reservoirs

Reservoir	Maximum Creditable Space (MAF)
Powell	3.8500
Navajo	1.0359
Blue Mesa	0.7485
Flaming Gorge and Fontenelle	1.5072

The target storage from this procedure at Lake Mead for the current month can be written as:

$$S_{M,t}^{\text{target}} = S_{M}^{max} - min\left[1.5MAF,\ RS_t - \sum_{UBres} min((S_{UBres}^{max} - S_{UBres,t-1}), C_{UBres})\right] \quad \textbf{(III-3)}$$

where RS_t is the required space from Table 9, $S^{\text{target}}_{M,t}$ is the storage at Mead required by this procedure, and C_{UBres} is the maximum creditable space for that Upper Basin reservoir from Table 10. Again, Mead's outflow for flood control is the release that yields this storage value.

Procedure 3, Exclusive Space Requirement, January - December: During the entire year, available space in Mead is required to be at least 1.5 MAF (million acre-feet). If the available space would be below 1.5 MAF, whatever release necessary to maintain that space is used, with no upper bound. This is the policy as implemented in CRSS and the 24 Month Study. On a monthly operations level, this is sufficient, since operational targets and planning does not make use of this space. A more detailed series of elevation and release triggers is included in the Mead Flood Control Manual (Corps of Engineers, 1982), and would be followed as needed on a daily basis.

Powell

None of the Powell rules are present in the current 24 Month Study used by USBR operations personnel. Therefore, these rules were adapted from those found in CRSS.

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" (USBR 1994). This storage is termed "602(a) storage," after the legislation mandating equalization (Colorado Basin Project Act, 1968). From January, on a monthly basis, if the predicted end of September storage for Powell is higher than that of Mead, and the total Upper Basin storage is greater than the 602(a) storage, a monthly release is made from Powell to bring the storages of the reservoirs closer together. This release is constrained by the 602(a) requirement, the Powell maximum powerplant release, and the exclusive Mead flood control space (USBR 1994).

602a storage is calculated by the following equation:

$$Storage602a = \left(\left(\frac{UBD}{CP} + UBEvap\right)(1 - \%short) + ObjRel - NatFlow\right)CP + MinPowerUB \tag{III-4}$$

where:

CP is the length of the historically observed worst drought, currently 12 years (called the critical period).

UBD is the sum of the Upper Basin depletions for the length of the critical period, beginning at the current year. These come from the demand database of the USBR.

UBEvap is the average annual Upper Basin evaporation (0.560 MAF).

%short is the percent of shortage that the Upper Basin will receive during the drought, currently zero.

ObjRel is the annual minimum objective release requirement from Powell, (8.23 MAF) described in a subsequent section.

NatFlow is the average annual natural flow at Lees Ferry during the critical period (12.18 MAF).

MinPowerUB is the storage equivalent of the minimum power pool to be held in the Upper Basin (5.179 MAF).

For 1998, the 602a storage requirement is 12.674 MAF, and for 1999, this value is 13.112 MAF. The increase is due to forecasted increases in Upper Basin demand from 1998 to 2011. The total Upper Basin storage for the purposes of these calculations is the sum of the storages in Navajo, Blue Mesa, and Flaming Gorge reservoirs at the previous month, plus the forecasted end of water year storage at Powell.

The equalization process begins with the annual minimum objective release value or minimum flow out of Powell if the annual target has been fulfilled. It then adds to that release half of the difference of the forecasted end of water year storages, and iterates until the forecasted end of water year storages are within the equalization tolerance value, currently set to 10,000 acre-ft. The iteration is necessary because of the evaporation and bank storage processes at each reservoir. As mentioned above, this release is constrained to not decrease the Upper Basin storage below the 602a storage value, to not be greater than the maximum controlled release from Powell (48,000 cfs), and to not violate the exclusive flood control space at Mead. This last check does not consider the gains between Powell and Mead.

The equalization rule can be expressed by the following three equations, which are solved iteratively:

$$EOWYStoragePowell = S_{t-1} + I_P - Q_P - EstEvap - EstBankS \quad \textbf{(III-5)}$$

$$EOWYStorageMead = S_{t-1} + Q_P - Q_M + G_{PM} - EstEvap - EstBankS - Div_M \quad \textbf{(III-6)}$$

$$Until(Abs(EOWYStorageMead - EOWYStoragePowell) \le Tol) \quad \textbf{(III-7)}$$

$$\text{DO:} \ \ Q_P = Q_p + \frac{(EOWYStoragePowell - EOWYStorageMead)}{2}$$

where:

S_{t-1} is the storage at the previous simulation timestep for the indicated reservoir.

I_P is the inflow into Powell for the rest of the water year. Because this is an operational model, with the rest of the Upper Basin manually operated, these values are fully determined for the entire run.

Q_P is the release from Powell for the rest of the water year. A seed value of the minimum objective release remaining for the year or minimum outflow (5000 cfs) for Powell is used.

Q_M is the forecasted release from Mead to fulfill downstream demands, disregarding flood control.

G_{PM} is the gains between Powell and Mead for the rest of the water year.

Div_M is the diversion from Mead for the rest of the water year.

EstEvap and EstBankS are the estimated evaporation and bank storage that will occur, given that the reservoir will fill to the forecasted storage at the end of the water year. The estimation of evaporation uses a forecast storage that is constrained to be less than or equal to the live capacity of the reservoir, while the bank storage estimation does not, an apparent inconsistency in the CRSS rule.

Minimum Objective Release: The Upper Basin is required to meet a 10 year delivery to the Lower Basin of 75 MAF (Nathanson 1978), 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 1.5 MAF annual delivery to Mexico. These requirements have been translated to an operating criterion of an annual minimum release from Powell of 8.23 MAF, 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. The monthly values for the minimum objective release as found in CRSS are given in Table 11:

Table 11: Monthly Values for Minimum Objective Release

Month	Outflow Volume, acre-ft.
January	800,000
February	700,000
March	600,000
April	600,000
May	600,000
June	700,000
July	800,000
August	900,000
September	630,000
October	600,000
November	600,000
December	700,000

Powell Rule Curve: In CRSS, Powell is operated with a single rule curve, which can be over-ridden 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. Table 12 lists the monthly storage values from the rule curve, as found in CRSS.

Table 12: Monthly Values for Powell Rule Curve

Month	Storage, thousands of acre-ft.
January	22,322
February	24,322
March	24,322
April	24,322
May	24,322
June	24,322
July	24,322
August	24,322
September	24,322
October	23,322
November	22,322
December	22,322

Note the rapid changes from January to February, and from September to November. For the scenario used in this model, the operation of Powell was controlled by the rule curve and minimum objective release in October through December, and by the equalization rule during the other nine months of the year.

Normal Lower Basin Reservoir Operations

Lakes Havasu and Mohave Rule Curves: These two reservoirs are modeled along single rule curves every year, and therefore make specific positive or negative contributions to the downstream demands from Mead (these rule curves are shown in the next chapter). These requirements are based upon studies done by the USBR (Kaser and Diamond 1951; USBR 1989). 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 two diversions on the Lake (Metropolitan Water District of Southern California (MWD) and Central Arizona Project (CAP)).

Meet Requested Diversion Demands: The 24 Month Study uses schedules that are manually input for all diversions modeled. The monthly diversion schedules from the stakeholders on the river are used in this decision making. No returnflows are modeled in the 24 Month Study, so the efficiency of all diversions are effectively 100%. For three of the diversions modeled, this is truly the case, as MWD, CAP, and Mexico essentially return no water to the Colorado River system. The other three, the Southern Nevada Water Project (SNWP), the Gunnison River Tunnel Diversion, and the Navajo Indian Irrigation Project all return water to the system, but the return flows are not modeled in the current 24 Month Study. Instead, these diversions use the scheduled depletion, (diversion - return flows) and assume 100% efficiency. As noted above, instead of using the depletion schedules, the calculated historical depletion amounts were used for this study.

Further, the outflow from Lake Havasu is used as the controlling value for the Lower Basin. This value is manually derived from all diversions requested below that point. This value is automatically simulated upstream to Mead, where it becomes the outflow, and considers all diversions, local inflow, and storage changes that intervene. The flood control policies may override this value, and will result in more water travelling through the system to Mexico.

Optimization Methodology

Preemptive Goal Programming in RiverWare

The pre-emptive goal programming (GP) optimization solution technique available in Riverware is presented in Eschenbach et al. (unpublished paper). This technique was implemented in RiverWare based on positive previous experience by TVA (Shane et al. 1988). The optimization result for reservoir outflows and diversion deliveries are then used by the simulation to calculate the rest of the system. This allows the optimization model to have the same accuracy as the simulation. A short description of the actual optimization technique is worthwhile for this thesis. The basis of the solution is the efficient and robust commercial linear program solver by CPLEX (CPLEX, 1999). “Pre-emptive GP insures the optimal solution of a higher priority goal is not sacrificed in order to optimize a lower priority goal." (Eschenbach et al. 1999)

The major point of this formulation is that the optimization can have priority levels, which can then be used to represent the priority ordered rulebased simulation policies. Further, this formulation allows the optimization to change the feasible region for the problem as the next priority level is introduced and optimized.

The object-oriented approach to reservoir operations modeling as used by RiverWare (Zagona et al. unpublished paper) allows each object to handle the data and variables associated with that object. Each object, representing a diversion, river reach, confluence, or reservoir, generates its own mass balance, turbine capacity, diversion-depletion, routing, or other physical constraints. The user of the software then adds the operational policy as optimization constraints and objectives using a constraint editor. These statements are then automatically translated for inclusion in the linear programs, with appropriate linearizations, so that the only variables in the translated set of constraints are directly represented by linear program variables.

The linearizations that are of interest are those relating to power and evaporation. The linearization of power is not needed to match the rulebased simulation, but is discussed and used in the next chapter. Linearization is used in this context as the replacement in an optimization expression of one variable or set of variables for another. The available linearization methods in RiverWare are substitution, tangent, line, and piecewise. Substitution may be used when there is only a single variable present in the constraint, and does not produce any error. For example, if a constraint is written to keep Mead's elevation below 1219.61 feet, it may be substituted with an exactly equivalent constraint to keep Mead's storage below 25.877 MAF.

Tangent, line, and piecewise methods use one, two, or three or more approximation points chosen automatically or by the user. The tangent method uses one point and finds the tangent line to that point in the two dimensional space defined by the linearized variable and its replacement. The line method takes two points in the same space and finds a similar line. These methods then replace the linearized variable with a slope and intercept equation in the replacement variable.

The piecewise method uses three or more points and finds the line segments between those points. The linearized variable is replaced by a combination of equations representing the line segments. Therefore, any singularly convex or concave curve may be closely represented. However, a classical problem with piecewise approximations is the desire for the optimization to “cheat,” or use the line represented by the two ends of the approximation when it would be beneficial for the current objective to do so. In Figure 5, the piecewise approximation is the dashed line, and the path of “cheating” is the dotted line. Because “cheating” introduces large errors, piecewise approximations are disallowed by the software when maximizing using the linearization of a concave function or when minimizing using the linearization of a convex function.

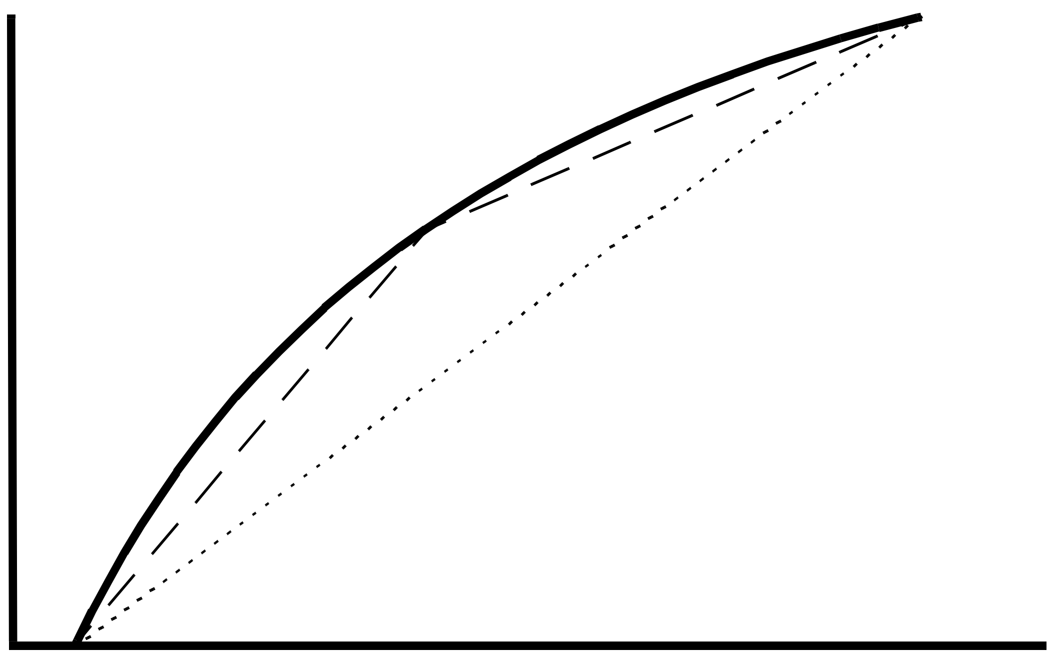


Figure 5: Piecewise Linearization Method

In RiverWare, the formulation of an objective function can be chosen from three options. *Objective* allows the direct formulation of the objective statement to be maximized or minimized. *Summation* allows for the minimization of the sum of deviations from a set of constraints. *MaxMin* allows for the repeated maximization of the minimum satisfaction level in a set of constraints until all variables involved are fixed or the constraints are completely satisfied. All of the objectives used to replicate the rulebased simulation are formulated as the MaxMin of the constraints listed. The MaxMin objective tends to balance the relative satisfaction of constraints and this leads to solutions that more closely approximate the solutions generated by rules.

Each objective has a preemptive priority, meaning that higher priority objectives should not be sacrificed while improving a lower priority objective. The optimal value of an objective can be enforced with an explicit constraint as in the algorithm below. Thus, future objectives cannot change this optimal value. However, for reasons of numerical stability, RiverWare instead enforces this constraint explicitly by fixing the value of non-basic variables with non-zero reduced cost. By adding constraints on prior objectives, either explicitly or implicitly, preemptive goal programming incrementally shrinks the feasible region.

The MaxMin formulation of a constraint written for all reservoirs at all timesteps at a priority level p is (with r in the set of R reservoirs and t in the set of timesteps, and j as the number of iterations):

> "A satisfaction variable, Z_p, is assigned for each goal or priority level p. For each goal, Z_p is maximized, while requiring that all higher priority satisfaction levels are maintained as hard constraints.... Do until all $Z_{p,r,t} = 1$ or are fixed:

1. Max Z_p^j

   subject to

   $Z_p^j \le Z_{p,r,t} \quad \forall r = 1 \ldots R, t = 1 \ldots T$ such that $Z_{p,r,t}$ is not fixed

   $Z_i = Z_i'$ for i = 1 to p-1

   $Z_p^k = Z_p^{k'}$ for k = 1 to j-1

   and all other physical constraints.

2. Fix the value of any $Z_{p,r,t}$ which is restricting Z_p^j in the optimal solution: $Z_p^j = Z_{p,r,t}$

3. Replace Z_p^j with Z_p^{j+1} in all remaining constraints

4. Go to the next subgoal (j = j +1)" (Eschenbach et al. unpublished paper)

The decision variables that were previously available in the RiverWare solution were: (for reservoirs) storage, turbine release, spill, and outflow, and (for reaches) outflow. In addition, three new variables on reservoirs were created for this work. These were forecasted future outflow (QW, Equation III-2), effective space (alters $I_{M,T}$, Equation III-1)for the effect of Upper Basin reservoirs), and creditable capacity (allow space in Upper Basin reservoirs to reduce the space required in Mead in the fall, Equation III-3). Because diversion had not been a concern of TVA, this variable was also added to the optimization. Details about the implementation of diversion are available in Appendix E, including some possible linearizations of nonlinear efficiency (depletion/diversion) relationships. All other variables used in the constraints were translated to one of these variables.

Colorado River Optimization Model

For the model that was built for this study, the decision variables were a subset of those available in RiverWare. Every reservoir in the system used storage and outflow. Every diversion used diversion. These are indicated by the S (storage), Q (outflow), and D (diversion) in the legend in Figure 6. All of the large Upper Basin reservoirs used the creditable capacity, and all of these except Powell also used the available space. This is indicated in the figure below by the AS and CC next to those reservoirs. Both of these variables were created to replicate portions of the Mead flood control policy. For the purposes of replication of the rulebased simulation result, the Upper Basin reservoirs, except Powell, had their outflows constrained to be equal to their historical operations. Also, the distinction between spill and turbine release is not important to the rules result, but is important for the analysis in the next chapter.

The linearization of most concern for the matching of the rule results is the linearization of surface area to storage. Since evaporation uses surface area, and evaporation is part of the mass balance, modeling of evaporation introduces small mass balance errors. This is not of great concern on a two year model run, but for much longer runs, the mass balance error could become significant. For example, at the final step of a representative two year run, the optimization had a value for the storage at

Mead that was 1,828 acre-ft lower than the simulation value for the same operations. This is an error of 0.008%, and is therefore fairly inconsequential for this run length.

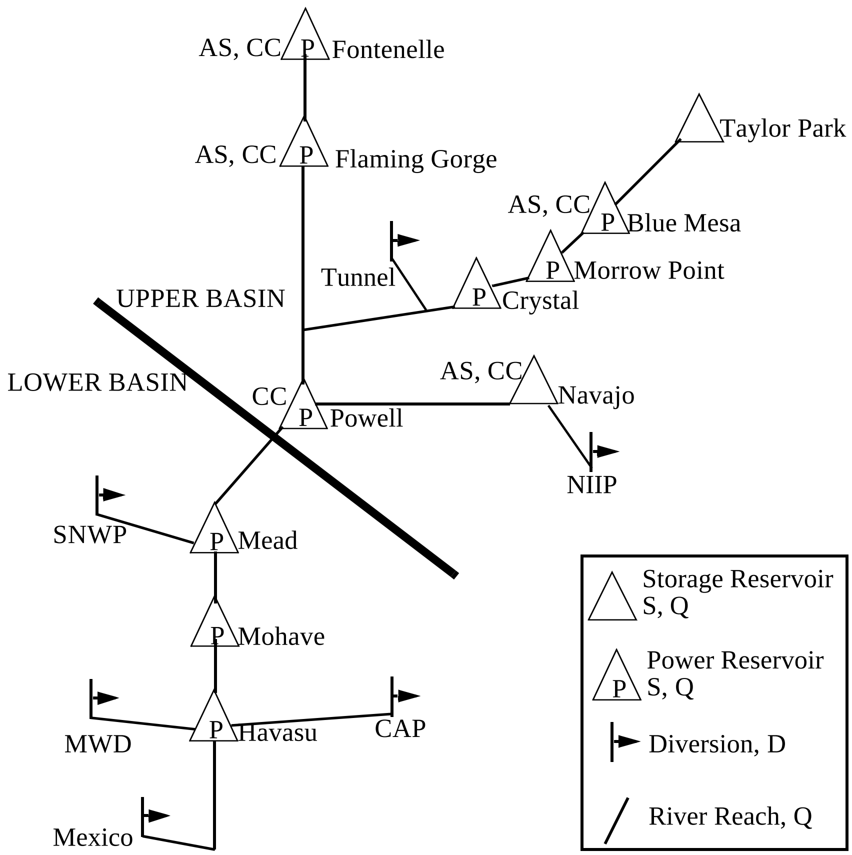


Figure 6: Decision Variables in Optimization Model

Matching Rule Policy With Optimization

Each of the constraints listed below is written for each timestep referenced in the involved policies. Because the MaxMin objective formulation was used in all of these cases, the satisfaction of every constraint at every time period was maximized, the least satisfied being handled first.

Mead Flood Control

Procedure 1, Route Max Inflow, January - July

The set of rule-based policies is translated into the following set of constraints in relative priority order:

$$\left(\sum_{i=t+1}^{JUL}(\Delta t)_i\right)QW_t + (\Delta t)_t Q_{M,t} \geq I_{M,T} - (S_{M,JUL} - S_{M,t-1}) \tag{III-8}$$

$$- (S_{P,JUL} - S_{P,t-1}) - E_{M,T} - E_{P,T} - B_{M,T} - B_{P,T} - D_{M,T}$$

$$Q_{M,t} \leq 73,000 cfs \tag{III-9}$$

$$QW_t \leq 73,000 cfs \tag{III-10}$$

$$Q_{M,t} \leq 40,000 cfs \tag{III-11}$$

$$QW_t \leq 40,000 cfs \tag{III-12}$$

$$Q_{M,t} \leq 35,000 cfs \tag{III-13}$$

$$QW_t \leq 35,000 cfs \tag{III-14}$$

$$Q_{M,t} \leq 28,000 cfs \tag{III-15}$$

$$QW_t \leq 28,000 cfs \tag{III-16}$$

$$Q_{M,t} \leq 19,000 cfs \tag{III-17}$$

$$QW_t \leq 19,000 cfs \tag{III-18}$$

$$Q_{M,t} \leq 0 cfs \tag{III-19}$$

This set uses the same set of symbols as the rulebased flood control policy description. Note that Equation III-8 can be derived by combining Equations III-1 and III-2 and writing the result as an inequality. Note that each QW_t constraint is at a priority level just below its corresponding $Q_{M,t}$ constraint. The optimization will attempt to maximize the satisfaction of these constraints, and will therefore be lowering the flow values as each priority level is attempted. The consequence of these constraints and priorities is that the two outflow variables Mead are conceptually driven along the path shown in Figure 7.

