Modeling Water Resources Management Institutions:

An Application to the Truckee-Carson River System

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ABSTRACT

As competition for scarce water resources increases and pressures to reallocate existing water supplies among diverse users rises, so does the need to more accurately represent in water resources system modeling the institutional framework governing regional water allocation. The "institutional framework" most often refers to water use priorities as specified by an existing water rights structure. However, water righted uses are not necessarily the only "prioritized" water uses in a system, nor the only institutional factors. Often, because of historical precedent, force of habit, or judicial or legislative action, non-water righted purposes, such as environmental or recreational uses, gain stature and must be incorporated in system operation plans. Incorporating such institutional constraints in technical analyses is fundamental for reaching a compromise solution in conflict situations.

Network flow programming models have been used to model water rights and water use priorities. However, no systematic approach exists for determining unit penalty coefficients which guarantees proper representation of water right priorities. As part of this research, a general algorithm was developed for determining unit penalty coefficients that preserve water use priorities. The algorithm, which can accommodate both storage and flow related water uses, as well as return flows, is presented as a set of rules that subsequently are formulated as a linear program.

A network flow optimization model, HEC-PRM, was used to evaluate the potential of improving water allocation in the Truckee-Carson system by relaxing several institutional constraints to water management, and relying solely on water use priorities to drive system operations. By removing these constraints and not placing ownership rights on reservoir storage allocations were made in an optimal manner. Also, the effect on water-righted uses of varying priorities assigned to the non-water righted, environmental demands was assessed. The relative priority among the environmental purposes, as well as their priority relative to water-righted uses, was investigated. Trade-offs among the two main environmental purposes are presented and some suggestions for improving water management in the Truckee-Carson basin are made. Improvements to system performance are possible by modifying some of the institutional policies governing system operation.

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CHAPTER 1
INTRODUCTION

Current water use conflicts in the Truckee-Carson Basin, Nevada and California, are representative of issues facing water resource managers and planners worldwide. The sources of these conflicts are varied. Some have origins in the historical development of the basin's water resources, while others stem from changing societal attitudes, values, and concerns towards water resources management, and changes and increases in water use, both of which are exacerbated by hydrologic variability. Regardless of their source, these conflicts are forcing reassessment of the system's operation and management plans, and where possible, the consideration of capacity expansion projects. This research seeks to provide an improved methodology for equitable allocation of limited water supplies in a conflictive environment.

Alternatives for ameliorating conflict, whether parties are actively seeking resolution or not, are shaped largely by the prevailing institutional environment. This is particularly true in the western United States and other arid and semi-arid regions in which traditional supply-side, structural approaches to water development no longer may be adequate or even feasible. In these instances, physical, technical, and, economic constraints are often overshadowed by institutional barriers, and it is these institutional barriers that often determine the fate of proposed solutions. As Butcher *et al.* (1986) note "economics [and engineering] provide an objective, or standard for the allocation of water, the actual outcome of competition between [users] of water depends on the water institutions and significant actors." Nickum (1991) adds "Few conflicts can be resolved in the traditional way by developing unclaimed water supplies…the nature of conflicts is as much institutional in origin as it is technical."

Generally, institutions refer to the rules and organizations that govern the use of water resources in a region. These will include water law, water rights, pricing and allocation rules, and administrative and contractual arrangements. Institutions are often helpful in establishing bounds for framing possible alternatives for the resolution of conflict, but they also may pose severe barriers to implementing otherwise feasible solutions and cast doubt on the outcome of certain alternatives.

Approaches for capturing the increasingly interdisciplinary and institutional nature of water resources management in a quantitative way suitable for decision-making are evolving rapidly. The approaches include, for example, a series of well-coordinated, interdisciplinary studies such as a recent effort in which biologists, engineers, political scientists, and lawyers evaluated the possible effects of a sustained drought on the Colorado River system (Young, 1995).

The Truckee-Carson system is a relatively simple physical system. Institutionally, however, it is one of the more complex river systems in the country. System operation must conform to a myriad of legislative and judicial mandates and decrees. For most of this century conflicts over water use in the Truckee-Carson basin have been the rule rather than the exception. Over the years numerous approaches have been implemented in an attempt to resolve these conflicts. All levels of government - local, state, federal, and tribal - as well as private and non-governmental interests, have at one time or another been involved in the conflict resolution process. However, decades of turbulent relations among the many parties have produced an environment of distrust and uncertainty that has been an obstacle to integrated systems planning and management and equitable allocation of limited water resources. Furthermore, until now all proposed solutions have been constrained to fit within the existing complex institutional framework. A motivation for this study was to evaluate system operation by stripping away many of the institutional constraints, retaining only the water rights structure.