It is instructive to compare Figure 7 with Figure 4. The paths that the rules and optimization take for Mead spring flood control are similar, but the differences are important. First, note that in optimization, the dotted lines below the squares from the rules are gone, and are replaced with horizontal lines. The effect of this is that in rules, QW will take on only discrete values, but in the optimization, the value of QW is continuous, because binary variables are not possible with the current formulation of optimization in RiverWare. The optimization will therefore use the smallest value possible for QW, and it may be different from the discrete value that the rules found. However, the value that the rules and the optimization find for Q_M will be the same.

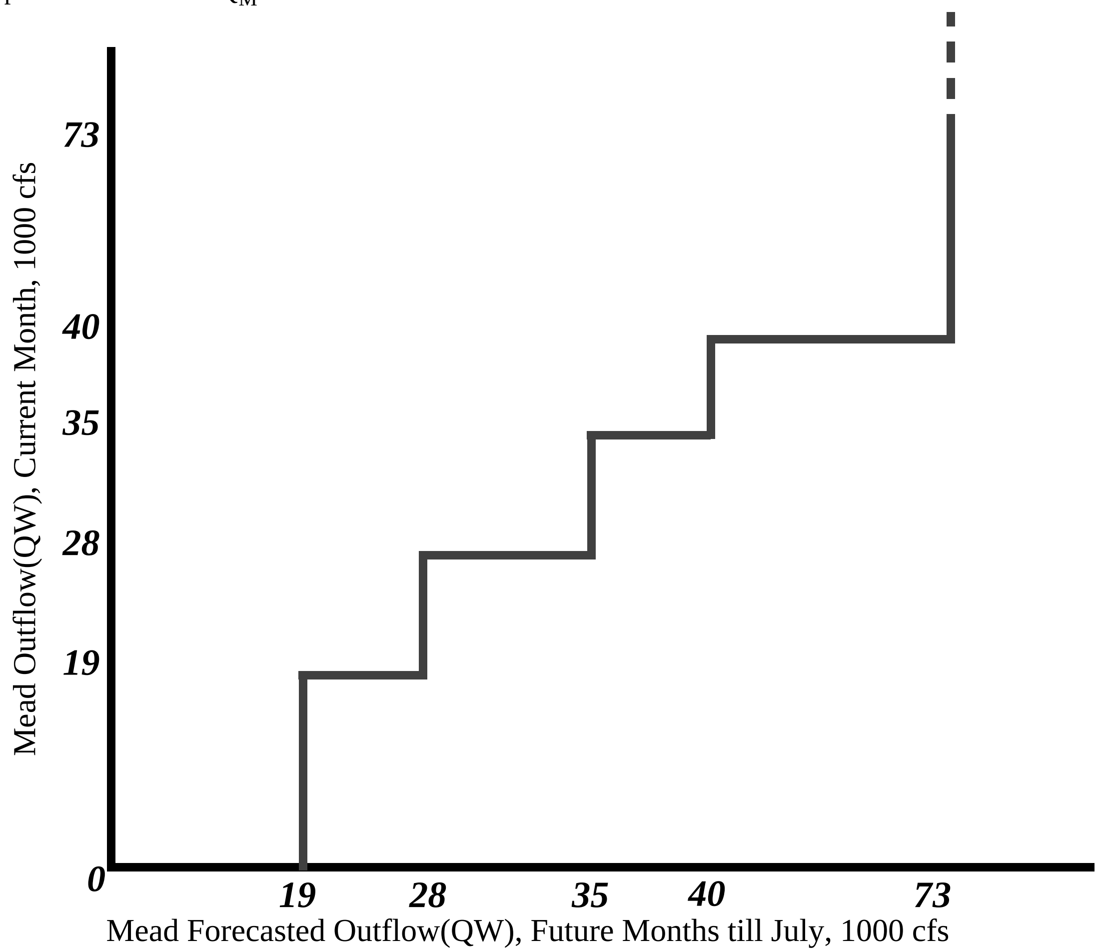


Figure 7: Mead Flood Control in Optimization

For further insight into how this path is followed, and how the feasible region can change, an example is needed. This example is taken from the “Sample Flood Control Release Calculation” in the Water Control Manual (Corps of Engineers, 1982). Let the current month be April, and the inflow forecast into Mead is 12.315 MAF. For simplicity, assume that the optimization has fixed the end of March storage for Powell and Mead. From Equation III-1, the water that must be released from Lake Mead equals 5.090 MAF, or 2,566,208 cfs-days. There are 92 days in the future months until July 31, and 30 days in April. Equation III-8 can then be represented as a constraint in the variables QW_t and $Q_{M,t}$ (in 1000 cfs):

$$92(QW_t) + 30(Q_{M,t}) \geq 2566 \qquad \textbf{(III-20)}$$

This line is shown in Figure 8. The constraint that the forecasted future outflow (QW) must be greater than the Q_M is also shown in Figure 8. Then, the constraints which "push" down on the two variables are introduced. At the point where the 28,000 cfs constraints (Equations III-15 and III-16) have been satisfied, the feasible region appears as Figure 8.

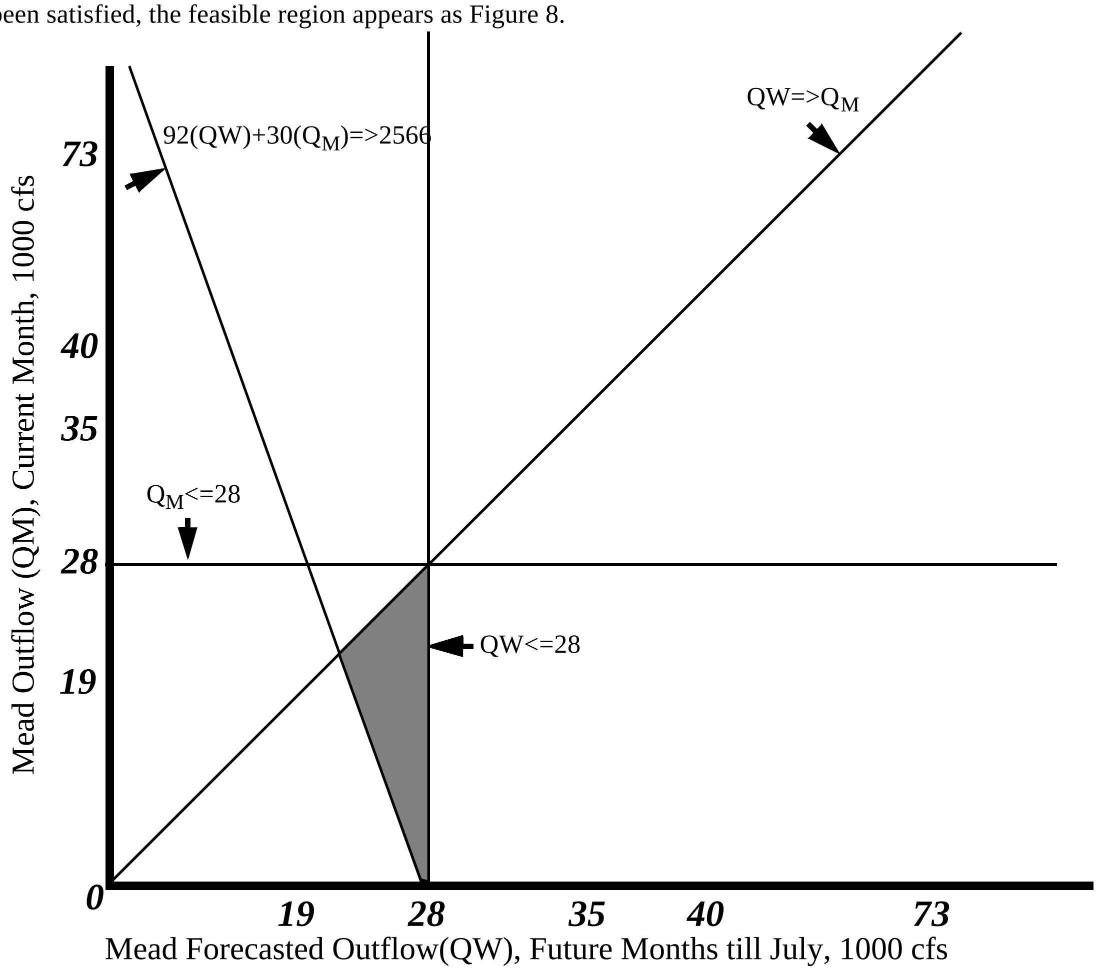


Figure 8: Optimization Spring Flood Control Example I

At the next priority, the 19,000 cfs constraint on the current month's outflow (Equation III-17) is satisfied. At this point, the feasible region appears as in Figure 9. When Equation III-18 is attempted, and the future forecasted outflow is pushed towards 19,000, the feasible region becomes a single point at 19,000 cfs for the current month's outflow (Q_M) and 21,667 cfs for the future forecasted outflow

(QW), as shown in Figure 9. Even though the QW is different from the rules (28,000), the $Q_{M,t}$ is the same.

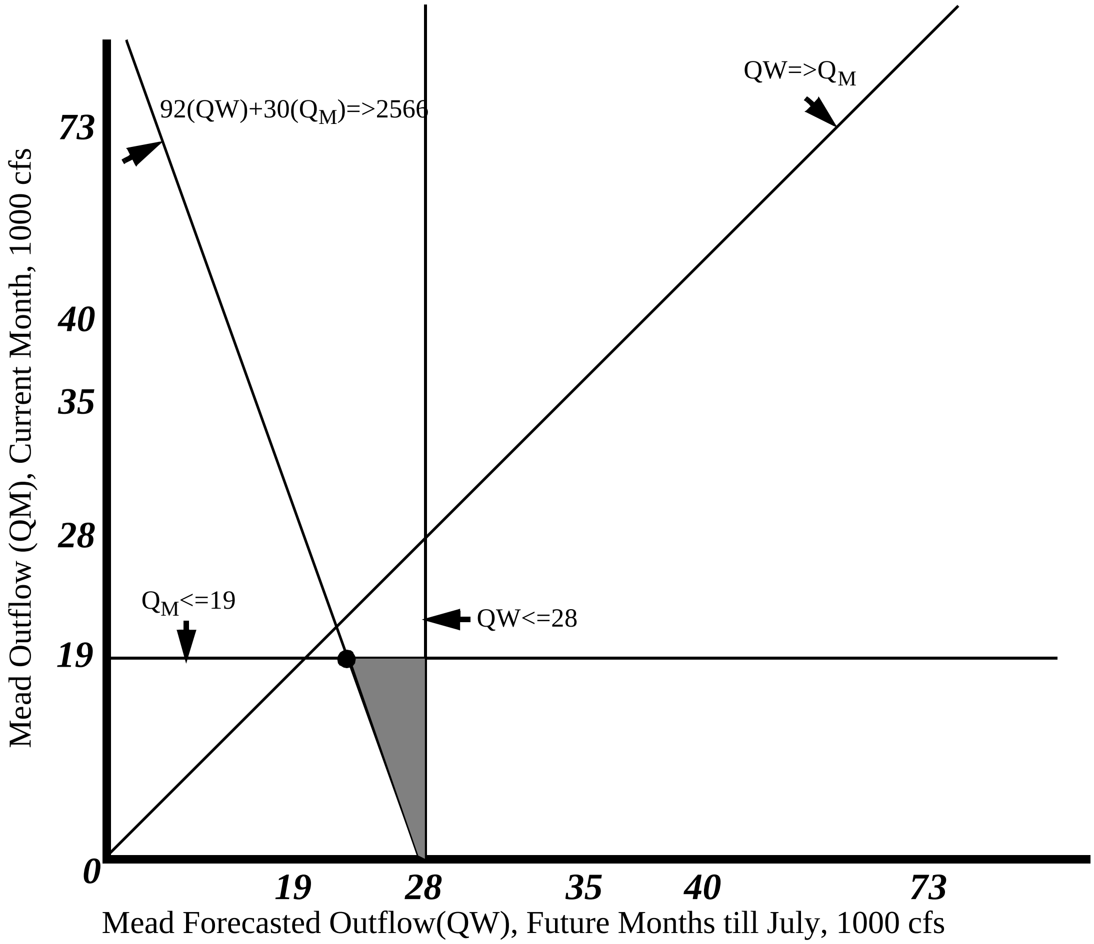


Figure 9: Optimization Spring Flood Control Example II

Procedure 2, Space Building, August - December

To allow the use of limited creditable space in Upper Basin reservoirs in optimization, a new variable was added and an appropriate physical constraint generated. The physical constraint for each reservoir where creditable space was needed can be written:

$$S_{UBres,\,t} + Cap_{UBres,\,t} \le S_{UBres}^{max} \tag{III-21}$$

where Cap is the “creditable capacity” variable.

This was an inequality because the credits may not exceed some value, but the reservoir storage may be lower. As long as the maximum value of the creditable space was desirable, this equation would be an equality when it could be. The bound on the amount of credit from each reservoir was enforced by a maximum bound on the value of that variable (from Table 10).

The policy constraint generated from the spacebuilding rule policy will be valid from August to December, and can be written as:

$$S_{M,\,t} - \sum_{UBres} Cap_{UBres,\,t} \leq S_M^{max} - RS_t\,, \quad \textbf{(III-22)}$$

where:

Cap is the creditable capacity at the subscripted reservoir, and RS is the required space mandated by the flood control policy, from Table 9.

Because Flaming Gorge and Fontenelle have a combined creditable space, an additional policy constraint is written as:

$$C_{flam} + C_{font} \leq 1.5075MAF \quad \textbf{(III-23)}$$

Procedure 3, Exclusive Space Requirement, January - December

As noted, this policy is simple at a monthly timestep, and consists of a single constraint:

$$Elev_M \leq 1219.61ft \quad \textbf{(III-24)}$$

Normal Lower Basin Reservoir Operations

Lakes Havasu and Mohave Rule Curves

The constraints generated are written as:

$$E_{hav,\,t} = E_{hav,\,t}^{\text{target}} \quad \textbf{(III-25)}$$

$$E_{moh,\,t} = E_{moh,\,t}^{\text{target}} \quad \textbf{(III-26)}$$

where E is the reservoir elevation, and E^{target} is the rule curve value.

Meet Requested Diversion Demands

Because the shortage/normal/surplus decision and requested diversion values are set manually in the 24 Month Study, this information already exists in the model. Therefore, for diversions, a constraint that requires all diversion values be equal to the diversion requested is needed:

$$Div_{D,t} = DivReq_{D,t}, \qquad \textbf{(III-27)}$$

where the subscript D is the diversion point, and t is time (month of simulation).

The outflow from Havasu is used as a minimum flow through that point from Mead, and is written:

$$Q_{hav,t} \geq Q_{hav,t}^{demand}, \qquad \textbf{(III-28)}$$

where Q_{hav} is the outflow from Havasu, t is time, and Q^{demand} is the data manually determined by the reservoir operators. Further, an attempt is made to bring the flows at Havasu down to this point during August through December. This constraint must be an inequality to allow the flood control policies to set higher outflows if required:

$$Q_{hav,t} \leq Q_{hav,t}^{demand} \qquad \textbf{(III-29)}$$

Lower Basin Constraint Organization

Each of the above equations will have its own priority level. The normal reservoir operations (reservoir rule curves and meeting demands below Mead) constraints have priorities between the 28,000 and 19,000 cfs constraints. The general plan here is to place the exclusive flood control and runoff storage constraints at the beginning, then gradually clamp down on the outflow from Mead until 28,000 cfs. After the 28,000 cfs constraints, the space building storage constraint is met, demands on the system are met as minimums, then the lower constraints including a Mead 0 flow constraint are attempted. Obviously, the 0 constraint will not be met, but this strategy will bring outflow from Mead down to the required flood control release, or to the required release for demands, if that is higher.

Powell Operation

Equalization

The equalization policy translated into optimization constraints in relative priority order is as follows:

$$\sum_{UBres} S_{UBres,\ Sep} \geq 602aStorage \tag{III-30}$$

where Sep indicates the time subscript for September of every year. 602aStorage is a data value calculated before the run.

$$S_{M,\ Sep} \geq S_{P,\ Sep} \tag{III-31}$$

$$S_{M,\ Sep} - S_{P,\ Sep} \leq 0 \tag{III-32}$$

This set of constraints is at a fairly high priority level, above the spring runoff and space building flow constraints. The results from adding this set of constraints to the optimization are presented in Figure 12. These simple constraints, combined with the rest of the policies, equalized Mead and Powell to the same storage in September.

Minimum Objective Release

The Minimum Objective Release constraint was translated into two constraints. The first was on the sum of the annual release from Powell, at a high priority level:

$$\sum_{t} Q_{P,\ t} \geq 8.23MAF,\ \forall t \in year \tag{III-33}$$

Second, a constraint was written with the monthly release values as a minimum:

$$Q_{P,\ t} \geq MinObjRel_{P,\ t} \tag{III-34}$$

This constraint was written for two different time intervals, October through December above the Mead Flood control, and January through September at a much lower priority. This was done because these policies generally dominated the October through December operations, and were not needed during the rest of the year.

Powell Rule Curve

The Powell Rule curve constraint was also written at two priority levels in time (October through December and January through September), both just below the respective Minimum Objective Release constraints.

$$S_{P,\,t} = RuleCurve_{P,\,t} \tag{III-35}$$

The complete set of constraints used to match the rulebased simulation is presented in Appendix F in priority order in equation form.

Results

Lower Basin Operations including Mead Flood control

For this scenario, the rulebased simulation was run with the historical Powell operation. Therefore, the active rules governed only the Lower Basin operations. This gives the ability to concentrate on the generated Lower Basin constraints matching the Lower Basin rules, and to reproduce an actual 24 Month Study run. Figure 10 shows the comparison of Mead’s outflow for both the rulebased simulation and optimization model results. Figure 11 shows the same comparison for Havasu’s outflow.

Clearly, 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 3,286 acre-ft. less than the rules at Mead, an error of 0.4% in outflow. This error is due to the spacebuilding 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).

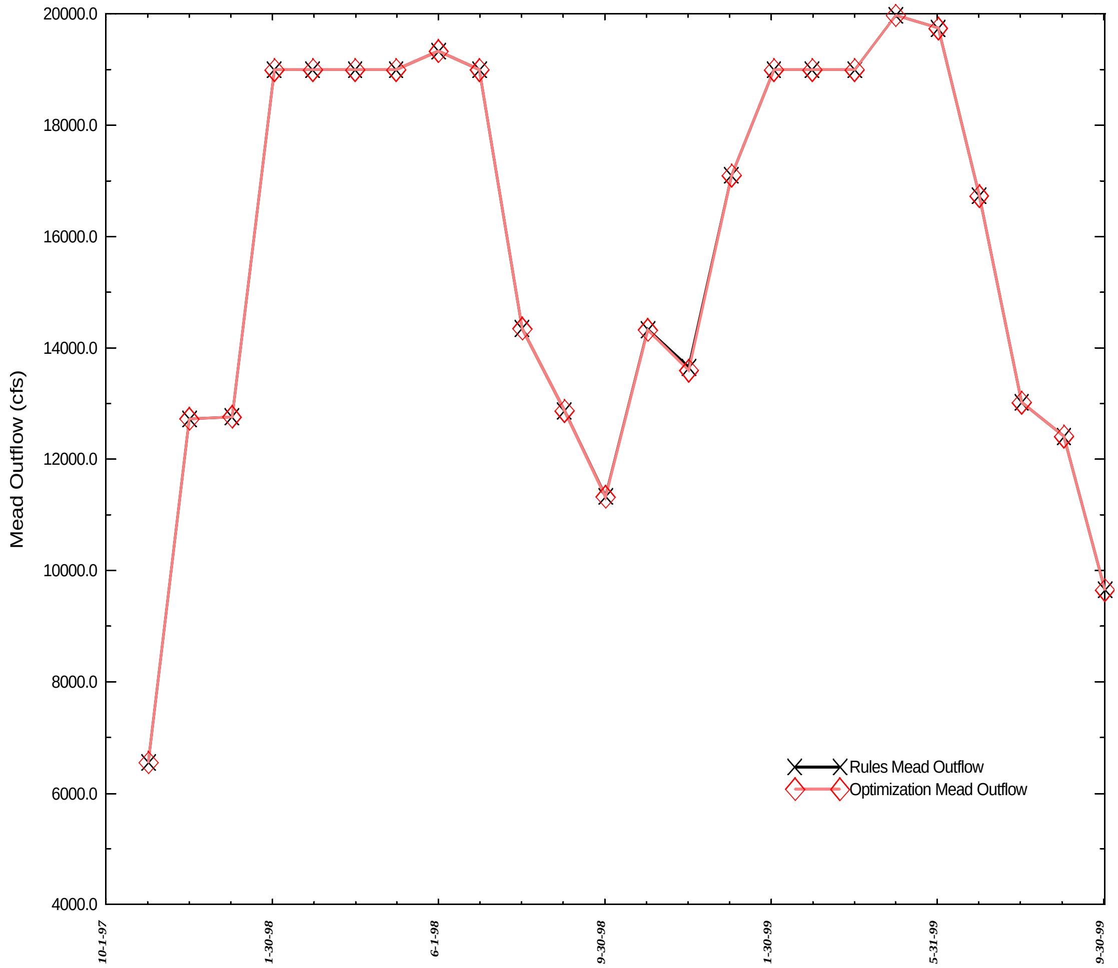


Figure 10: Optimization Matching Lower Basin Rules: Mead Outflow

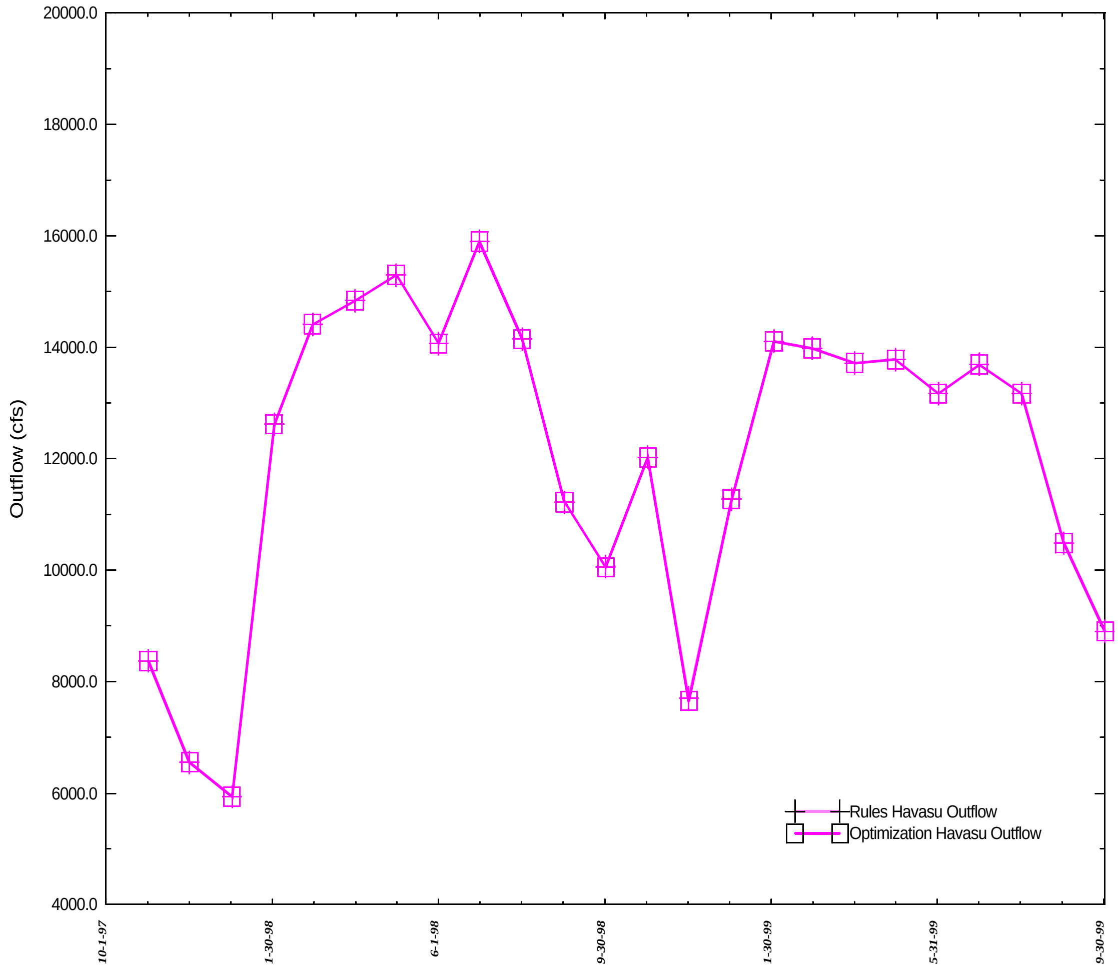


Figure 11: Optimization Matching Lower Basin Rules: Havasu Outflow

Powell Operations

The rulebased simulation was then run using the rules for Powell operations, in addition to the Lower Basin rules, and compared to the corresponding optimization. Two scenarios were studied: In the first scenario, the constraints in Equation III-30 through Equation III-32 were used to implement end of water year equalization, at a high priority level, and the constraints to implement the other Powell operations were also added. Second, the constraint in Equation III-36 (Powell's outflow) at a priority level just above the constraint in Equation III-18 (19,000 cfs forecasted future outflow) was added to better match Powell's release. These scenarios are represented in the next few figures. Note that the gray lines are results at Mead and the black lines are results at Powell.

As shown in Figure 12, the two reservoirs equalize at the same point for both runs, and have very similar outflows during the September - November region. Further, Mead’s outflows are extremely close during the entire run, only differing during August through December, the spacebuilding section, which would be expected because of a small difference in storage at Powell at the same time.

The total volume of water released from Powell over the water year is fixed by the equalization policy. However, timing of releases from Powell in December through August are governed by Mead spring flood control. This is essentially due to the Mead spring flood control taking advantage of the increased evaporation that occurs at Mead, and therefore releasing as much water as possible to Mead early. This may be viewed as a case where the flood control policy is too “greedy” in its use of this increased evaporation.

The second scenario, graphed in Figures 13 and 14, added a constraint on Powell’s outflow. The release pattern that was chosen by the optimization is different, but this reflects the known flexibility present in the choice of when to equalize. An attempt was made to reproduce the rules release pattern as well with the following constraint, that is fairly close to what is present in the rules (Equations III-5 through III-7). This flow constraint is set at a lower priority:

$$\begin{aligned} Q_{P,t} = {} & MinObjRel_t + \frac{1}{2(n)} \times ((S_{P,t-1} + I_{\Sigma P} - Q_{\Sigma P} - Evap_P - BankS_P) \\ & - (S_{M,t-1} + I_{\Sigma M} - Q_{\Sigma M} - Evap_M - BankS_M - Div_M)) \end{aligned} \qquad \textbf{(III-36)}$$

where:

$Q_{P,t}$ is the outflow from Powell during the January through September timesteps.

MinObjRel is the monthly minimum objective release flow.

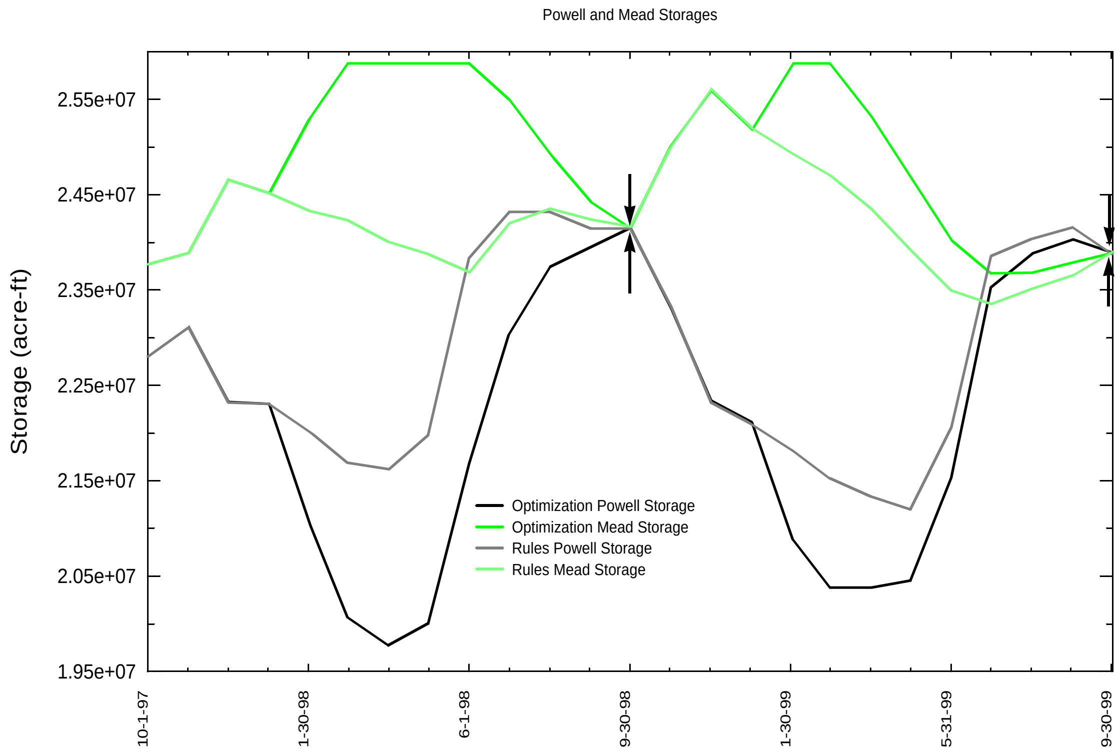
n is the number of months remaining until the end of the water year including the current month.

S is the reservoir storage at the subscripted reservoir and month.

Evap and Bank are evaporation and bank storage for the subscripted reservoir. For these, the actual reservoir storages and surface areas at the previous timestep and the end of the water year are used.

I_{Σ} and Q_{Σ} are the sum of the inflows and outflows from the current month until the end of the water year for the subscripted reservoir.

This constraint did much better at matching Powell's flows, but did not do a perfect job, and interfered with the flood control policy at Mead. This was an attempt to address the limitations of the first scenario, and does a better job with Powell's outflow. In fact, the optimization picks a less varying flow schedule for outflow than the rules. However, notice that in this scenario, the spring runoff outflows from Mead are affected as shown in Figure 14 by the equalization flow constraint. The peak in November is driven by space building, and is not related. Notice also that the storage at which the two reservoirs equalize is now different.



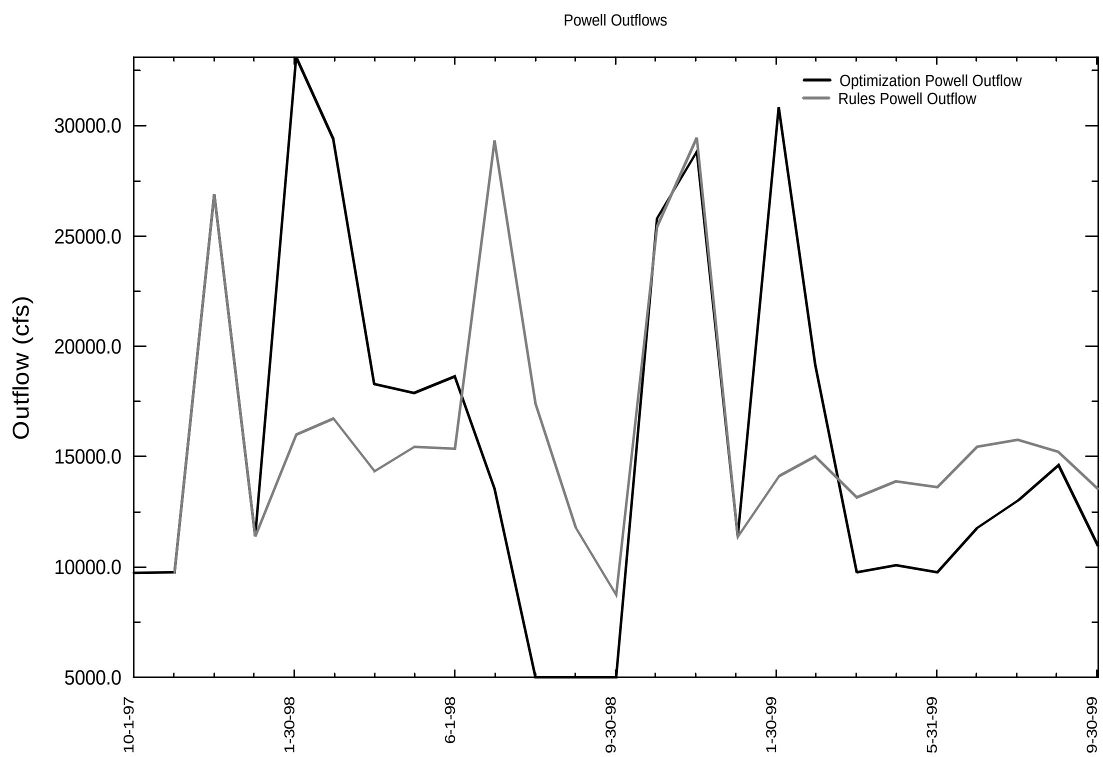


Figure 12: Match Equalization Storage

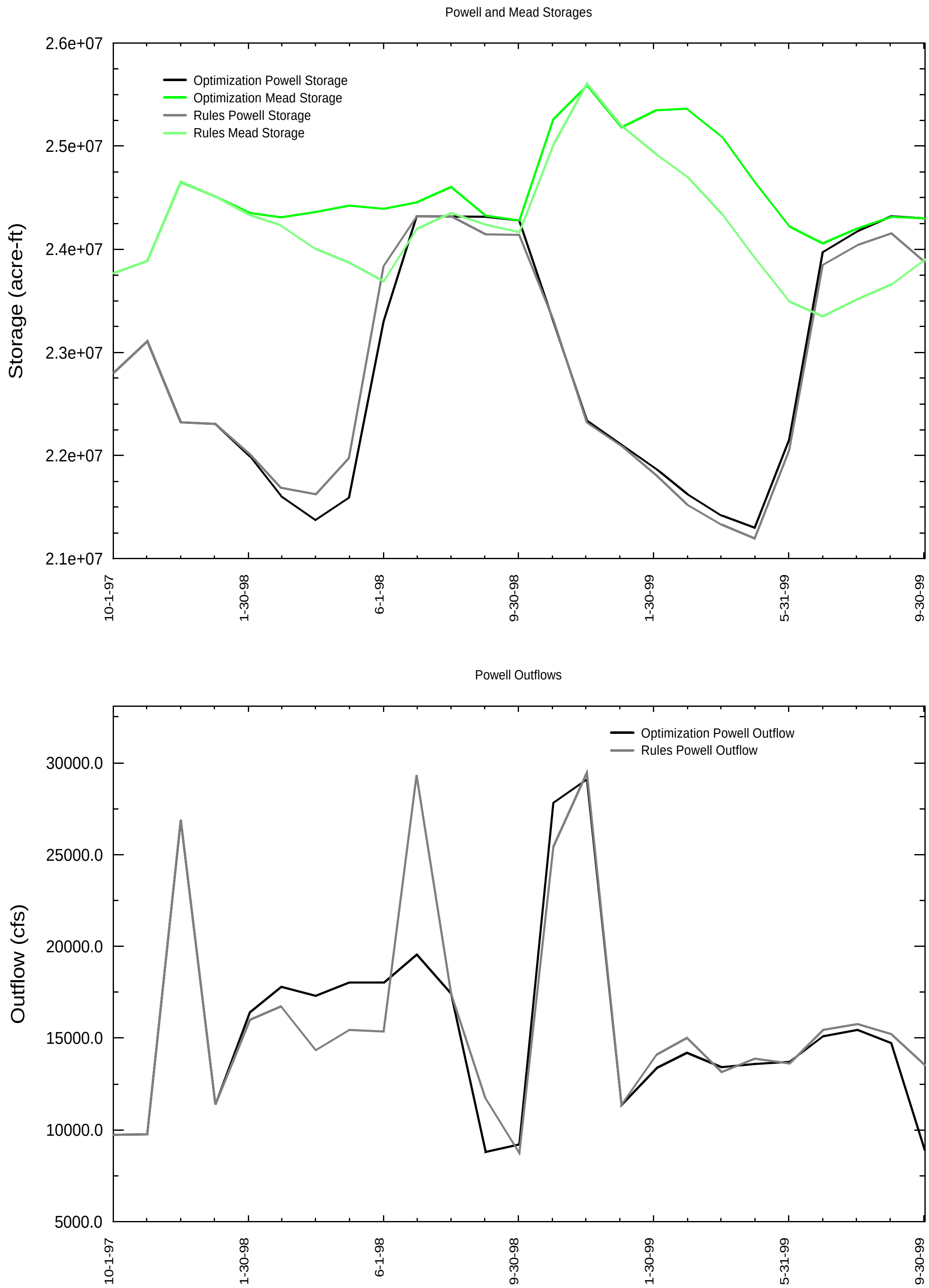


Figure 13: Effects of Equalization Powell Outflow Constraint

Figure 14: Mead Outflow Showing Effect of Equalization Outflow Constraint

Discussion

A major issue that arose from this work is the difference between the timestep-by-timestep and forecast based solution approach of the rulebased simulation and the perfect foresight, planning horizon approach of the optimization. Rulebased simulation has the advantage that it mimics the operational methodology, i.e. in actual operations, only the current and past states of the system are known, and any knowledge needed about the future must be forecasted (e.g. end of water year storages). The rulebased simulation must also forecast the future states of the system based on the current state. Then, at every timestep, the forecast is updated. This timestep-by-timestep approach is a limitation of rulebased simulation when compared to optimization.

Optimization as it is implemented in RiverWare, solves the entire system at once over the entire time horizon, with a deterministic forecast of the future states of the system. This deterministic forecasting is both the advantage and the limitation of the optimization approach. While it can provide insights into how to respond to a forecasted inflow hydrology, it may be too optimistic in the results that it provides.

To overcome the difference in these approaches, some timestep dependent constraints were associated with the flood control policy. Otherwise the optimization would evacuate space in August through December knowing the forecast to allow for lower flood control flows in January through July. For example, the minimization of outflow from Havasu (Equation III-29) for the fall of 1998 has a higher priority than the Mead outflow flood control policy of 19,000 cfs for the spring of 1999. Further, the problems matching the rulebased simulation equalization could have been eliminated if the flood control policy and the equalization policy were satisfied one timestep at a time. However, this would have required a proliferation of priority levels, from the current 50 up to 100 or more.

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. The policies which were implemented were flood control for Hoover Dam, equalization of Lakes Powell and Mead, the Lower Basin reservoir rule curves, and the satisfaction of diversion demands. Model results for both the rule based simulation and the optimization show that these policies have been matched. The timing of equalization releases from Lake Powell has not been matched as thoroughly as the rest of the policies, but the result does show equalization occurring to the same storage value. While this result is not sufficient to allow for further analysis of the timing of equalization releases, it will allow for further analysis of the rest of the Lower Basin policies.

Chapter IV: Analysis of Hydropower Generation Value Sensitivity to Policy Change on the Lower Colorado River

Introduction

Analysis of the operational policies of the Colorado River is necessary on some level to allow policy evolution to occur. Rulebased simulation models allow policy alteration and comparison, but are still only descriptive models. As reported in the last chapter, the complicated and discrete operating policy of the Colorado has been successfully represented using RiverWare's pre-emptive goal programming optimization solver. Two advantages come from this accomplishment: the ability to provide prescriptive solutions and the ability to access the cost of current policy.

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 (1991) 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. A variety of policy studies have been done based using simulation models (Veselka et al. 1999; Nash and Glieck 1994; Oamek 1988).

By using the model developed in the last chapter, a policy analysis can be done. 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. The modeling scenario used is the same that was presented in the last chapter (24 Month Study, October 1997 to September 1999, using historical data). This analysis does not consider uncertainty or the nature of forecast values and therefore may be optimistic in its results.

However, for this modeling scenario, the flexibility explored in operating policy increased the value of hydropower generation on the order of 6% on the Lower Colorado River, a significant gain.

This chapter is structured as follows: First, the Lower Colorado River system and the potential operating flexibilities are described. Second, the modeling of hydropower in both the simulation and optimization models of the Lower Basin, along with the value of hydropower, are discussed. Third, the results of the optimization exploiting the potential flexibility are presented. Finally, the results are discussed, including initial conditions, accuracy of hydropower, and possible effects of uncertainty.

Lower Colorado River System

The Lower Colorado River includes the river from a point below Lake Powell until the river's outlet into the Gulf of California. The Bureau of Reclamation operates the three mainstem reservoirs. The vital statistics of those reservoirs are included in Table 13 as reference points for the description of the potential flexibilities and application of the results.

Table 13: Lower Basin Reservoir Statistics[a]

Reservoir	Dam	Maximum Storage (MAF)	Installed Powerplant Capacity (MW)	Maximum Powerplant Discharge (1000 cfs)
Mead	Hoover	27.5	2074	49
Mohave	Davis	1.8	240	23.5
Havasu	Parker	0.62	120	21

a. Data from Fulp et al. (1994)

The Lower Basin was selected because the operational rules are already in place. Equalization was not analyzed because it has effects on a longer scale than the 24 Month Study, and without it, Powell operations would not be reasonable. Further, rules to operate the rest of the Upper Basin are not included in the rulebased simulation (24 Month Study), as previously noted.

On an monthly scale, the operations of Lake Mead can be classified into two basic modes. The first mode is flood control (a "top-down" operation), where the water to be released from Mead is determined by an exact policy based on forecasted spring runoff, fall space building, or evacuation of the exclusive flood control space. The second mode is demand driven (an “bottom-up” operation). The diversion demand downstream from Mead (including MWD, CAP, other diversions below Lake Havasu, and the Mexican delivery) are all satisfied out of storage at Lake Mead. Because Lakes Mohave and Havasu are operated along single rule curves, they may contribute in a positive or negative way to the total downstream demand. The effect of this policy on the 24 Month Study is to completely determine the storages at these reservoirs.