Often the "institutional framework" for water resources management refers to water use priorities as represented by an existing water rights structure, such as the prior appropriation doctrine. However, water righted uses are not necessarily the only "prioritized" water uses in a system, nor the only institutional factors. Often, because of historical precedent, force of habit, or judicial or legislative action, non-water righted purposes, such as environmental or recreational uses, gain stature and must be incorporated in system operation plans. Incorporating such institutional constraints in technical analyses is fundamental for reaching a compromise solution in conflict situations. Network flow programming (NFP) models have been used to model water rights and water use priorities (Labadie, 1995; Andrews *et al.* 1992; Graham *et al.* 1986). However, no systematic approach exists for determining unit penalty coefficients for NFP models which guarantees proper representation of water right priorities. Such an algorithm is developed as part of this research.

Increasingly, the consumptive use sectors are being required, often through litigation or legislation, to surrender some of their water supply reliability to satisfy environmental demands. Recently, however, it has become apparent in the water-scarce West that the urban and agricultural sectors alone are no longer able to provide sufficient water to satisfy the growing environmental demands. Environmental purposes are beginning to compete among themselves for water. In the Truckee-Carson system the principal environmental water demands are inflows to Pyramid Lake to support threatened and endangered species and inflows to Stillwater National Wildlife Refuge to maintain wetland habitat for migratory fowl. Proposed management alternatives for the Truckee-Carson basin must routinely evaluate the water needs of these environmental uses and ultimately may have to choose between them. Several management alternatives are evaluated as part of this research.

OBJECTIVES

This research has two primary objectives. The first is development and implementation of an algorithm for incorporating priority-based penalty functions in network flow modeling that properly reflect institutionally specified water allocation priorities. The second objective of this research is to evaluate potential improvements to water allocation in the Truckee-Carson basin by relaxing some institutional constraints to water management, and to assess the impact on water-righted demands of varying the allocation priority of non-water righted, environmental water demands. Attainment of these objectives should result in improved understanding of the system and the sources of conflict.

ORGANIZATION

Chapter 2 provides a description of the Truckee-Carson system, traces the history of water conflict, the parties involved, and identifies efforts undertaken to resolve these conflicts.

A general algorithm for determining unit cost coefficients to reflect water use priorities within a network flow programming framework is presented in Chapter 3. The algorithm, which can accommodate both storage and flow related water uses, is presented as a set of rules that subsequently are formulated as a linear program. A special feature of the algorithm is the ability to account for the effects of return flow on flow allocation. Return flows introduce a complexity which inhibits the use of intuitive or trial and error methods for determining cost coefficients.

In Chapter 4, results are presented of an analysis of the Truckee-Carson system to assess the potential of relaxing some institutional constraints to improve system performance. The U.S. Army Corps of Engineers Hydrologic Engineering Center's Prescriptive Reservoir Model (HEC-PRM) is used. Existing operation based on satisfying a set of legally mandated flow constraints, known as the Floriston Rates, is compared to operation based solely on satisfying prioritized water demands specified by existing water rights without Floriston Rates. Within this framework, the response of the system to relaxing maximum water surface elevations at Lake Tahoe and closing the Truckee Canal are evaluated. The Truckee-Carson application presented here extends previous applications of HEC-PRM in several ways. First, the analysis is formulated in terms of priority-based penalty functions instead of economic-based functions. Second, a branching system, with multiple diversions from a single node is represented. And, third, return flow components are included for agricultural and municipal uses.

In Chapter 5, analysis of the Truckee-Carson system is extended to include competing environmental demands and the effect on upstream urban and agricultural users of varying the priority of these environmental demands. The relative priority among the environmental purposes, as well as their priority relative to other water-righted uses in the system is investigated, and the trade-offs among the two main environmental purposes are discussed.

Principal conclusions of the research are presented in Chapter 6.