Potential Policy Flexibility

The monthly operations of the Colorado River are governed by a set of policies and operational decisions which have a variety of sources. From this set of policies, there are some where flexibility has been used previously and some where flexibility could possibly be introduced with varying degrees of difficulty. There are two policies where flexibility has historically been used in operations, and are therefore the most promising. These are the rule curves for the operation of Lakes Mohave and Havasu and the timing of the fall spacebuilding procedure of the Mead Flood Control policy (Fulp 1999).

The set of policies where flexibility could possibly be introduced includes the rigid nature of the water demands on the Lower Basin, and the rest of the flood control policy. Because water demand forms the basis of the second operational mode, it can be expected that any flexibility in the timing of the demand might allow for better hydropower generation.

While it is recognized that some policies are not realistically going to change, flexibility in all policies may be explored as examples of what the optimization model can do. For example, the effects of removing the flood control policy are also included in this analysis, even though that policy is very unlikely to be removed.

Lower Basin Reservoir Rule Curves

Lake Mohave was built in the 1940s for the primary purpose of re-regulating the peaking flows below Lake Mead. Operating it on a monthly basis by a strict rule curve, however, limits the ability to move hydropower generation to months that is more valuable. Lake Havasu was originally built to provide storage for the MWD delivery and the other deliveries further downstream. Therefore the expected degree of flexibility at Mohave is much larger than that at Havasu. The historical results from the time period modeled show that the rule curves 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). In the graphs below (Figures 15 and 16), two timeseries are shown. The dashed lines are the historical values. The black lines are the rule curve as published by the USBR. For this analysis, both the rule curves at Mohave and Havasu are allowed to vary. This scenario is referred to as “Rule Curve Flex” for the rest of the thesis.

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. However, a possible formulation for such an analysis is presented in Appendix H. 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 spacebuilding could be released earlier in the spacebuilding season by the optimization. This scenario is called “Space Building Flex” for the rest of this thesis.

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. The two diversions are to the Metropolitan Water District of Southern California (MWD) and the Central Arizona Project (CAP). The demands below Havasu are mostly large agricultural users, including the delivery to Mexico. 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.

This freedom will allow the optimization to shift water deliveries around to increase the value of hydropower generation, while still delivering the same amount of water. CAP in particular could be a likely candidate, because they have the storage and canal capacity to handle fairly large changes in flows. MWD, on the other hand might not be able to store diversions as easily, and under surplus conditions (as now), they often divert the maximum their canal can hold. Allowing the optimization to varying the timing of the deliveries is a scenario is referred to as “Water Demand Flex” for the rest of the thesis.

Figure 15: Mohave Historical Pool Elevation and Rules Values

Combined Flexibility

A run was also made that combined the flexibilities described in the Water Demand Flex, Spacebuilding Flex, and Rule Curve Flex scenarios. This scenario is referred to as “Combined Flex” for the rest of the thesis.

Maximize Hydropower

Finally, a scenario was made that removed most of the constraints from the system. This was done to see what the maximum value of hydropower that could be generated with the constant outflow sum. Although this last scenario does not represent an operation that would ever occur, it is useful as a maximum, for comparison with the other scenarios. This scenario is referred to as “Max HP” for the rest of the thesis.

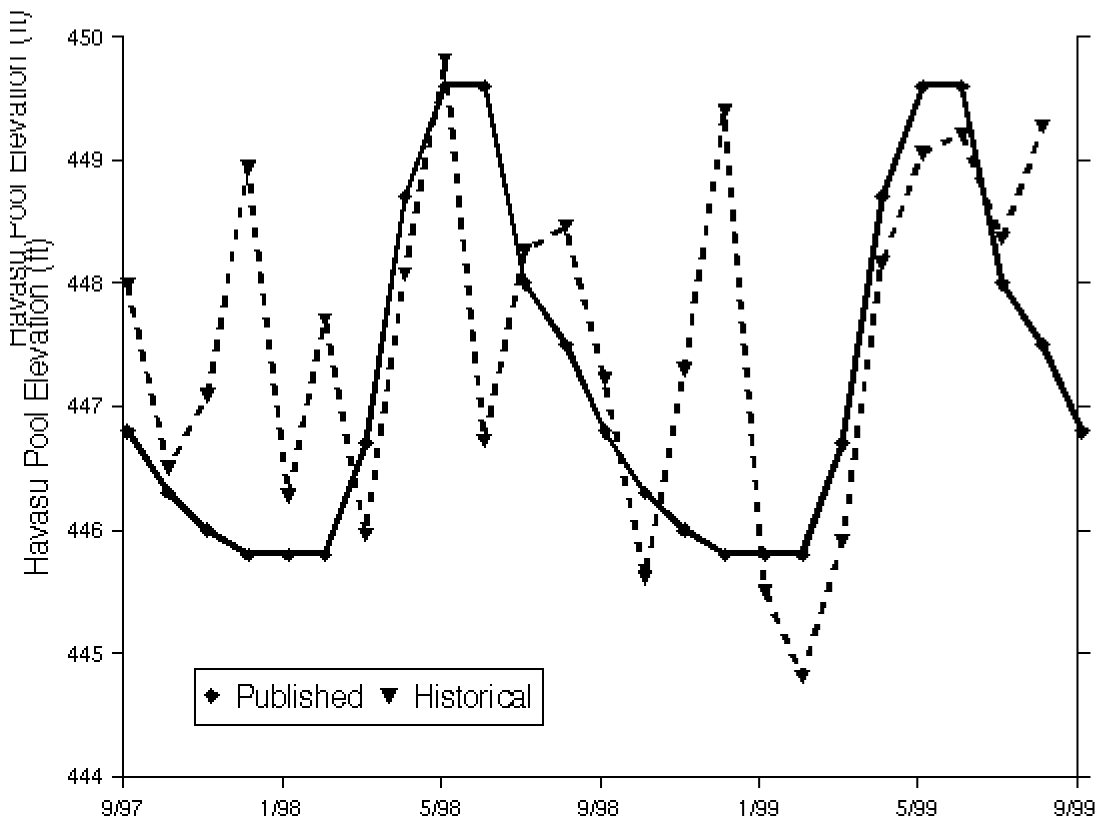


Figure 16: Havasu Historical Pool Elevation and Rule Curves

Modeling of Hydropower

Hydropower generation is a function of the turbine flow and head, and is usually written as:

$$P = e \cdot Q \cdot H \tag{IV-1}$$

where P is power, e is an efficiency value for the plant, Q is turbine release, and H is the net head (forebay elevation - tailwater elevation).

Since the tailwater elevation is a function of flow and head, this is a nonlinear relationship in the decision variable Q. Typically, data are supplied for the P vs. Q, and Q vs. tailwater relationships and simulation methods iterate to find the flow and head simultaneously. When the plant consists of multiple turbines, composite relationships are used and the plant is modeled as a single unit. For a monthly timestep, the simulation is further complicated by the fact that the powerplant will not operate for all hours within the month at peak (or best) power. Therefore, an estimate of the number of peak operating hours must also be made.

The rulebased simulation model uses a method derived from the old FORTRAN versions of the 24 Month Study and CRSS models. The method assumes that the powerplant will operate at a base flow throughout the month. The total volume of water released at base flow is then subtracted from the total volume of water to be released over the month to arrive at the volume available for peaking. The peak release (Q) is determined in the iterative way previously described. This peak release and the peaking volume can then be used to determine the number of peaking hours within the month and the peaking energy produced. Similarly, the energy produced at base flow can be computed.

For the optimization model, the effect of base flow was ignored, i.e., all energy is assumed to be produced as peak power. In terms of simulation, this has the effect of overestimating the amount of energy generated, and did so on the order of about 8%. For comparison purposes, however, the optimization solution is used as an input into a post-optimization simulation, and those simulation values for energy are then compared with the energy values from the rulebased simulation. Therefore, a comparison between the rulebased simulation energy values and the simulation energy values from the optimization results is sound.

Linearization of Power

RiverWare’s optimization solver up until now had only been applied to models with a daily timestep or shorter, where the variation in head is either small or predictable. Therefore, the power linearization methods which existed before this work either assumed a constant head, or required a user-input prediction of the head variation. At a monthly timestep over more than a few months, this is not sufficient because the head can vary greatly. Further, for all three dimensional linearizations then available in Riverware, a two dimensional approximation was used, with the third dimension approximation held constant at some point, in effect selecting which “slice” of the three-dimensional space to be used in the linearization. This applied for both the tailwater calculation and for the power calculation.

An improved three dimensional linearization scheme for these cases was implemented for use at longer timesteps. Specifically, the previous linearization of power as a function of outflow was altered to include the effect of changing head. The equation used for a two dimensional (line or tangent) linearization in a power-turbine release plane is:

$$P = m_Q(Q) + b_Q, \tag{IV-2}$$

where P is the power, Q is the outflow, m_Q is the slope of the line in that plane, and b_Q is the intercept of the line, found at an operating head approximation point. The improvement is an adjustment to this equation to include the effects of changing head. By using a tangent in the power-head plane, the linearization equation was written as:

$$P = m_Q \cdot Q + b_Q + m_H \cdot (H - H_0) \quad , \tag{IV-3}$$

where H_0 is the approximation point used to find the slope and intercept, and m_H is the slope of a tangent line in a power-head plane, as shown in Figure 17. The tangent value for the turbine release was used as the point for the slice in the power-operating head plane.

A similar improvement was also applied to piecewise approximations of this relationship, where the effects of changing head were applied with the slope of a single tangent line in the power-head plane. A similar linearization improvement was used for the tailwater-outflow relationship.

Power linearization necessitates a data table that expresses the relationship between operating head, turbine release, and power. Three approximation points of flow and power were used for each operating head in the table: no flow and power, maximum flow at that head, power at that flow, and maximum flow, maximum power possible. The linearization then finds the tangent, line and piecewise approximations from this table. Although this is not the same as the simulation method, it preserves the same relationship between an increase in turbine release and an increase in power. Generally, if the volume to be released increases, the simulation method increases the number of hours to run the plant at peak outflow. The optimization method increases power between 0 power and 0 flow and maximum power at that head and maximum flow at that head in a similar fashion.

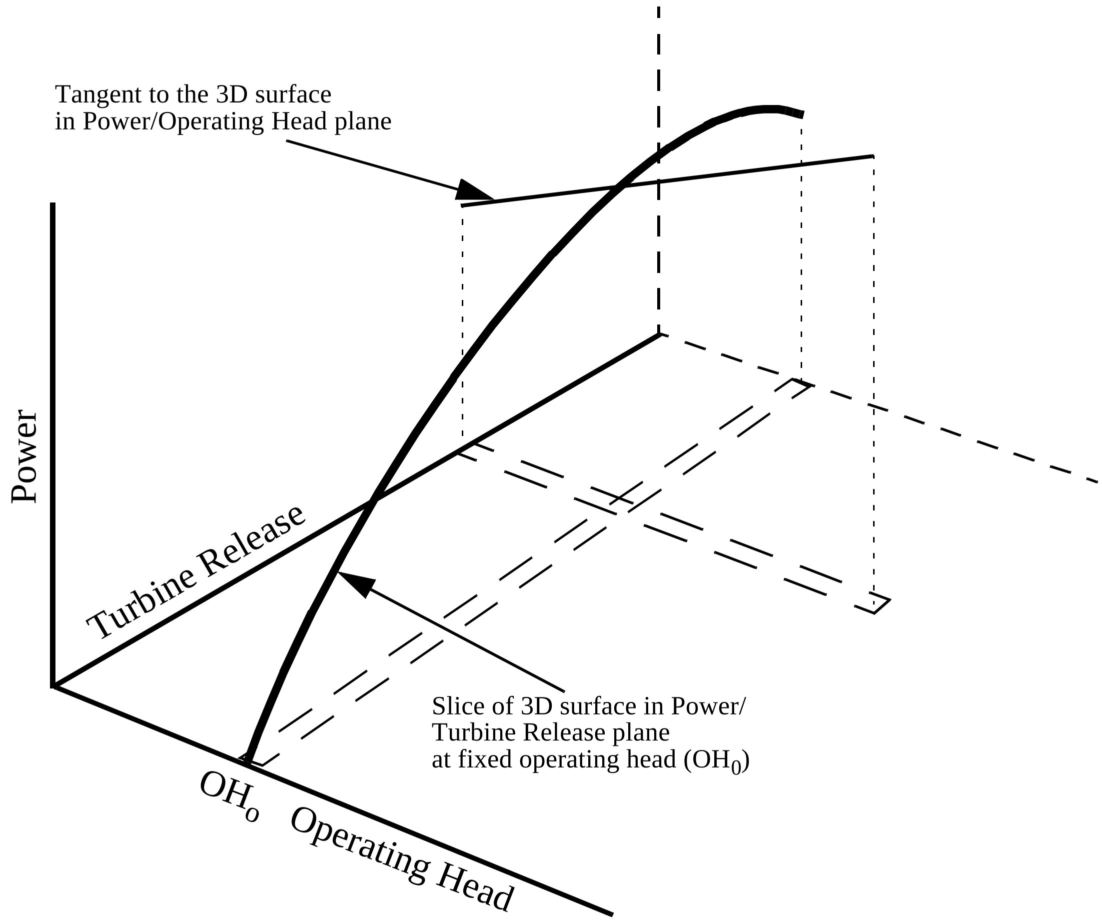


Figure 17: Three-Dimensional Approximation Improvement

Energy Value Forecast

As previously mentioned, this analysis uses the value of hydropower as the comparison measure between scenarios. 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. Historically, because the power markets were served by monopolies, this information was a trade secret. Recently, however, the electricity markets have been moving towards deregulation. California in particular has taken the lead in deregulation, driven by the fact that the retail cost of energy there is among the highest in the nation. Due to this deregulation, information about the cost of power in California is now available. Since the hydropower generated in the Lower Colorado River basin is directly accessible to the Southern California power markets, these data were used to assess the value of that hydropower generation.

Two sources of information about the value of peak power are available: the California Power Exchange (CalPX), and the New York Mercantile Exchange (NYMEX) electricity futures contract. Both sources were investigated to see if the data were consistent, and to find values that cover the time horizon of the model (24 months, from October 1997 to September 1999).

CalPX publishes information about the results of its hourly, same day, and day ahead power auctions on the World Wide Web (California Power Exchange 1999), but has only 18 months of history, beginning in April of 1998. Therefore, the auction data did not cover the entire period of interest, and could not be directly used. From the data available, the day-ahead peak power price index was selected as a good representation of the results of the auction. Although CalPX does not explicitly define this index, it appears to be an average over the day weighted by demand. These data were aggregated to both monthly average and monthly median prices in dollars/MWH.

The NYMEX contract is for delivery to the California Oregon border (COB) of a specified amount of energy at peak times. These contracts are available for trading for 18 months into the future, and began in March 1996 (Fiedler 1996). Since the focus of this study is not on the forecasting problem, the closing price for each contract, which is 4 business days before the beginning of the delivery month, was used.

The COB values and the average and median auction values from CalPX are presented in Figure 18. A visual comparison shows that the futures data roughly trends with the auction results. The r^2 between COB and the auction values are 0.79 and 0.64, respectively. From this comparison, and the fact that the COB future values span the monthly time frame of this model, they were selected as the energy price values for this thesis.

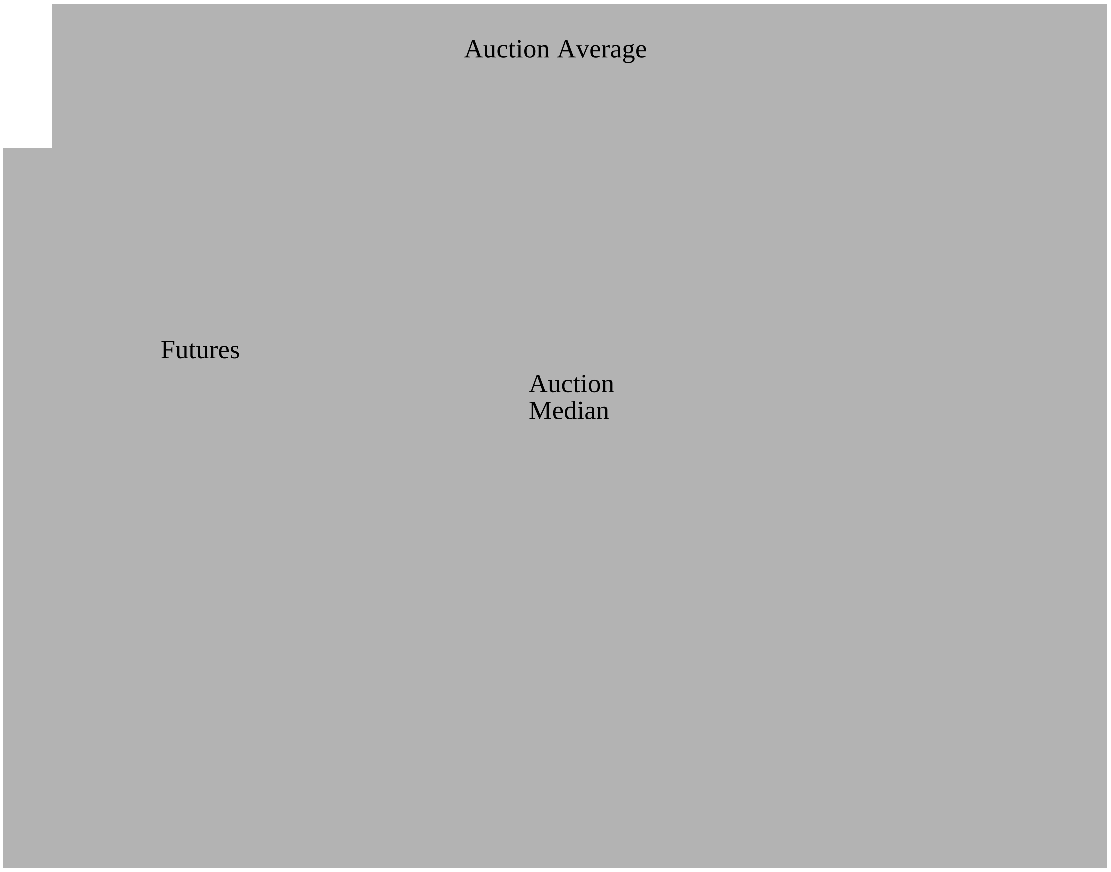


Figure 18: Auction Spot Price Measures and Futures Contract Closing Prices

Optimization Formulation

Several different scenarios were studied to demonstrate the usefulness of the optimization as an analysis tool, and to investigate the increases in hydropower value due to the flexibility in these scenarios.

The baseline for the comparisons is essentially the previous formulation that matched the rules, with two exceptions. First, because a future value of water was not used, additional constraints were added to prevent the optimization from emptying the reservoirs for hydropower. The sum of the flows from Mead and Havasu were required to equal the sum of the flows produced by the optimization replication of the rules:

$$\sum_t Q_{M,t} = \sum_t OptResult_{M,t}, \forall t \in \text{ current water year} \qquad \textbf{(IV-4)}$$

$$\sum_{t} Q_{hav,\,t} = \sum_{t} OptResult_{hav,\,t},\ \forall t \in \text{ current water year} \quad \textbf{(IV-5)}$$

Second, the formulation for the Mead Flood Control policy as given in Chapter 3 was found to be too greedy, as explained previously. Therefore, to prevent this policy from using all of the flexibility in the system, the constraints given in Equations III-8 through III-19 were replaced by the following constraint:

$$Q_{M,\,t} \geq FCReq_{M,\,t} \quad \textbf{(IV-6)}$$

where $FCReq_{M,t}$ is the flood control release requirement generated by the rules. Unfortunately, this requires two model runs: one in "baseline" mode (using either rules or optimization), to produce $FCReq_{M,t}$, followed by an analysis run. This alternate formulation of the spring flood control policy gave identical results to that of the optimization results from the last chapter, while allowing for the needed flexibility in flows.

To allow hydropower value to help determine the system operation, the following objective was added at the lowest priority in the constraint set:

$$\textbf{Objective Max: } \sum_{T}\left(\sum_{LBR} EnergyPrice_{t}(Energy_{LBR,\,t})\right), \quad \textbf{(IV-7)}$$

where:

EnergyPrice is the price series described in the previous section, closing price for the futures contract for energy delivered to COB for the current month.

Energy is the energy produced by each Lower Basin reservoir.

The subscript t is time in the set of all timesteps in the model run, and the subscript LBR stands for the Lower Basin Reservoirs (Mead, Mohave, and Havasu.)

Formulation and Analysis of Scenarios

Because of the history and origin of the Lower Basin policies, they are not expected to be changed lightly. However, this analysis may show that the hydropower generation is worth more than some of these rigid operations. Note also that none of these policy changes explicitly alter the annual amount of water released from Mead. Historically, no water release is scheduled just to satisfy hydropower needs, but hydropower considerations have altered some of the release patterns (Fulp, personal communication).

A set of equations that represents the constraints used in all of these scenarios is included in Appendix G.

Baseline

As previously discussed, this problem included Equations IV-4 through IV-7. The value of hydropower generated in this scenario was 191.4 million dollars per year.

Rule Curve Flex

It was chosen to explore the effects of relaxing the rule curve constraints by observing the result of 1, 3, 5, 10 and 15 feet of monthly operating range around the Mohave rule curve. Since the rule curve for Havasu has only 4 feet of operating range, the Havasu requirement was relaxed by only 1 foot to see what that effect would be.

For Lakes Mohave and Havasu, the previous model had the constraint written below (Equations III-25 and III-26).

$$E_{R,t} = E_{R,t}^{\text{target}} \quad \textbf{(IV-8)}$$

For this analysis, these were replaced by this new set of constraints:

$$E_{R,t} \geq E_{R,t}^{\text{target}} - X \quad \textbf{(IV-9)}$$

$$E_{R,t} \leq E_{R,t}^{\text{target}} + X \quad \textbf{(IV-10)}$$

where:

X is the measure of flexibility to be given. (in feet), and R is the reservoir (Mohave and Havasu)

The major effect of this change is to allow some of the demands downstream of Mead to be met out of storage from Mohave and Havasu. This in turn allows Mead to change the timing of water released in response to the monthly differences in hydropower generation value. The values (in millions of dollars per year) from these scenarios were 192.2 for the 1 foot of flexibility at Havasu, and 192.6, 194.2, 195.8, 198.9, and 200.1 for the 1, 3, 5, 10, and 15 feet of flexibility at Mohave.

In the Mohave graph (Figure 19), only three of the five runs are graphed. The one and five foot flexibility results follow the exact shape of the three foot result, just spaced slightly differently. Notice also how close the 15 foot result is to the 10 foot result.

In the Havasu graph (Figure 20), a major feature is the amount of variability. The reservoir moves from one foot below to one foot above in several months (August 1998).

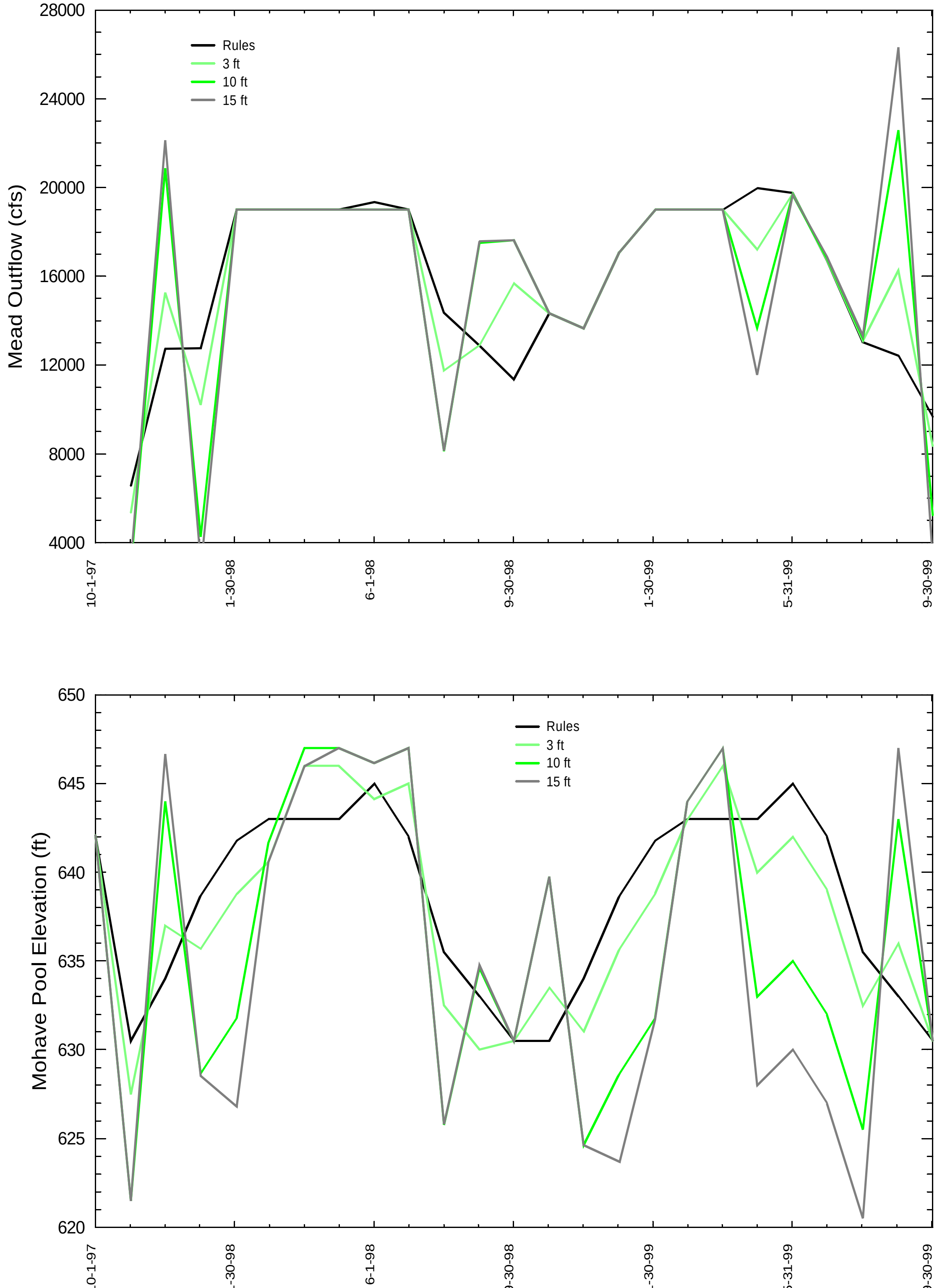


Figure 19: Mohave Rule Curve Flexibility

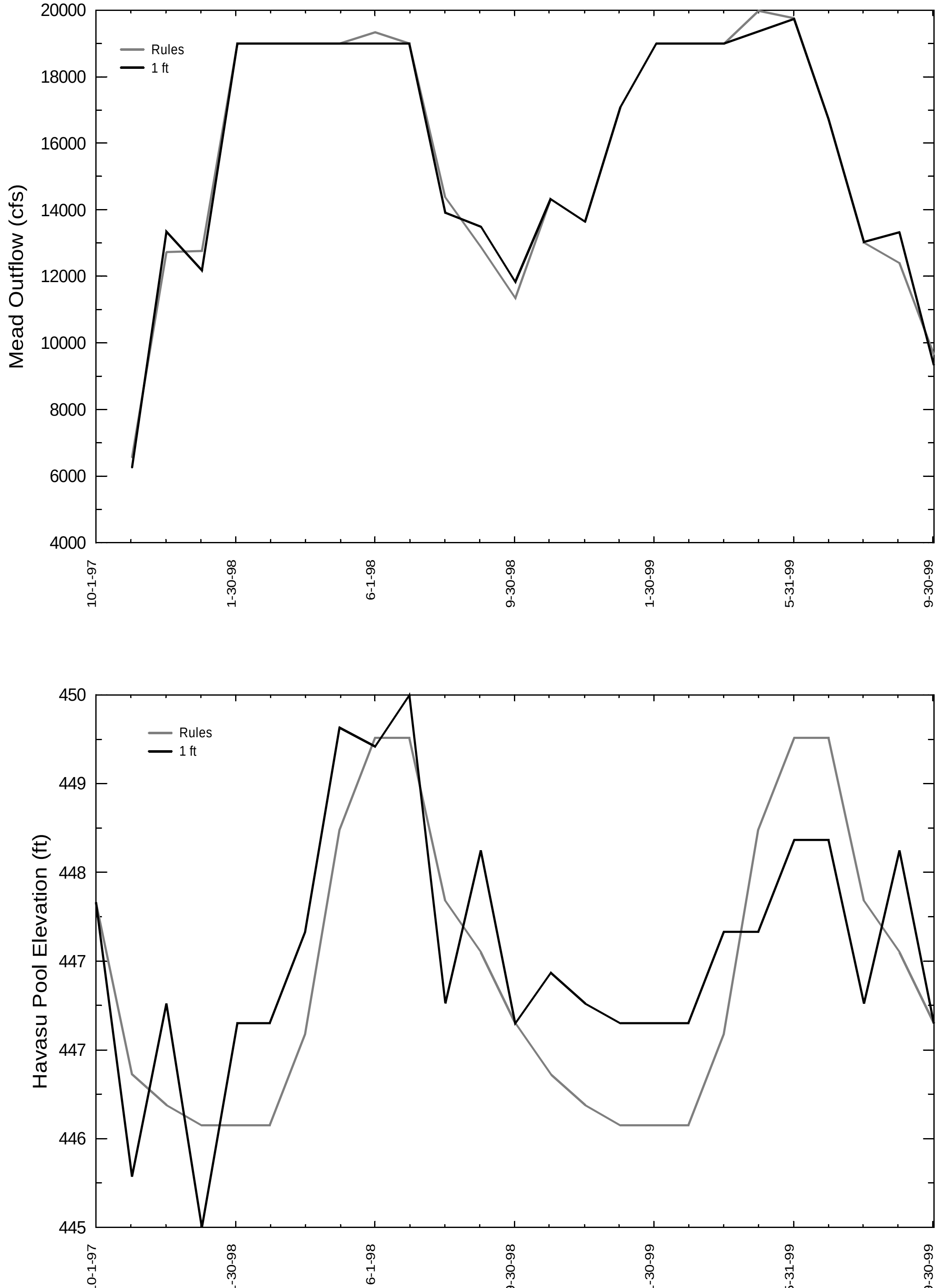


Figure 20: Havasu Rule Curve Flexibility

An interesting result is the general increases in value as the flexibility in Mohave's pool elevation increases. There does seem to be a diminishing return after about 10 feet of flexibility, as shown in Figure 21.

Figure 21: Value of Flexibility in the Mohave Rule Curve

Water Demand Flex

Flexibility in water delivery was implemented as some percentage of the water demand that may be shifted in time. These constraints were altered from the previous chapter (Equation III-27) to be:

$$Div_{D,\,t} \geq (1 - X)DivReq_{D,\,t} \tag{IV-11}$$

$$Div_{D,\,t} \leq (1 + X)DivReq_{D,\,t}, \tag{IV-12}$$

where:

Div is the diversion.

DivReq is the historical actual diversion, and is represented as the diversion requested.

D is the subscripted diversion point.

X is the fraction of freedom to be given (10% in this analysis).

The sum total of all water delivered was kept constant with the simulation:

$$\sum_t Div_{D,\,t} = \sum_t DivReq_{D,\,t},\ \forall t \in \text{ current water year}, \tag{IV-13}$$

Since the flood control can cause more water than demand to flow out of Havasu, only the following is needed to provided flexibility in the Havasu outflow. Remember also that an annual sum constraint was already written for the Havasu outflow. Equation III-28 from the previous chapter was altered to include some flexibility:

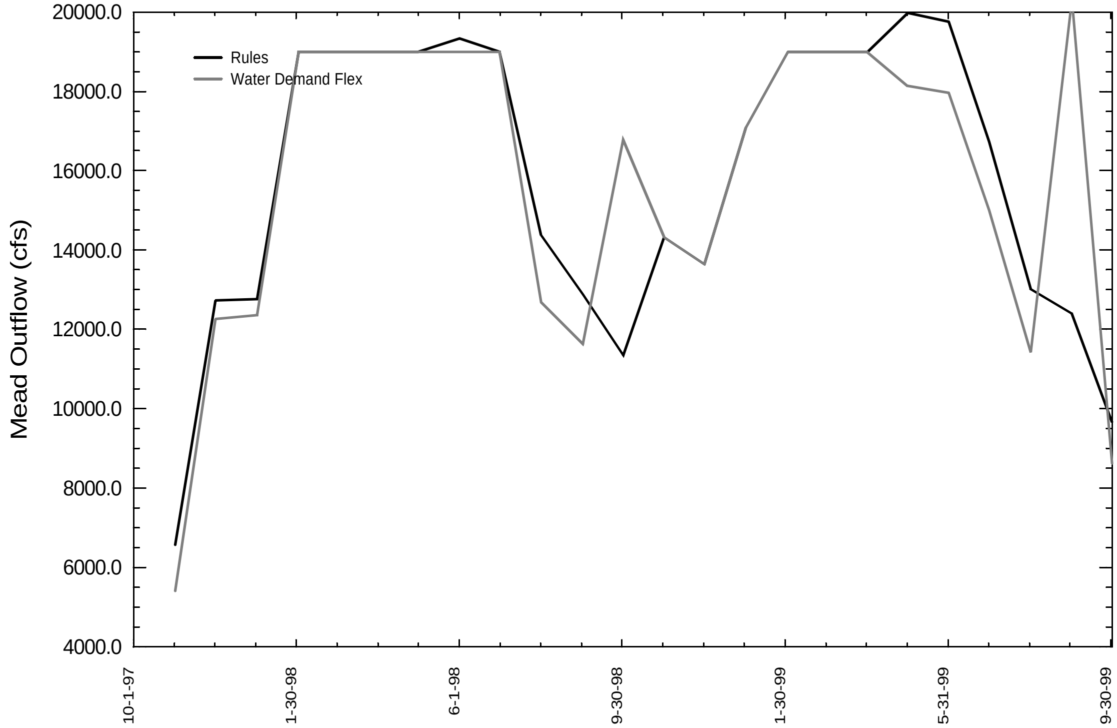
$$Q_{hav,\,t} \geq (1 - X)QReq_{hav,\,t}, \tag{IV-14}$$

where:

X is the fraction of freedom to be given (10% in these runs).

These water demands already have generally the right shape for hydropower generation, given the highest diversion demand and highest electricity prices in the Southwest typically occur in August. Another effect of this flexibility may be adverse towards agriculture. Depending upon crop type, the relationship between water delivered and income can be highly nonlinear during various seasons. This effect was not considered in this study. The hydropower value from this scenario was 195.6 million dollars per year.

The result of the Water Demand Flex scenario is graphed in Figures 22 and 23. Note that the Havasu outflow does not have a less than or equal constraint, which is why the flow can be so high in August of 1998 and 1999. Generally, the flexibility is used at MWD and CAP to give them more water in the spring, and less water in the fall (within the 10% limitation). The reverse is true for the Havasu demand, primarily because the Havasu demand is along the run of the river. The fact that a 10% flexibility in the timing of water deliveries gave a 2.2% increase in hydropower value suggests that some amount of flexibility should be considered.



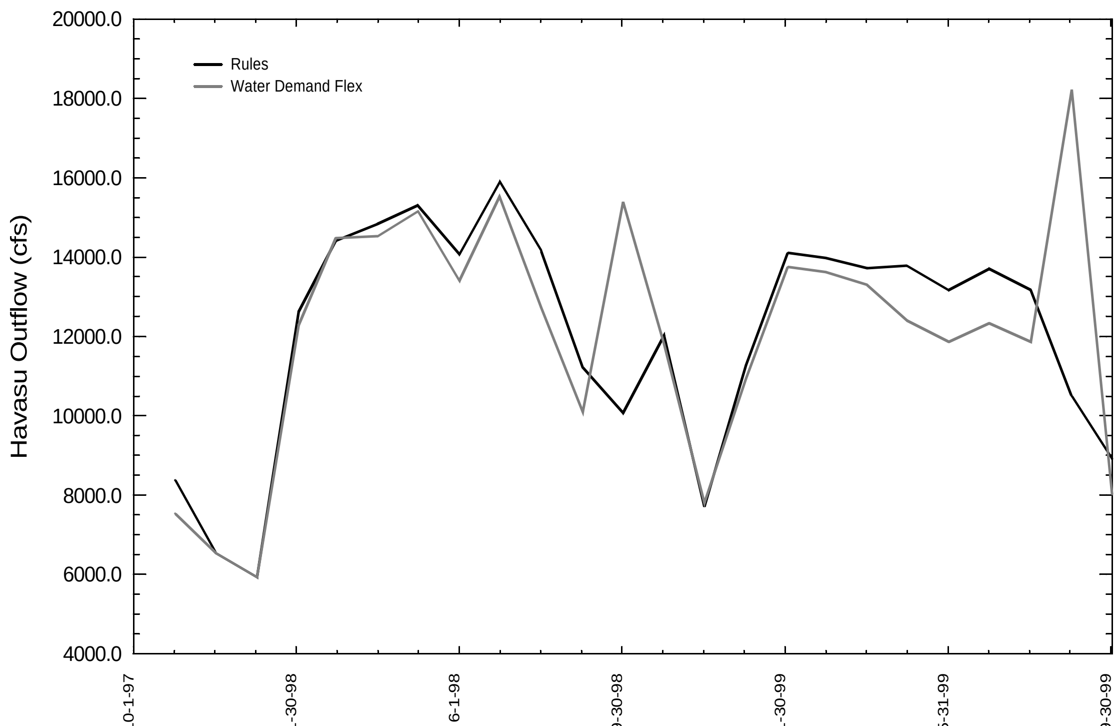


Figure 22: Water Demand Flexibility I: Mead and Havasu Outflows

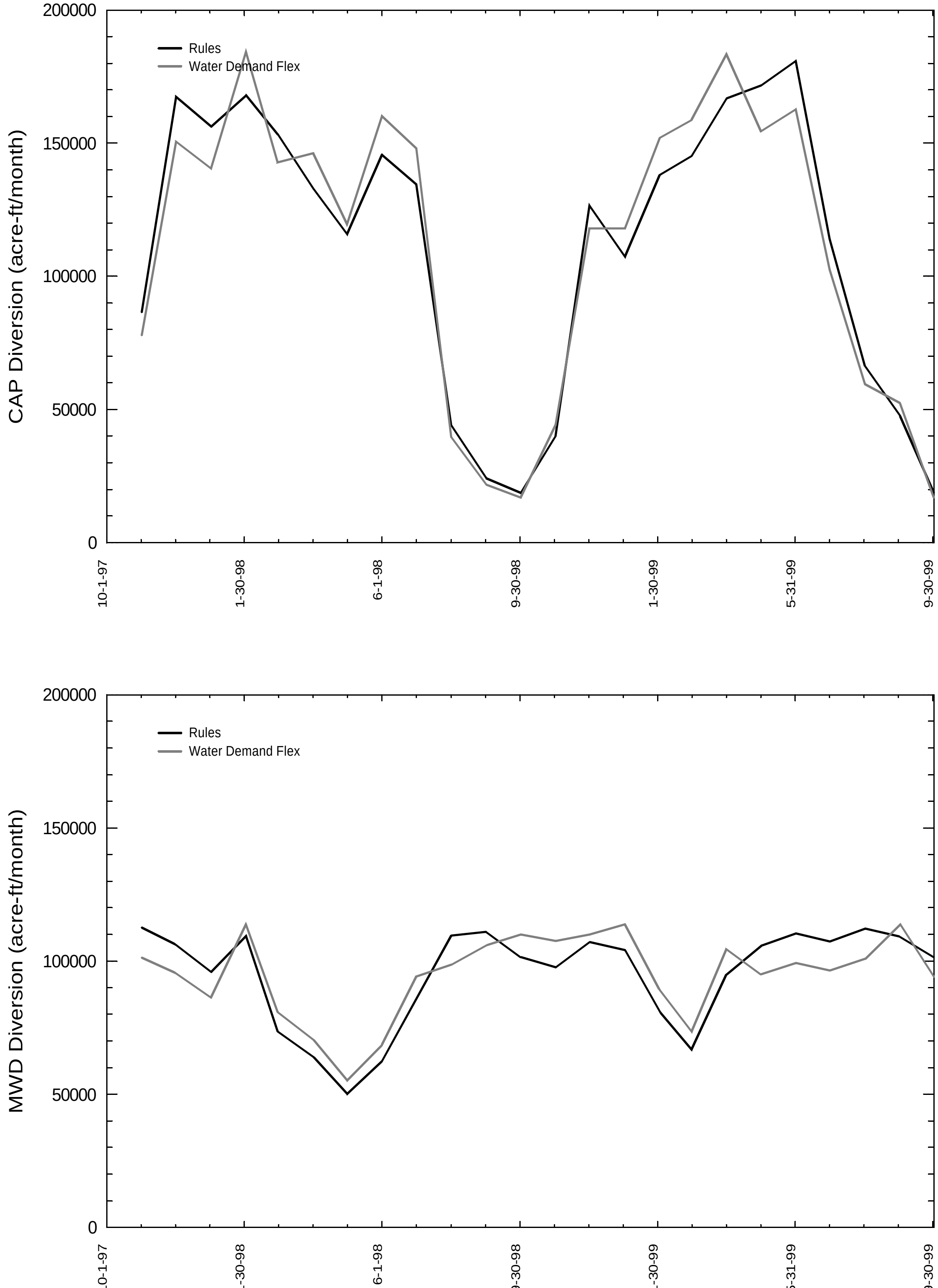


Figure 23: Water Demand Flexibility II: CAP and MWD Diversions

Spacebuilding Flex

Recall that in the space building case, the flood control policy ensures that a specified monthly amount of storage is available. This is a requirement for storage space in Mead, but the requirement can be reduced if there is available space in the Upper Basin reservoirs. In the rule based simulation, and in the optimization replication of it, the outflow from Mead is during August through December is the minimum of the outflow necessary to meet this target at the current month, or is the outflow to meet demand. This was accomplished in the previous chapter by minimizing the outflows from Havasu, one timestep at a time, decreasing in priority as the timestep increases. To allow flexibility in the timing of the space building releases, this requirement was relaxed, and these flows could occur at any time, as long as the space building requirement was fulfilled.