CHAPTER 2
THE TRUCKEE-CARSON SYSTEM

2.1 INTRODUCTION

Among the many stipulations of Section 205 of the Truckee-Carson-Pyramid Lake Water Rights Settlement Act of 1990 (Public Law (PL) 101-618) is that presumably by December 1997 all parties involved with or having interests in the allocation of waters from the Truckee River must reach agreement on criteria for operating the basin's water facilities and allocation of Truckee River supplies. This operating agreement, known as the Truckee River Operating Agreement (TROA), is the latest and most comprehensive effort to resolve water use conflicts in the basin. It is by no means the first effort.

For most of this century conflict over water use in the Truckee-Carson basin has been the rule rather than the exception. Initially, mining interests competed with lumber interests. Later, as agriculture began to flourish in the region, it too entered the competition for water. More recently, urban and environmental interests have staked their claim to the region’s scarce water supplies, while the Pyramid Lake Paiute Indian Tribe attempts to reclaim water rights to the Truckee River for the protection of endangered fish. Over the years numerous and varied efforts have been undertaken to ameliorate these conflicts, including court decrees, legislation, interstate compacts, bi- and multi-lateral agreements, and direct negotiations among the parties. These efforts have relied on a host of management measures, including capacity expansion, modified reservoir operation, improved irrigation efficiency, increased urban conservation efforts, and expansion of existing water markets. All levels of government - local, state, federal, and tribal - as well as private, and non-governmental interests, at one time or another, have been involved in the conflict resolution process. Currently, a multitude of parties representing the major water use sectors are negotiating the reallocation of the basin's water resources through TROA.

For decades, water users in the Truckee and Carson River basins have debated over management of the region’s overextended water resources. Issues involved include administration of legal decrees regarding water use, reclamation law, water rights, the Endangered Species Act, and federal trust responsibilities to Indian tribes and environmental preservation. Today numerous water needs, in addition to the early irrigation needs that drove development of the basin, must be considered in management plans. These additional demands have evolved in response to increasing population, changing societal values, and an increased commitment to environmental and wildlife preservation.

This chapter presents a brief description of the Truckee-Carson system, traces the history of water conflict and the parties involved, and identifies current efforts to resolve these conflicts and some potential constraints to their long-term success.

The Truckee-Carson River basin is a fairly small closed basin straddling the California-Nevada border, yet it has a rich history in issues of interest to water resource planners and managers. Several excellent sources provide additional details on some of the topics mentioned in this chapter, including the history of conflict in the basin (Pisani, 1975; DWR 1991a,b); the basin’s legal history (Kramer, 1988; Scott, 1984); the Pyramid Lake Paiute Indian Tribe (Knack and Stewart, 1984; Townley, 1977) and Indian water law (Brookshire *et al.*, 1985; DuMars *et al.*, 1982; Burton, 1987; Lord and Wallace, 1989; McCool, 1993a,b); the Newlands Project and Reclamation Law (Dawdy, 1988; Pisani, 1993); and current water marketing activity in the basin (Colby *et al.*, 1991; NRC, 1992).

2.2 DESCRIPTION OF THE TRUCKEE-CARSON SYSTEM

The headwaters of the Truckee and Carson Rivers are in the Sierra Nevada Mountains of California - the Truckee River at Lake Tahoe and the Carson River in high Sierra streams south of Lake Tahoe (See Figure 2.1). Similarly, both rivers drain to