Further, the requirement that the sum of the outflows be constant over the water year was relaxed to make the sum of the outflows over the entire run a constant, and a constraint was written to keep the sum of the flows from August - December constant. This allowed the space building season, which is split over two water years, to be viewed as a single requirement. Lastly, the flood control minimum outflow requirement from Mead (Equation IV-6) was removed for the August through December season. The value produced from this scenario was 193.7 million dollars per year.

This result (graphed in Figure 24) is the simplest to understand of all the scenarios, because it involves only Lake Mead. The flexibility only occurred in the fall of 1998 for two reasons. First, the other spacebuilding seasons (October - December 1997, and August - September 1999) are only parts of the whole season (August through December). Second, the rules and the optimization did not make space building releases during those times, and therefore no flexibility was available.

For the last two scenarios, a constraint was added to require that Mead’s outflow be below 28,000 cfs in any month. This constraint was included because of the nature of this analysis. The maximum turbine release from Mead is approximately 45,000 cfs, depending on head and unit availability. The 28,000 cfs number was derived given that a base flow of approximately 3,500 cfs is required. Given that the energy values are for peaking power, it is unrealistic to expect peaking power value for more than approximately 420 hours a month. This results in a monthly average outflow maximum of approximately 28,000 cfs.

Combined Flex

This scenario included all the flexibility discussed in the previous sections: 15 feet of latitude in Lake Mohave's pool elevation, 1 foot of latitude at Lake Havasu, 10% flexibility in meeting water demands, and the spacebuilding relaxation. The value from this scenario was 203.3 million dollars per year.

Max HP

This scenario included all the changes of the Combined Flex scenario, and also removed the flood control minimum release requirement, the spacebuilding storage requirements, and the spring flood control constraint (Equation III-8). The value from this scenario was 219.9 million dollars per year.

These last two scenarios (graphed in Figure 25) generated the greatest hydropower values. Such wildly fluctuating flows and elevations are probably unrealistic. As noted previously, Mead's outflow was limited to 28,000 cfs for these runs to keep the valuation of power reasonable. Also note that Mohave's maximum pool elevation is 647 feet.

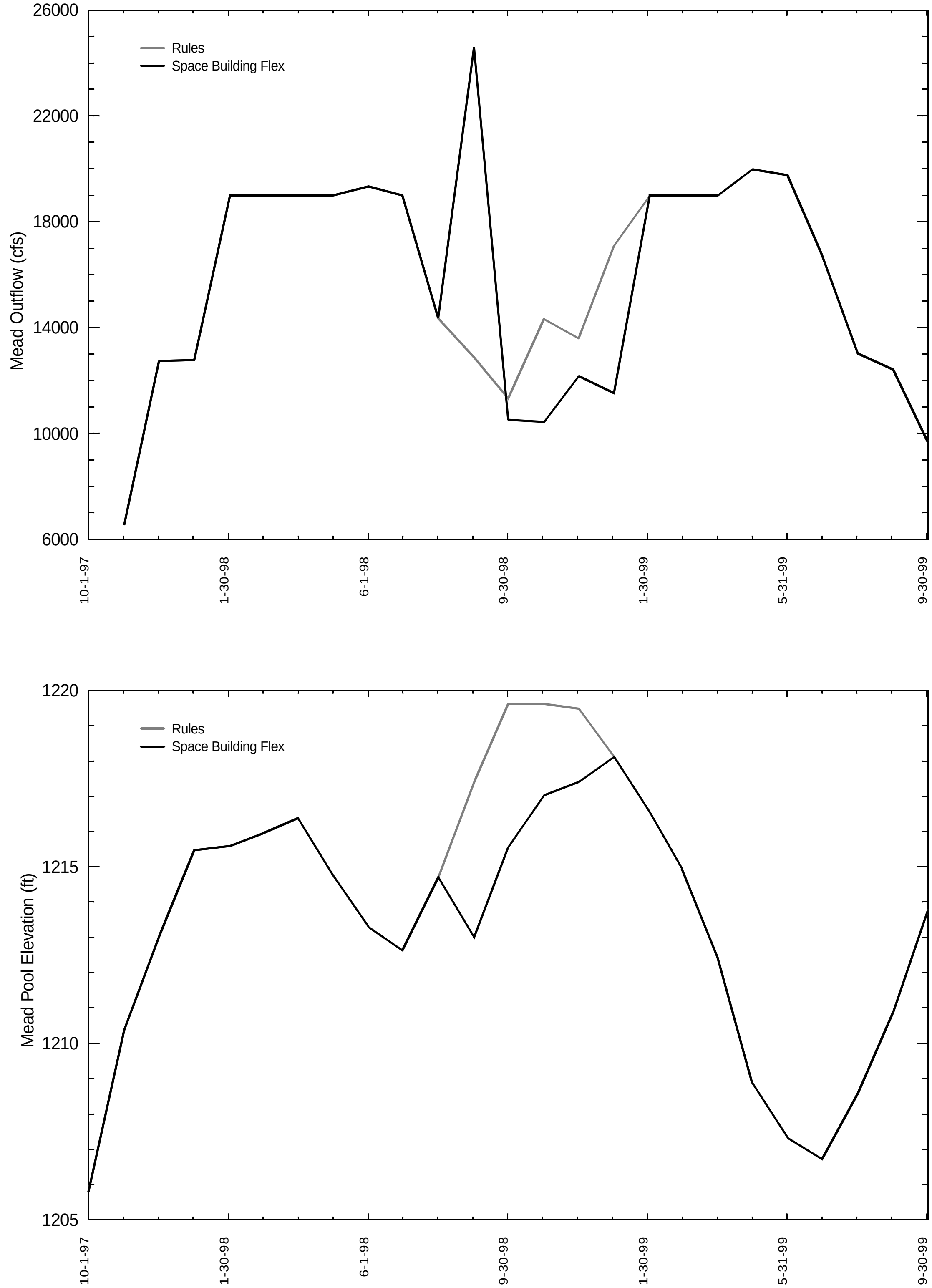
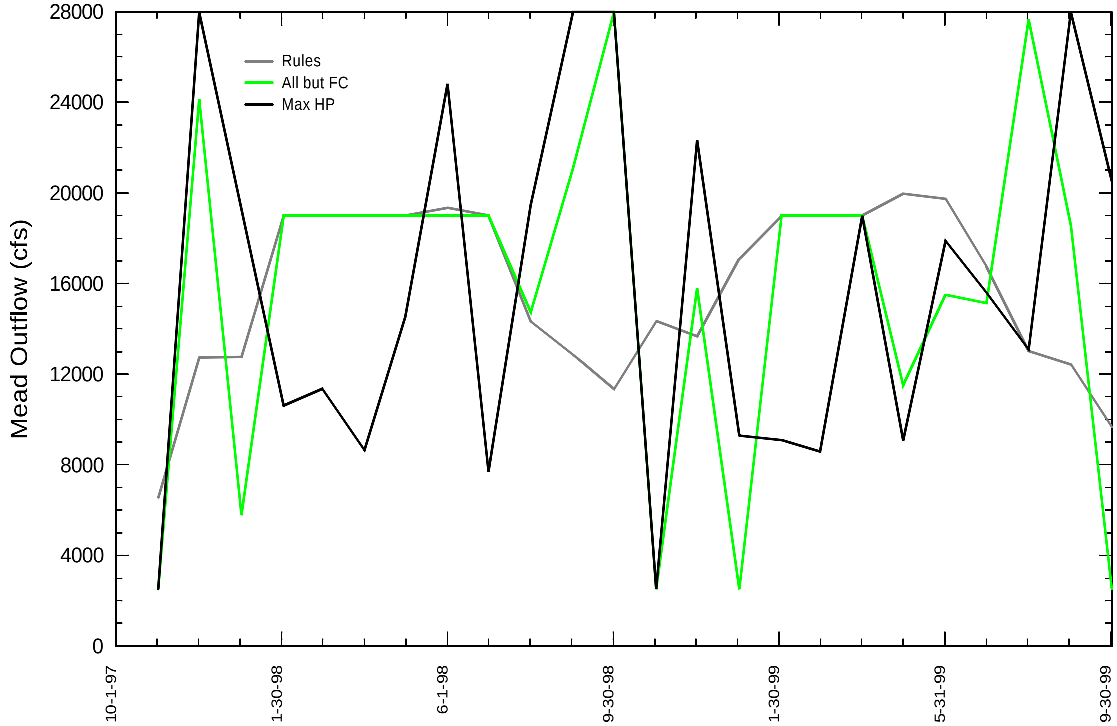


Figure 24: Space Building Flexibility



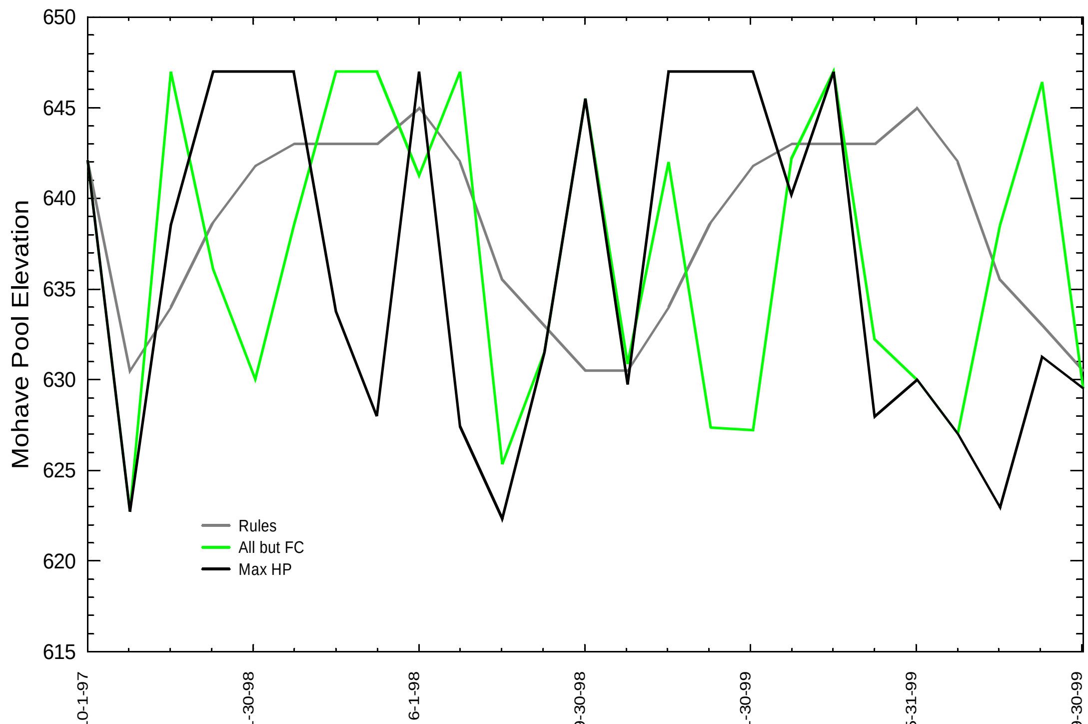


Figure 25: Combined Flex and Max HP Results

Discussion

There are a multitude of other objectives and values which have not been represented, including agriculture, environment, recreation and tourism. While these have not been quantified, an attempt at a qualitative indication of how they might be effected by the alternate scenarios compared to the rules result is contained in Table 14.

Table 14: Annual Energy Values and Scenario Effects[a]

Scenario	Simulated Average Annual Energy Value, (millions of US dollars)	Percent Increase Over Rules	Agriculture	Recreation	Environment
Actual Operations[b]	203.1	6.14%	--	--	--
Baseline	191.4	--	--	--	--
Rule Curve Flex, Havasu 1 ft.	192.2	0.4%	<>	v	v
Rule Curve Flex, Mohave 1 ft.	192.6	0.6%	<>	v	v
Rule Curve Flex, Mohave 3 ft.	194.2	1.4%	<>	v	v
Rule Curve Flex, Mohave 5 ft.	195.8	2.3%	<>	v	v
Rule Curve Flex, Mohave 10 ft.	198.9	3.9%	<>	v	v
Rule Curve Flex, Mohave 15 ft.	200.1	4.6%	<>	v	v
Water Demand Flex, 10%	195.6	2.2%	v	<>	^
Space Building Flex	193.7	1.2%	<>	<>	<>
Combined Flex	203.3	6.2%	v	v	v
Max HP	219.9	14.9%	v	v	v

a. v is a relative decrease, ^ is a relative increase, <> is neutral, and -- is not evaluated
b. The actual operations releases 3.46% more water from Mead than the rules operation, but only 2.16% from Havasu.

For the purposes of this table: Recreation is adversely effected by rapidly varying reservoir elevations and flows. Agriculture is adversely effected by water shortages. Environment is adversely effected by many things, and is diverse enough that one area’s increase may be another’s decrease. However, it can be generally stated that more water to the Gulf of California is a good thing for the environment and rapidly varying flows and reservoir elevations are bad for the environment.

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 14. A marginal analysis was conducted with the rulebased simulation outflows 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 (19.03 $/acre-ft), 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 Spacebuilding 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. The water would need to be released anyway, so releasing it where a 1.1% gain in the annual hydropower value can be found makes sense. When the system is not as full as for this analysis, spacebuilding is not required, and therefore there would be no ability to gain this benefit.

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.

The fact that both future energy prices and hydrologic inflows are stochastic in nature is acknowledged, but this was not addressed explicitly in this study. However, some discussion is warranted. The uncertainty in the energy values was examined using the daily trading history for the futures contracts beginning with the February 1999 contract. The available data is sufficient to understand some of the uncertainty in these prices. In Figure 26, representative trading histories for the recent completed contracts have been graphed. The black boxes in this figure represent the closing prices for several representative months, and are the prices used in this analysis. The contract for April is representative of the price histories for February through May. Note the volatility represented by the months June through September, when power is at its highest value. This uncertainty would have a large effect on the decision to release water to maximize the hydropower value.

The Colorado River experiences large variabilities in flow from year to year. As noted earlier, the natural flow at Lee's Ferry, AZ, has varied between 5 and 24 MAF annually since 1906, with an average of 15 MAF, and a standard deviation of 4.36 MAF. Such variability in both the quantity and timing of the inflows has a significant impact on operational decisions. This uncertainty was not explicitly considered in this work, but would need to be included in the operational application.

The historical initial condition on September 30, 1997 on the Colorado River was just over 90% full. For this reason, both spring and fall flood control had effects on the system. Therefore, flexibility using these rules was possible. With a lower initial condition, the water released from Lake Mead would be strictly to meet water demand. This case might not give opportunities to explore flood control flexibility, but would provide a chance to investigate the effect of water demand and rule curve flexibility in a less complex scenario.

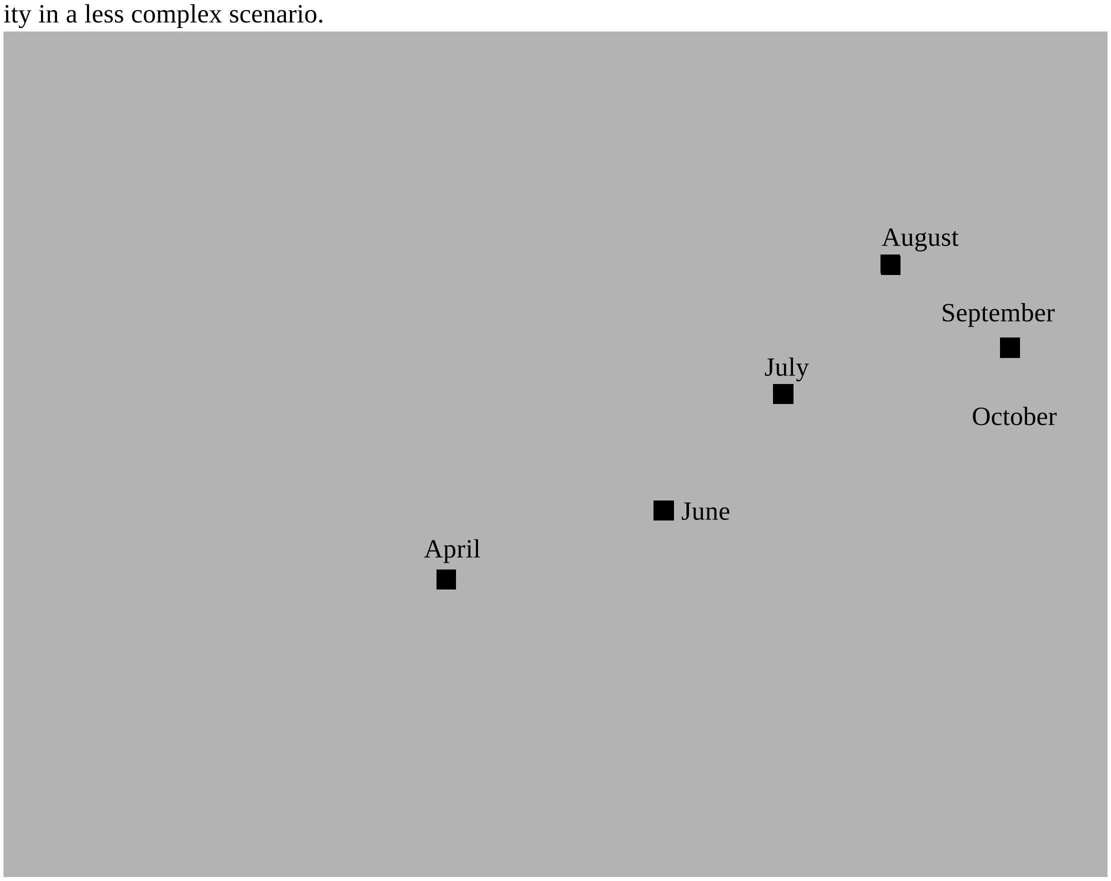


Figure 26: Three Month Histories of Representative Energy Futures Contract Prices

Conclusion

The optimization model developed in the last chapter 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.

Chapter V: Conclusions and Future Work

This thesis has explored the usefulness of pre-emptive goal programming to replicate and analyze policies of the Colorado River. A literature review showed that monthly optimization has rarely been tried, and has not succeeded in replicating the “Law of the River.” Simulation models, on the other hand, have been successful but cannot prescribe operations to best fulfill some set of objectives. A set of constraints was built that replicated the results of the policy in the current 24 Month Study model, and also included operations at Powell, including equalization. The pre-existing optimization solver in RiverWare was extended to include diversions and improved three-dimensional linearization algorithms. Flexibility in the Lower Basin was confirmed by looking at the historical record and the constraint set was then used to find improved operations in terms of hydropower generation value, given varying scenarios of flexibility in the system. These scenarios produced increases in the hydropower value between 0.4% and 14.9%, without changing the annual amount of water released from Mead or from the entire Lower Basin.

This research has the potential to improve the operation of the Lower Basin system, as well as facilitating further policy analysis. Although many possibilities exist, the work needed to allow practical use of this optimization model is most important.

The most obvious practical use involves the application of this model to the AOP process and operational forecasting. The constraint set could be simplified because it is unnecessarily large in the following sense. A block of constraints are written for a range of time, typically a season or a year. Subsequent seasons or years often have the same constraints, but with a lower priority. In principle, this prioritization of seasons and years could be expressed more concisely. Other constraints might also need to be written, to better reflect ramping rate limits at Mohave, or the complaints of residents along the shores of Lake Havasu. Third, the methodology must gain the confidence of USBR operators, as well as the stakeholders on the river. Although this has often times proved impossible (Yi, 1996), the model developed in this thesis may have a better chance of acceptance, since it is based on the 24 Month study, a model already implemented in RiverWare, and the successful application of this optimization solver by TVA. Further work assessing other goals on the river system would be needed to broaden acceptance of this model.

The uncertainty in the value of hydropower and the effects of the hydropower value forecast should also be considered. One methodology might be to produce a range of possible forecasts of hydropower value and use those much as the current AOP processes uses ranges of hydrologic inflows. Improvements in the forecasts might be made as well, as more history of the spot price auctions expands. Other sources of future price information might also include average values for contract prices over the last month before closing, the Dow Jones COB price index, historical retail industry prices for energy, and fuel prices (coal, gas, oil).

Another research direction is to consider the effects of changing the equalization policy and Upper Basin policies in general. The equalization analysis might have two components: first, the timing of equalization releases, and second, the effect of the equalization policy on costs and other polices. Clearly, the Upper Basin policies must first be codified and included in the rulebased simulations before an optimization model could realistically be applied.

Time-dependent Flexibility in agricultural water demand would also be interesting to incorporate. This would draw on the knowledge of an agriculture scientist, who could specify some of the non-linear processes involved in irrigation/crop return relationships for use in the model.

Finally, there are at least two other directions for possible methodological work that are suggested by this research. The implementation of integer programming into the optimization methodology would allow complete representation of discrete policies, perhaps providing a better reproduction of the combined action of the equalization and Mead flood control policies. Incorporation of stochastic variables to explicitly address the uncertainty of hydrology and energy values might also be helpful. However, both of these directions would involve substantial work.