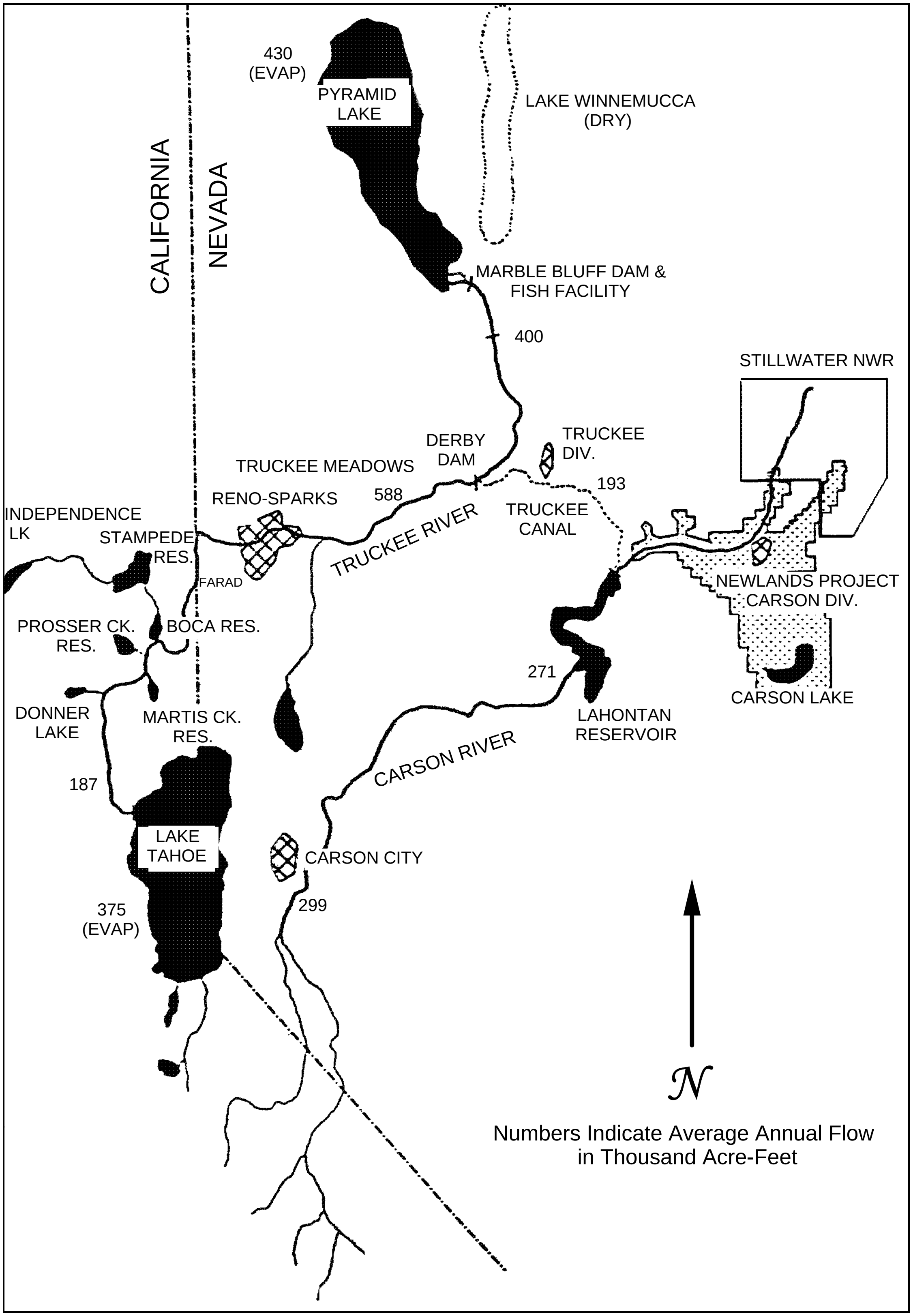

Figure 2.1 - Major Features of the Truckee-Carson River Basin

natural sinks in the Nevada desert - the Truckee River to Pyramid Lake, and the Carson River to the Carson Sink and Lahontan Wetlands. The Truckee-Carson River basin has a drainage area of approximately 3,450 square miles, with a mean annual inflow of approximately 1.055 million acre-feet (MAF). Mean annual flows at selected points in the system are identified in Figure 2.1. Sixty percent of the total runoff occurs in the months of April, May, and June, while the three months of August, September, and October amount for only 10 percent of total flow in the two rivers.

Until passage of the Reclamation Act of 1902 and subsequent development of the Newlands Irrigation Project, the Truckee and Carson Rivers were separate hydrologic systems. Since construction of the Derby Diversion Dam and the Truckee Canal in 1905 approximately one-third of the mean annual flow of the Truckee River has been diverted through the Truckee Canal to supply the Newlands Project. This has generated a seemingly endless trail of conflict and animosity in the basin.

2.1.1 Truckee River System

The Truckee River system includes three natural lakes with controlled outlets (Lake Tahoe, Independence Lake, and Donner Lake) and four reservoirs (Boca, Stampede, Prosser Creek, and Martis Creek). A summary of reservoir characteristics and operating purposes is provided Tables 2.1 and 2.2 and a brief description of each follows. Reservoir ownership, storage rights, and water accounting/classification are important aspects of system operation, and sources of controversy, conflict and operational complexity (DWR, 1991a). Numerous agreements and compacts guide reservoir operation, as discussed in Section 2.4.