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APPENDIX A. Simulation Model Summaries

A. 24-Month Study (24MO)

Description: 24MO was a monthly timestep operations model which included the entire Colorado River basin, but with much less detail than the CRSS model. It was typically run for a period of two years to set monthly target releases and lake elevations for the major reservoirs. The flood control policy at Lake Mead was the only policy contained in the model. The 24-Month Study did not track TDS (Fulp et al. 1991, Stevens 1986).

Intended Use: Prior to the start of each water year, the 24-Month Study was used to set an Annual Operating Plan using different hydrologic scenarios for inflows (typically most probable, probable minimum, and probable maximum). The model was used to revise that plan throughout the year as hydrologic forecasts were updated.

Acceptance: The 24-Month Study was the accepted model for use in setting monthly operations on the Colorado River. In 1997, it was replaced by a new monthly operations model implemented by the USBR using the RiverWare^{TM} modeling system.

Limitations: As a derivative of the CRSS code, the 24-Month Study had the same hardwired limitations. Again, this limitation has been overcome with the use of RiverWare.

B. Binary Hoover Operations Study (BHOPS)

Description: BHOPS was a operations simulation model used by the USBR that ran on a daily timestep for 4 to 6 weeks. The FORTRAN-based model could operate in energy demand, diversion demand, or flood control driven modes. (Stevens 1986).

Intended Use: BHOPS was used to schedule releases for the Lower Basin dams, especially Davis and Parker. Using monthly targets, as set by the 24-Month Study, daily operations were determined using this model. Energy and flood control release forecasts were also an important output from the model.

Acceptance: The USBR used this model as part of daily operations for many years. It has recently been replaced by a new model using RiverWare.

Limitations: The old BHOPS model was a hardwired, site specific model.

C. Colorado River Simulation System (CRSS)

Description: CRSS was a policy and planning model developed and used by the USBR in the 1970s through the early 1990s. It modeled the entire Colorado River basin on a monthly timestep for typical time horizons of 50-70 years to track the quantity of water throughout the system and the quality of the water with respect to salinity (total dissolved solids, or TDS). A feature of CRSS was that the system incorporated operational criteria that had been established to satisfy certain legislative requirements (the Law of the River). CRSS is the “base” model for CRSSez, the 24-Month Study, CRMM, and CRM, all described below (Zagona et al. unpublished paper; Ouarda et al. 1997; Nash and Gleick 1993; Merritt 1993; Kendall and Dracup 1991; Mohammadi et al. 1991; Schuster 1989; Oamek 1988; Cowan et al. 1981).

Intended Use: CRSS was used to assess the long-term effects of various operational strategies, basin development plans, and water usage plans on the Colorado River basin. CRSS was also used to forecast future energy yield for rate and repayment analysis and to assess the need for future salinity mitigation measures.

Acceptance: CRSS was the accepted model for use in long-term planning studies on the Colorado River basin. In 1996, it was replaced by a new Colorado River basin policy and planning model, implemented by the USBR using the RiverWare modeling system.

Limitations: CRSS was “hardwired” with respect to the operating rules that were used to govern the simulation, making the study of new policies virtually impossible. The new CRSS model in RiverWare overcomes this limitation due to RiverWare’s rulebased simulation option.

D. CRSSez

Description: CRSSez was developed to by the USBR's Lower Colorado regional office in the early 1990s. It is an annual timestep model that tracks water quantity. CRSSez spatially aggregates the Upper Basin (the Green, San Juan, Gunnison and Upper Colorado Rivers) into a virtual basin with one inflow point and one reservoir. It models the interaction of Lakes Powell and Mead, as well as the operation of the other Lower Basin reservoirs (USBR 1998).

Intended Use: CRSSez was developed primarily to facilitate Lower Basin surplus and shortage policy studies.

Acceptance: CRSSez has been used extensively in the past few years by the USBR and other interested parties for Lower Basin studies. One major advantage is that the model runs very quickly on desktop computers.

Limitations: Due to the spatial aggregation, CRSSez is not used for Upper Basin studies. The operating policies are hardwired in the source code, limiting the ability to modify them.

E. Colorado River Model (CRM)

Description: CRM was developed by Hydrosphere, Inc. to mimic CRSS, while allowing some policy flexibility and presenting a graphical-user interface. CRM uses the "out-of-kilter" algorithm to solve the river network (Harding et al. 1995; Sangoyomi and Harding 1995; Brown et al. 1988).

Intended Use: CRM was used for several policy studies, including the Severe Sustained Drought (SSD) investigation.

Acceptance: The CRM mimicked CRSS while allowing for some policy flexibility by adjusting the network capacities.

Limitations: CRM had some of the limitations of CRSS. Also, a network algorithm's efficiency rapidly decreases when non-network constraints are added.

F. Colorado River Microcomputer Model (CRMM)

Description: CRMM was built to mimic the USBR's CRSS model, while allowing model runs on a desktop computer. It used the demand and hydrology data from CRSS, but aggregated them to decrease the computing power needed (Mohammadi 1989).

Intended Use: The Metropolitan Water District of Southern California built this model for internal use.

Acceptance: While it is unknown how useful this model once was, it is no longer in use.

Limitations: CRMM had all the of limitations of CRSS plus the limitations of aggregation (mostly of many diversions into a single diversion), and also had problems mimicking CRSS's sedimentation routines. CRMM did not track TDS.

G. Neff - MITSIM application

Description: MITSIM was a generalized monthly river basin simulation model designed for planning of river basin development projects. The model was extended to allow for the modeling of prior appropriation doctrine of water rights on a monthly timestep (Neff 1987).

Intended Use: MITSIM was altered to be able to model water allocation on the Gunnison River.

Acceptance: This research was theoretical.

Limitations: The application was geographically limited. The complete Law of the River was not modeled.

H. Weiss - MODSIM application

Description: MODSIM is a well-respected generalized river basin simulation model based on the "out-of-kilter" network flow algorithm. MODSIM is used to simulate the allocation of water supplies in a river basin with observance of the prior appropriation doctrine of water rights and other legal constraints (Weiss et al. 1997).

Intended Use: The MODSIM tool was used to analyze environmental impacts of proposed hydropower development on the Gunnison River.

Acceptance: This application of MODSIM had only one intended use; the results were compared against the model that the USBR used to generate the Environmental Impact Statement for a proposed development. This research was theoretical.

Limitations: This application was geographically limited. Again, network flow algorithms become less efficient as non-network constraints are added.

I. RIVER I

Description: RIVER I was a simulation model of water rights on the Piney and Eagle Rivers. The model determined the virgin flow at several points and then determined what the effect of senior water rights would be on the available flow (Michel and Oliger 1975).

Intended Use: The model was used to determine available water for diversion to Denver.

Acceptance: Based on the output of this model, several configurations of diversion structures, reservoirs, etc. were considered as possible solutions for Denver's water needs.

Limitations: The model was geographically limited; it only modeled portions of the Law of the River.

J. RiverWare Applications

Description: RiverWare is a generalized riverbasin simulation and optimization modeling tool. Three FORTRAN models previously discussed (CRSS, 24-Month Study, BHOPS) have been reimplemented in RiverWare by the USBR. These replacement models have been at different timesteps, and utilized both rulebased and strict simulation solution mechanisms for mimicking the results of the old models (Zagona et al. unpublished paper).

Intended Use: These models support a hierarchy of decisions on the Colorado River, including long-range policy and planning (CRSS), mid-range operations (24-Month Study), and short-range operational scheduling (BHOPS). The models built using RiverWare are intended to replace—and reproduce—the older models, while allowing for easy alteration and improvements in modeling technique and policy in the future.

Acceptance: The new long-range planning model was adopted by the USBR and interested stakeholders in December 1996. The mid-range operations model has been in use since November 1997. The Lower Colorado short-range operations model is currently in beta-testing.

Limitations: As a first phase, these models were implemented to mimic the results of the old models and are, therefore, limited to the same spatial and temporal resolutions. None of the models are currently run in optimization mode.

K. River Simulation System (RSS)

Description: This model was a simulation model of the Colorado River basin. It could simulate at different timesteps. A case study of the operation of Glen Canyon Dam for five conflicting objectives relative to the Grand Canyon was reported (Reitsma and Carron 1997).

Intended Use: RSS was designed to provide decision support to an operator who is required to schedule monthly releases based on inflow forecasts to maximize hydropower generation. RSS was a prototype built to investigate the use of an object-oriented decision support system.

Acceptance: RSS successfully demonstrated the advantages of an object oriented-decision support system and was delivered for use to the USBR.

Limitations: The lack of flexibility and full functionality, associated with any prototype, was this model's major problem.

L. STATEMOD

Description: STATEMOD models stream flow and water rights, and is based on BESTSM (Brazil and Bethel 1994; State of Colorado 1999).

Intended Use: STATEMOD is used as part of a decision support system. The model is used to study the effects of policy decisions and to administer water rights.

Acceptance: Currently, STATEMOD is used by various Colorado state institutions. It can be used to simulate only portions of the river.

Limitations: STATEMOD does not perform time lag routing, and is specific to the State of Colorado.

M. Hyatt - Dissertation

Description: This model was a hybrid analog-digital computer that simulated the Upper Colorado River basin, including salinity. The model used one second to represent a time period of one month (Hyatt et al. 1970; Hyatt 1970).

Intended Use: This model was used to prepare a report on the possible effects of salinity on the system. The specific paper discussing the salinity results is listed separately in the water quality section. These listings are discussing the development of the model.

Acceptance: The technical report produced was accepted by their sponsors.

Limitations: This model was limited to the Upper Basin and had all of the challenges inherent in an analog model.

APPENDIX B. Optimization Model Summaries

A. AZCOL - STELLA II application

Description: AZCOL was a gaming simulation model built in Stella-II, an "interactive simulation modeling tool" (Henderson and Lord 1995; Hardy 1995) developed by High Performance Systems, Inc.

Intended Use: AZCOL was built to simulate a severe drought and provide decisionmakers with feedback on the environmental, societal, and economical consequences of water allocation. It was built specifically to facilitate a gaming simulation of a severe, sustained drought. The researchers attempted to negotiate policy changes to better handle the hypothetical impacts of severe drought on the states they represented.

Acceptance: The model was successfully used as part of the SSD policy study.

Limitations: AZCOL, using a yearly timestep, was used for allocation policy decisions, and not operational issues.

B. Colorado River Gaming Model (COLGAM)

Description: COLGAM was an hourly timestep model running for a one or two week horizon to set the releases from the major dams (Hoover, Davis, and Parker) on the Lower Colorado River basin to maximize the value of the hydropower, while meeting water priorities. It used a heuristic scheme to determine the operational solution (Sheer 1992; Over and Horsey 1990).

Intended Use: COLGAM was envisioned to be a tool used by water schedulers at Hoover Dam, as well as a tool to explore alternative operating policies.

Acceptance: COLGAM was not used in water operations. It was, however, used in a "gaming mode," whereby both water and power schedulers could postulate alternative operating scenarios and see the effects on the system.

Limitations: COLGAM relied on forecasts of the spot market energy prices to determine the "best" schedule, and these prices were very difficult to predict (Fulp 1990).

C. Colorado River Institutional Model (CRIM)

Description: CRIM allocated water according to the Law of the River, while finding economic damages/income due to water allocation. It was written in GAMS, and is solved using MINOS. The allocation of water was driven by a prioritized list of "uses" (Booker 1995; Booker and Young 1994; Booker and Young 1991).

Intended Use: CRIM was used in several research studies, including the SSD investigation.

Acceptance: The model was successfully used in several studies.

Limitations: CRIM used an annual timestep, and policy was hard coded. Some aggregation of reservoirs and diversions was also performed.

D. Colorado State University Dynamic Programing (CSUDP)

Description: CSUDP was used to develop a monthly timestep optimization model of the Colorado River basin to maximize the hydropower production while considering all other operational constraints on the system (Fontane et al. 1986).

Intended Use: CSUDP was envisioned to be used as a tool to assess alternative operating strategies while still maximizing hydropower production.

Acceptance: This model was not used within the USBR; however, several studies were done to assess the limitations on the number of reservoirs that could be included.

Limitations: Due to the computer limitations of the time and the "curse of dimensionality," the model was limited in the number of reservoirs that could be realistically modeled. It was also concluded that although the Law of the River constrains operations, there was still enough flexibility left that the dynamic programming approach was overly time consuming.

E. Liang - Dissertation

Description: This model sought the best-compromise solution for an aggregated reservoir as a surrogate of the multi-reservoir systems by using two methods: the constraint method and the method of combined stochastic and deterministic modeling (Liang et al. 1996a; Liang et al. 1996b).

Intended Use: Two major objectives of this research were: maximization of hydroelectric power production and maximization of the reliability of annual water supply. The research focused on development of optimal multi-criteria operation of the reservoir system.

Acceptance: This research was theoretical.

Limitations: The model's limitations were: Upper Basin only, large amounts of aggregation (both reservoirs and diversions), and development of a static operating policy.

F. Yi - Dissertation

Description: The model used dynamic programming to find the optimal commitment for individual hydropower units on Parker, Davis, and Hoover Dams on a daily or hourly timestep (Yi 1996).

Intended Use: The model produced as a result of this research was installed at Hoover Dam, but not used.

Acceptance: This was initially theoretical research, but an attempt was made to place it into operation.

Limitations: The research was specific to the Lower Colorado River.

G. Stillwater - Paper

Description: This model was a monthly simulation/optimization model of the Upper Basin. The model simulates real-time monthly release decisions for the five major reservoirs (Fontenelle, Blue Mesa, Flaming Gorge, Navajo, and Lake Powell) and four major power plants in the Upper Basin. At each month of simulation a dynamic programming algorithm is called to determine the monthly release volumes for the current month through the next target month (Stillwater 1993).

Intended Use: This model provided decision support to an operator who is required to schedule monthly releases based on inflow forecasts when limited competing water-use objectives exist.

Acceptance: This model was not implemented.

Limitations: This model focused on the Upper Basin only.

H. Behrens - Dissertation

Description: This model was a hierarchical river basin simulation/optimization model that employs object-oriented programming, knowledge-based reasoning, and stochastic programing. At each month of simulation, a stochastic dynamic programming algorithm was called to optimize a single "Upper Basin aggregate reservoir-power plant." The objected oriented simulator, using "intelligent" agents then negotiate among the actual upper basin reservoirs and power plants to produce the overall power suggested by the stochastic dynamic program while preserving the legislated minimum release from Powell. (Behrens 1991; Behrens et al. 1991).

Intended Use: This model used a combination of techniques to investigate the application of object-oriented programming to water resources, and specifically the operation of the Upper Basin of the Colorado River.

Acceptance: The model focused on methodological research, not on accurate physical system modeling.

Limitations : Physical process modeling was restricted. The model used a substantial amount of reservoir aggregation.

I. Cummings - Paper

Description: This modeling effort used dynamic programming to determine the optimal Upper Basin water allocation, using several estimates of the mean and variation of annual flow. A chance constraint was used to control the risk of water shortage. The variables considered were: amount of water allocation, levels of reservoir storage, and income gained or lost due to usage of water (Cummings and McFarland 1977).

Intended Use: This research focused on finding the level of water allocation that balanced regional economic growth and damages due to water shortage. The storage in Upper Basin reservoirs was a key variable.

Acceptance: The results of this study were widely used to describe the need for careful management of Upper Basin water usage.

Limitations: Reservoir storage and releases were state variables, not decision variables.

J. Jensen - Dissertation

Description: This was a simulation model of the Colorado River basin, including Glen Canyon and Hoover Dam operations. “Simulation,” as used here, is the “operations research” meaning of the word; i.e., observe the operation of the system over a long period of time using “stochastic streamflow inputs” in order to determine an “optimal” policy (Jensen 1976).

Intended Use: This model was used to study policy changes and the effect of institutional constraints on the Colorado River basin. One application compared operations based on water supply reliability and current (1975) operational policy.

Acceptance: This research was theoretical.

Limitations: This model used large amounts of aggregation, modeling only Lakes Powell and Mead. It attempted to observe a static operating policy based on various demand and supply states.

K. Myers - Dissertation

Description: This research developed a dynamic programming model of the Colorado River Storage Project, without Navajo Dam, but with Fontenelle Dam added. The primary focus was optimal hydropower generation (Myers, 1975).

Intended Use: The research attempted to find the optimal operating policy for several Upper Basin reservoirs.

Acceptance: The research was theoretical, but based on interaction with USBR personnel.

Limitations: This research was obviously limited to the Upper Basin.

L. Heaney - Dissertation

Description: This research developed an LP model with 4,000 constraints. A wet/dry seasonal timestep was used, and an approximation to a steady state was assumed. A piecewise linearization of the benefits curve was a major feature of the model (Heaney 1968a; Heaney 1968b; Heaney et al. 1967).

Intended Use: The research focus was optimization on the Colorado River basin. The value of water used for agriculture and the effect of water rights on the system were major components of the research.

Acceptance: This work was mostly of theoretical value and was a very large model for its time. It provided a first step for later modeling studies.

Limitations: The model did not consider hydropower. Additionally, wet/dry years were not considered, nor were year upon year effects.

APPENDIX C. Terms Used in Mead Spring Flood Control Policy

The forecasted Mead inflow ($I_{M,t}$ in the 24 Month Study is found from the following equation:

$$I_{M,t} = \sum_{i=t}^{JUL} (UI_{P,i} + G_i) + AI_{M,t} - ES_t \,, \qquad \textbf{(C-1)}$$

where UI is the unregulated inflow forecast into Powell, $AI_{M,t}$ is the additional inflow into Mead that corresponds to a 5% exceedence (from Table 7), G is the gains between Powell and Mead, and ES is the effective space in the Upper Basin flood control reservoirs (Flaming Gorge, Fontenelle, Navajo, and Blue Mesa). The effective space in a reservoir is the lesser of the difference between inflows and outflows until July, or the storage space left in the reservoir. In CRSS, this equation has additional randomness added to it, since the inflow hydrologies are all known.

E is the evaporation from the reservoir, assuming it fills,

$$E_t = \left(\frac{Area_{JUL} + Area_{t-1}}{2}\right) Evap \,, \qquad \textbf{(C-2)}$$

where Evap is the depth of evaporation from the current month till July.

B is the water lost to bank storage,

$$B_t = (S_{JUL} - S_t) Coeff \,, \qquad \textbf{(C-3)}$$

where Coeff is the bank storage coefficient for that reservoir.

APPENDIX D. Shortage/Normal/Surplus Diversion Policy in Optimization

The full CRSS policy for diversions includes determination of surplus and shortage for four sites. MWD and Mexico have normal and surplus requests, while CAP and SNWP have shortage, normal and surplus operating requests.

For the purposes of planning, several criteria for the declaration of surpluses and shortages have been proposed. One of them is the use of Mead's elevation as a trigger. Shortage would be triggered by Mead's elevation falling below 1120 ft. on January 1. If it gets this low, SNWP, and CAP divert only their shortage requests. The triggering of surplus is a highly political issue. However, one criteria might be Mead's elevation higher than 1180 ft. The choice of this elevation is implicitly a choice of preferred reservoir elevation, since if the elevation is higher, more water would be diverted, drawing the reservoir down. If it is lower, less water would be diverted, which may allow the elevation at Mead to rise.

There are several other very unlikely cases that are addressed in various pieces of documentation, including the user involvement group document (USBR 1994). This document states that if Mead is empty, then CAP gets the net inflow into Mead. If CAP diversion = 0, all diversions are shorted, including Mexico. These criteria are very unlikely, and are not modeled in CRSS or the optimization.

When this policy is brought into the optimization, the surplus and shortage criteria generate bounds of the operating region for Mead's elevation and the diversions, as well as the efficiency, if the efficiency is different between the schedules.

The orthogonal constraints in this setup use five priority levels with constraints on pool elevation at Mead and the diversions.

1) $$Elev_M \le 1219.61 ft \qquad \textbf{(D-1)}$$

2) $$E_{M,t} \ge 1083 ft \qquad \textbf{(D-2)}$$

3) $$Div_{LBA,t} \ge DivShort_{LBA,t} \qquad \textbf{(D-3)}$$

3) $$Div_{LBA,t} \le DivSurp_{LBA,t} \qquad \textbf{(D-4)}$$

Flood control provides the first constraint. The second constraint comes from the shortage trigger elevation. The shortage and surplus requests provide the second. At the priority level above flood control 28,000 cfs,

$$\textbf{4)}\ Div_{LBA,\,t} \geq DivNorm_{LBA,\,t} \qquad \textbf{(D-5)}$$

And at some low priority level:

$$\textbf{5)}\quad E_{M,\,t} = 1180ft \qquad \textbf{(D-6)}$$

This constraint works to drive diversions to surplus or to normal requests. This is possible because the reservoir will release lots of water trying to get to 1180 from above, and therefore the diversions will get surplus water. Conversely, the reservoir will hold back water from being diverted when trying to get to 1180 from below, and therefore the diversions will get their normal requests. This is why picking a trigger elevation for surplus strategies implies a “preferred elevation” on Mead.