Sierra Pacific Power Company (SPPC) operates four hydropower facilities on the Truckee River. These are listed in Table 2.3, along with the facilities at Lahontan Reservoir on the Carson River. The relevance of the Truckee River facilities is not so much their energy production, but their historical role as the reason for establishment of the Floriston Rates that currently govern system operation. Floriston Rates specify seasonal flow rates to be maintained at Farad near the California-Nevada border.

Water quality in the upper reaches of the Truckee River is fairly good. However, there are concerns about water quality in the Lower Truckee River, particularly in the summer months when river flow is principally municipal and agricultural return flows from Reno-Sparks and the Truckee Meadows area, respectively.

Table 2.1 - Reservoir Characteristics

Facility	Drainage Area (sq. mi)	Dam Height (ft)	Crest Length (ft)	Usable Capacity (ac-ft)	Minimum Storage (ac-ft)	MIF[1] (cfs)
TRUCKEE RIVER						
Lake Tahoe	506	18	109	732,000	0	50/70[2]
Donner Lake	14	14	34	9,500	2,890	3
Martis Creek Res.	40	113	2,670	20,400[3]	100	0
Prosser Creek Res.	50	163	1,830	29,800	1,200	5
Independence Lake	8	31	125	17,500	0	2
Stampede Reservoir	136	239	1,511	226,500	4,600	30
Boca Reservoir	172	116	1,629	41,100	0	0
Derby Diversion Dam	–	31	?	–	–	–
Marble Bluff Dam	–	35	1,622	–	–	–
CARSON RIVER						
Lahontan Reservoir	1,950	162	1,325	295,100 319,400[4]	4,000	0

1. MIF = Minimum Instream Flow requirements (typically for fisheries)
2. Lake Tahoe MIF is 50 cfs from October to March and 70 cfs from April to September.
3. Martis Creek Reservoir is used for flood control only.
4. With flashboards in place.

Table 2.2 - Reservoir Ownership and Operating Purposes

Facility	Owner	Operator	Construction Date	Principal Uses
TRUCKEE RIVER				
Lake Tahoe	SPPC	TCID	1913[1]	Recreation Irrigation M&I Power
Donner Lake	SPPC/TCID	SPPC	1930s	Recreation M&I Irrigation
Prosser Creek Reservoir	USBR	USBR	1962	Flood Control Recreation Fisheries
Independence Lake	SPPC	SPPC	1939	Power M&I Recreation
Stampede Reservoir	USBR	USBR	1970	Fisheries M&I Power Recreation Irrigation
Boca Reservoir	USBR	WCWCD	1937	Flood Control M&I Irrigation Recreation
Martis Creek Reservoir	USCOE	USCOE	1971	Flood Control
Derby Diversion Dam	USBR	TCID	1905	Irrigation Diversion
Marble Bluff Dam	USBR	USBR/PLT	1975	Fisheries
CARSON RIVER				
Lahontan Reservoir	USBR	TCID	1915	Irrigation Power Recreation

1. A wooden dam was first constructed at Lake Tahoe in 1870.

PLT = Pyramid Lake Paiute Indian Tribe
TCID = Truckee-Carson Irrigation District
USBR = US Bureau of Reclamation
SPPC = Sierra Pacific Power Company
USCOE = US Army Corps of Engineers
WCWCD = Washoe County Water Conservation District

Table 2.3 - Hydropower Facilities in the Truckee-Carson System

Facility	Construction Date	Max Flow Capacity (cfs)	Installed Capacity (MW)
TRUCKEE RIVER			
Farad (ROR)[1]	1901	500	2.6
Fleish (ROR)	1905	355	2.5
Verdi (ROR)	1911	425	2.5
Washoe (ROR)	1904	400	2.5
Stampede Dam	1988	?	3.0 and 0.65
CARSON RIVER			
Lahontan Reservoir #1	1915	?	1.92
Lahontan Reservoir #2	1989	?	4.00

1. ROR = Run-of-the-River Hydroelectric facility

Lake Tahoe

Lake Tahoe is the largest body of water in the Truckee River basin. Outflow from Lake Tahoe is controlled by the lake's natural rim at elevation 6223.0 ft (above mean sea level (msl) and by a small concrete dam located about 400 ft downstream of the natural outlet. The dam, which is owned by SPPC but operated by the Truckee-Carson Irrigation District (TCID) under the direction of a Federal Water Master, controls the upper 6.1 feet of Lake Tahoe. Although Lake Tahoe has over 122 million ac-ft of storage (with an average depth of 990 ft), only the 744,600 ac-ft stored between the natural rim and the top of the dam (el. 6229.1) can be used. Roughly 70 percent of the usable storage capacity available in the Truckee River system is in Lake Tahoe. Lake Tahoe is operated to minimize water surface fluctuations and to minimize high water damage to shoreline property.