Here is a graphical representation of the optimization part of this:

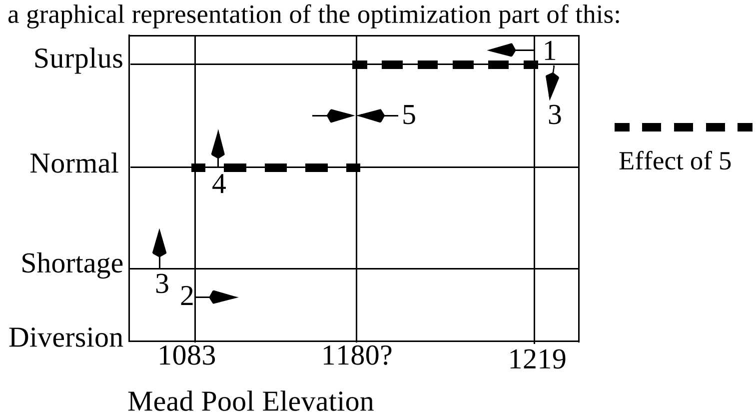

Figure 27: Optimization Constraints for Shortage/Normal/Surplus Diversions

In this case, it is good that the LP solver in use will push the diversion to it’s extreme points instead of balancing between diversion and elevation, since it will drive the diversion along the dashed paths while driving the Mead’s elevation towards the middle.

If the efficiencies change between the schedules, then an additional set of constraints would be useful to shrink the area to be considered by the optimization. Further, the nonlinear efficiency set, where depletion is also a variable would be used. The minimum and maximum efficiencies could be generated from the surplus and shortage schedules, and constraints could be added for them for them, as below:

- physical (priority -1):

$$depletion \leq \left(\frac{maxeffdepletionRequest}{maxeffdiversionRequest}\right) diversion \tag{D-7}$$

$$depletion \geq \left(\frac{mineffdepletionRequest}{mineffdiversionRequest}\right) diversion \tag{D-8}$$

APPENDIX E. Diversions on the Colorado River

Because the optimization solution in Riverware was originally developed for TVA, it did not include diversions. While diversions do occur on the Tennessee River, they have a very minor effect on the system. However, on the Colorado River, diversions play a large role in the operation of the system. Therefore, to allow this thesis research to occur, diversions had to be added into the optimization.

First, I summarize the simulation methods available in Riverware for diversions. Second, I discuss how diversions were implemented for this work. Lastly, how to handle the remainder of the diversion methods, and an even more non-linear method is discussed.

Simulation Summary:

Definition of Terms: (all can be functions of time)

Diversion: Amount removed from the river/reservoir.

Diversion Requested: Amount of diversion desired.

Available Water: Amount of water available to be diverted. Either the total flow in the river possibly minus some minimum outflow, or total storage at the previous timestep in the reservoir.

Depletion: Amount of water removed (depleted) from the system. Also known as consumptive use.

Depletion Requested: Amount of depletion desired.

Return Flow: Amount of water returned to the system after being diverted and depleted.

Efficiency: $\frac{depletion}{diversion}$

Maximum Efficiency: maximum value of efficiency. Cannot exceed 1.

Fraction Return Flow: $1 - efficiency$

Schedule: Diversion and Depletion requests stored on a data object.

Shortage Schedule: lowest level of water usage, highest efficiency.

Normal Schedule: middle range.

Surplus Schedule: highest level of water use, lowest efficiency.

Dispatching

The basic mechanism for diverting water from a reach or reservoir is to link the diverting object to the reach or reservoir as follows:

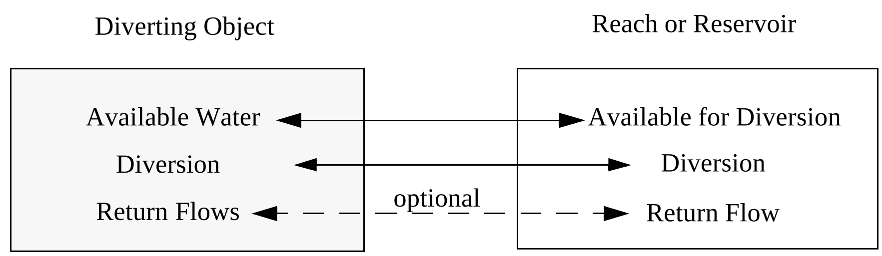

Figure 28: Structure for Linking Diversions

Summary of Dispatch Sequence:

1. Reach or Reservoir solves for Available for Diversion, then exits.
2. Diverting object solves all methods including Diversion and Return Flow.
3. Reach/Reservoir resolve, this time completing the mass balance.

The dispatch method for the object on the right executes first and sets a value for available for diversion based on the inflow for a Reach or the storage for a Reservoir. The dispatch does not complete, but exits to allow the diverting object to solve. The diverting object receives a value for available water via link propagation. This causes it to execute its dispatch method, solving for diversion and return flow. These values are propagated via links back to the Reach or Reservoir object. These objects can now solve their mass balance because they know the diversion and return flow values.

Depletion and Return Flow Calculations

Equations in Use:

$$diversion = min(diversionRequest, availableWater) \qquad \textbf{(E-1)}$$

$$returnFlow = diversion - depletion \tag{E-2}$$

$$depletion = efficiency \times diversion \tag{E-3}$$

There are two ways to determine efficiency in RiverWare.

1. Linear: efficiency is a constant coefficient of diversion.

   Methods specific to RiverWare:

   a) Proportional Shortage, user inputs depletion and diversion requests:

$$efficiency = \frac{depletionRequest}{diversionRequest} \tag{E-4}$$

   b) Fractional Return Flow: user inputs fraction return flow and diversion request.

1. NonLinear: efficiency is a function of diversion.

   Methods specific to RiverWare:

   a) Variable Efficiency, user inputs maximum efficiency, diversion and depletion requests:

$$efficiency = min\left(\frac{depletionRequest}{diversion}, maxefficiency\right) \tag{E-5}$$

For CRSS and for this thesis only the “Proportional Shortage” method is needed.

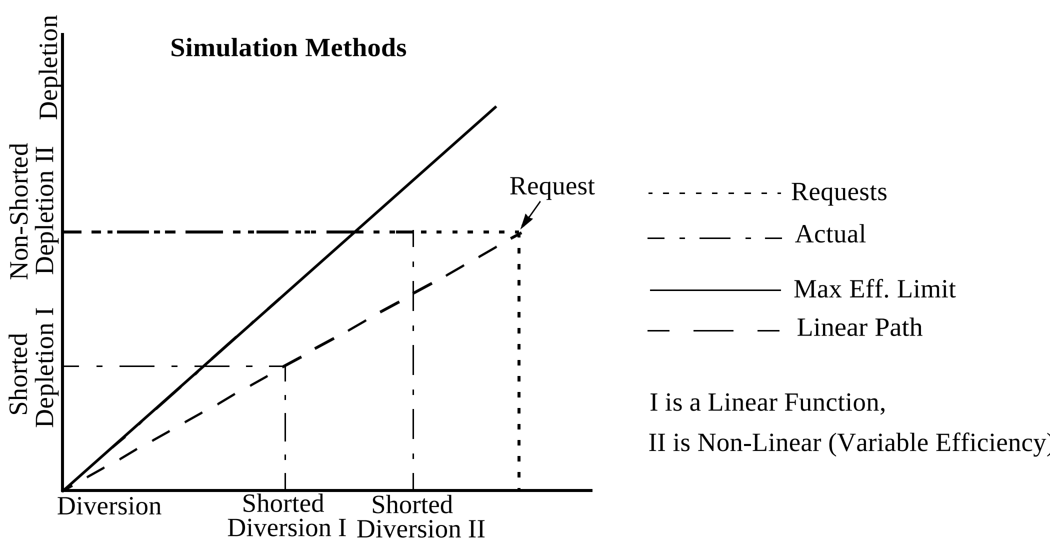

Figure 29: Linear and Non-Linear Shorted Diversion Scenarios in RiverWare

Note that the Variable Efficiency method is really only a piecewise linear method consisting of two line segments. Other more physically based (and probably non-linear) methods may be added in the future. See the last page of this appendix for one such method, and a possible linearization scheme.

Optimization Translation

The behavior of these objects must be translated into appropriate optimization variables, constraints and linearizations. Both physical and policy constraints are needed because the physical constraints cannot be violated, but the policy constraints can. Policy constraints cannot be automatically generated.

Variables:

Variables used in optimization must be carefully picked. Diversion will be always known to CPLEX. Depletion will be known to CPLEX, if a non-linear method is used.

Common constraint:

- physical (priority -1):

$$diversion \leq availableWater \quad \textbf{(E-6)}$$

Linear Efficiency:

Linearizations are:

$$depletion \;=\; efficiency \times diversion \quad \textbf{(E-7)}$$

$$returnFlow \;=\; diversion - depletion \quad \textbf{(E-8)}$$

Nonlinear Efficiency:

For the nonlinear method (variable efficiency), equation C-8 changes to:

- physical (priority -1):

$$depletion \leq (maxeff) diversion \quad \textbf{(E-9)}$$

Additional constraints are:

- policy (priority >0)

priority 1:

$$depletion \geq depletionRequest \quad \textbf{(E-10)}$$

$$depletion \leq depletionRequest \quad \textbf{(E-11)}$$

priority 2:

$$diversion \geq diversionRequest \quad \textbf{(E-12)}$$

$$diversion \leq diversionRequest \quad \textbf{(E-13)}$$

The effect of this set of constraints is to drive the diversion and depletion along the piecewise linear line that is the variable efficiency method.

Possible New Nonlinear Method

Although all of the current diversion methods in RiverWare are either linear or piecewise linear, there is no reason to expect that this will always be the case.

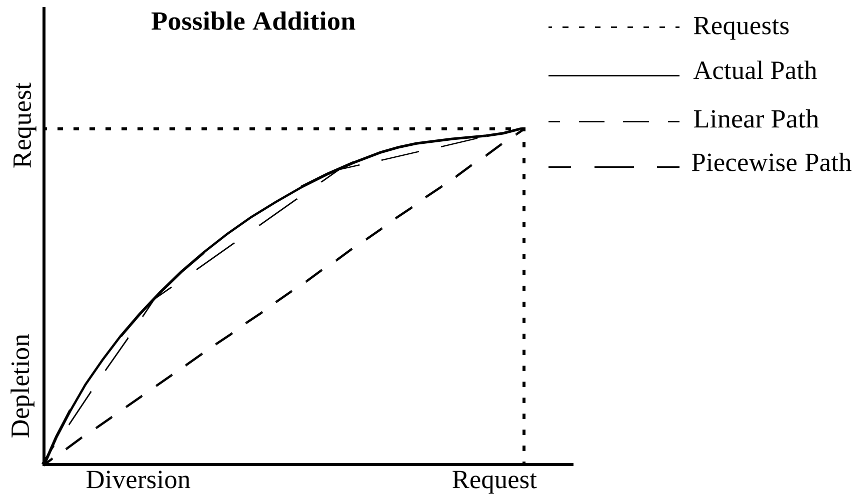

Figure 30: Possible Nonlinear Diversion Method

A method with the relationship between diversion and depletion as the solid line could be approximated by the optimization in two ways. The long dashed line represents a piecewise linearization of the curve and would represent the “depletion upper bound”. The short dashed line is the “depletion lower bound”. In almost all cases, the optimization would follow the upper bound, but in some cases it would “cheat” and choose the lower bound. An example of this might be a “trans-drainage diversion” where the returnflow goes to another drainage where high priority diversions can be fulfilled with the “extra” water. This type of linearization (upper + lower bound) has already been done for spill.

APPENDIX F. Optimization Constraint Set for Matching Rulebased Simulation

These constraints are listed in priority order, highest first. All constraints used in any scenario are listed at the priority where they were used. During the development, the Powell equalization constraints were turned off, and Powell's outflow was user-input.

Spring UB Flood Control Reservoirs (Fontenelle, Flaming Gorge, Blue Mesa, Navajo) Effective Space,
$$ES_{UBFCR,\,t} \le I_{\Sigma} - Q_{\Sigma} \qquad \forall(UBFCR, Jan \le t \le July, t \le \Sigma \le July) \tag{F-1}$$

Exclusive Flood Control Space, $Elev_M \le 1219.61ft$ **(F-2)**

UB Diversions (NIIP, Gunnison Tunnel), $Div_{D,\,t} = DivReq_{D,\,t}$ **(F-3)**

Minimum Objective Release, $\sum_t Q_{P,\,t} \ge 8.23MAF, \forall t \in year$ **(F-4)**

UBRes (includes Fontenelle, Flaming Gorge, Powell, Navajo, Blue Mesa) 602a Storage,
$$\sum_{UBres} S_{UBRes,\,Sep} \ge 602aStorage \tag{F-5}$$

Equalization, $S_{M,\,Sep} \ge S_{P,\,Sep}$ **(F-6)**

Equalization, $S_{M,\,Sep} - S_{P,\,Sep} \le 0$ **(F-7)**

Oct-Dec Min Obj Rel, $Q_{P,\,t} \ge MinObjRel_{P,\,t}$ **(F-8)**

Oct-Dec Powell Rule Curve, $S_{P,\,t} = RuleCurve_{P,\,t}$ **(F-9)**

SNWP Diversion, $Div_{D,\,t} = DivReq_{D,\,t}$ **(F-10)**

Fall 1997 Havasu Demand, $Q_{hav,\,t} = QData_{hav,\,t}$ **(F-11)**

Spring Flood Control,
$$(n-1)QW_t + Q_{M,\,t} \ge FI - SS_{M,\,t} - SS_{P,\,t} - E_{M,\,t} - E_{P,\,t} - B_{M,\,t} - B_{P,\,t} - SND_t \tag{F-12}$$

Spring Flood Control, $Q_M \le 73,000cfs$ **(F-13)**

Spring Flood Control, $QW \le 73,000cfs$ **(F-14)**

Spring Flood Control, $Q_M \le 40,000cfs$ **(F-15)**

Spring Flood Control, $QW \le 40,000cfs$ **(F-16)**

Spring Flood Control, $Q_M \le 35,000cfs$ **(F-17)**

Spring Flood Control, $QW \le 35,000cfs$ **(F-18)**

Spring Flood Control, $Q_M \le 28,000cfs$ **(F-19)**

Spring Flood Control, $QW \leq 28,000cfs$ **(F-20)**

LB Rule Curves, $S_{hav,t} = Curve_{hav,t}, S_{moh,t} = Curve_{moh,t}$ **(F-21)**

LB Diversions, $Div_{D,t} = DivReq_{D,t}$ **(F-22)**

Havasu Demand, $Q_{hav,t} \geq QData_{hav,t}$ **(F-23)**

Combined creditable space, $C_{flam} + C_{font} \leq 1.5075MAF$, **(F-24)**

Fall Spacebuilding, $S_{M,t} - \sum_{UBres} C_{UBres,t} \leq S_{M,max} - RS_t$ **(F-25)**

Minimum Mead Flow for Equalization Match, $Q_{M,t} \geq FCReq_{M,t}$ **(F-26)**

Spring 1998 Flood Control, $Q_M \leq 19,000cfs$ **(F-27)**

Powell Equalization Release 1998,

$$Q_{P,t} = MinObjRel_t + \frac{1}{2(n)} \times ((S_{P,t-1} + I_{\Sigma P} - Q_{\Sigma P} - Evap_P - BankS_P) - (S_{M,t-1} + I_{\Sigma M} - Q_{\Sigma M} - Evap_M - BankS_M - Div_M)) \quad \textbf{(F-28)}$$

Spring 1998 Flood Control, $QW \leq 19,000cfs$ **(F-29)**

Spring 1998 Flood Control, $Q_M \leq 0cfs$ **(F-30)**

August - December Havasu Flow, $Q_{hav,t} = QData_{hav,t}$ **(F-31)**

Spring 1999 Flood Control, $Q_M \leq 19,000cfs$ **(F-32)**

Powell Equalization Release 1999,

$$Q_{P,t} = MinObjRel_t + \frac{1}{2(n)} \times ((S_{P,t-1} + I_{\Sigma P} - Q_{\Sigma P} - Evap_P - BankS_P) - (S_{M,t-1} + I_{\Sigma M} - Q_{\Sigma M} - Evap_M - BankS_M - Div_M)) \quad \textbf{(F-33)}$$

Spring 1999 Flood Control, $QW \leq 19,000cfs$ **(F-34)**

Spring 1999 Flood Control, $Q_M \leq 0cfs$ **(F-35)**

Havasu Flow, $Q_{hav,t} = QData_{hav,t}$ **(F-36)**

Min Obj Rel, $Q_{P,t} \geq MinObjRel_{P,t}$ **(F-37)**

Powell Rule Curve, $S_{P,t} = RuleCurve_{P,t}$ **(F-38)**

Min Obj Rel, $Q_{P,t} \leq MinObjRel_{P,t}$ **(F-39)**

APPENDIX G. Optimization Constraint Set Used in Analysis:

These constraints are listed in priority order, highest first. All constraints used in any scenario are listed at the priority where they were used. Some of these were turned off for some scenarios. Further, the value of “X,” the amount of flexibility to be given, was altered separately for the Mohave and Havasu rule curves and the MWD, CAP, and Havasu demands.

Spring UB Flood Control Reservoirs (Fontenelle, Flaming Gorge, Blue Mesa, Navajo) Effective Space,
$ES_{UBFCR,\,t} \le I_{\Sigma} - Q_{\Sigma} \qquad \forall(UBR,\, Jan \le t \le July,\, t \le \Sigma \le July)$ **(G-1)**

Exclusive Flood Control Space, $Elev_{M,\,t} \le 1219.61ft$ **(G-2)**

UB Diversions (NIIP, Gunnison Tunnel), $Div_{D,\,t} = DivReq_{D,\,t}$ **(G-3)**

SNWP Diversion, $Div_{D,\,t} = DivReq_{D,\,t}$ **(G-4)**

Havasu Outflow Sum 1998 and 1999, $\sum_t Q_{hav,\,t} = \sum_t OptResult_{hav,\,t}, \forall t \in year$ **(G-5)**

Fall 1997 Havasu Flow, $Q_{hav,\,t} = QData_{hav,\,t}$ **(G-6)**

Spring Flood Control,
$(n-1)QW_t + Q_{M,\,t} \ge FI - SS_{M,\,t} - SS_{P,\,t} - E_{M,\,t} - E_{P,\,t} - B_{M,\,t} - B_{P,\,t} - SND_t$ **(G-7)**

Maximum Mead Flow, $Q_M \le 28,000cfs$ **(G-8)**

Mohave and Havasu Rule Curves, $E_{R,\,t} \ge Tar_{R,\,t} - X$, $E_{R,\,t} \le Tar_{R,\,t} + X$, $\forall t$ **(G-9)**

LB Diversions, $Div_{D,\,t} \ge (1-X)DivReq_{D,\,t}, Div_{D,\,t} \le (1+X)DivReq_{D,\,t}$ **(G-10)**

LB Delivery Sum 1998 and 1999, $\sum_t Div_{D,\,t} = \sum_t DivReq_{D,\,t}, \forall t \in year$ **(G-11)**

Havasu Demand, $Q_{hav,\,t} \ge (1-X)QReq_{hav,\,t}$ **(G-12)**

Combined creditable space, $C_{flam} + C_{font} \le 1.5075MAF$, **(G-13)**

Fall Spacebuilding (UBRes includes Fontenelle, Flaming Gorge, Powell, Navajo, Blue Mesa),
$S_{M,\,t} - \sum_{UBres} C_{UBres,\,t} \le S_{M,\,max} - RS_t$ **(G-14)**

Minimum Mead Flood Control Flow, $Q_{M,\,t} \ge FCReq_{M,\,t}$ **(G-15)**

Mead Sum 1998, $\sum_t Q_{M,\,t} = \sum_t OptResult_{M,\,t}, \forall t \in year$ **(G-16)**

Havasu Flow, $Q_{hav,\,t} = QData_{hav,\,t}$ **(G-17)**

Mead Sum 1999, $\sum_{t} Q_{M,t} = \sum_{t} OptResult_{M,t}, \forall t \in year$ **(G-18)**

Energy Value Objective Max: $\sum_{t}\left(\sum_{LBR} EnergyPrice_{t}(Energy_{LBR,t})\right)$ **(G-19)**

APPENDIX H. Other Possible Policy Flexibility Formulations

Spring Runoff Flood Control Flexibility

Although this policy would be very institutionally difficult to change because of the inter-agency agreement between the USBR and the Corps of Engineers, it would be interesting to see what the effect of some flexibility would be. The effect of the current policy is usually that January Mead outflow is fairly high, in expectation of high flows, but as the forecast is not realized, and the 95% confidence level flow to be added decreases, later months have lower flows required. It can be expected that for the most probable hydrology, a relaxation of this policy would result in higher flows in June and July when hydropower is more valuable than January through March. The risk here is that a large runoff does occur, and higher, even damaging, flows must be released later in the season.

In this case, the flood control policy adds a value to the monthly forecasts that represents the additional flow that a 95% confidence level would be. This currently constant value would be replaced with a new variable. The new variable would be constrained to have the same total sum, and also be within 10% of the data series:

$$AI_t \geq 0.9 Data_t \quad \textbf{(H-1)}$$

$$AI_t \leq 1.1 Data_t \quad \textbf{(H-2)}$$

where:

AI is the additional inflow into Mead used in the flood control policy, and the subscript t is time (month of runoff season from January to July).

$$\sum_t AI_t = \sum_t Data_t, \forall t \in season \quad \textbf{(H-3)}$$