Donner Lake

Donner Lake dam controls the upper 12 feet of the lake and has a storage capacity of 9,500 ac-ft. The dam is operated jointly by SPPC and TCID, who own rights to use the impounded waters. Storage in Donner Lake is classified as Privately Owned Stored Water (POSW) under the Truckee River Agreement, therefore, releases from Donner Lake are not used to satisfy Floriston Rates. There are no flood control requirements for Donner Lake.

Prosser Creek Reservoir

Prosser Creek Reservoir is federally owned and operated. The reservoir provides flood control storage and storage for exchange water as dictated by the Tahoe-Prosser Exchange Agreement. Storage capacity in Prosser Reservoir is 29,800 ac-ft.

Boca Reservoir

Boca Reservoir, the most downstream of the three reservoirs on the Little Truckee River, is owned by the USBR. However, it is operated by the Washoe County Water Conservation District for irrigation and M&I purposes. Of the 41,000 ac-ft of storage in Boca, SPPC owns the first 800 ac-ft of storage in Boca reservoir. There are no minimum instream flow (MIF) requirements for Boca reservoir. However, it must be operated to pass through all releases from Stampede Reservoir.

Stampede Reservoir

Stampede Reservoir is the second largest reservoir in the Truckee River system, with a storage capacity of 226,620 ac-ft. The multi-purpose facility was constructed three miles upstream of Boca Reservoir in 1970 by the USBR as part of the Washoe Project. In 1982, a court order mandated that storage in Stampede Reservoir be used exclusively for the benefit of endangered and threatened species in Pyramid Lake. Stampede Reservoir is the only reservoir on the Truckee River to have a hydropower facility at the dam. The 3.65 MW plant was constructed in 1988. Operation for hydropower is secondary.

Independence Lake

Independence Lake is the uppermost and the smallest of the three reservoirs on the Little Truckee River. Independence Lake is owned and operated by the Sierra Pacific Power Company, which has exclusive use of storage. Full storage capacity of 17,500 ac-ft in Independence Lake is classified as Privately Owned Stored Water by the Truckee River Agreement. There are no flood control requirements for Independence Lake.

Martis Creek Reservoir

Martis Creek Reservoir was constructed in 1971 by the U.S. Army Corps of Engineers for flood control purposes only. Poor subsurface conditions at the dam site prevent Martis Creek Reservoir from storing water for conservation purposes. Total flood control capacity of the reservoir is 20,400 ac-ft.

Derby Diversion Dam

The Derby Diversion Dam was constructed in 1905 as part of the Newlands Project. Its purpose is to divert water from the Truckee River for delivery via the Truckee Canal to the Newlands Project. Capacity of the Truckee Canal is 900 cfs and is subject to considerable seepage losses. The dam, which has no significant storage capacity, is operated by TCID, although it is owned by the USBR.

Marble Bluff Dam and Fish Facility

Marble Bluff Dam and Fish Facility were built in 1975 by the USBR and U.S. Fish and Wildlife Service. The dam was intended to stabilize the lower Truckee River streambed and serve as the headworks for the Pyramid Lake Fishway, which provides Cui-ui access to the Lower Truckee River when Pyramid Lake levels are too low for the fish to navigate the delta.

Pyramid Lake

Pyramid Lake is the only remnant of the pre-historic Lake Lahontan that once covered a vast portion of the Great Basin. Pyramid Lake has a volume of approximately 26 million ac-ft. Lake levels were fairly stable, subject only to natural variations, until the early 1900s. However, with construction of the Derby Diversion Dam and increased diversions in the upper Truckee basin, lake levels have fallen dramatically (Figure 2.2). Prior to construction of Derby Dam, Pyramid Lake water level was 3861.6 ft. By 1967, the last year of unrestricted and unmonitored diversions from the Truckee River, the lake level had dropped nearly 80 feet. Natural inflow to Pyramid Lake prior to construction of Derby Dam was about 600,000 ac-ft/year. Since the onset of diversions, average annual inflow has been about 400,000 ac-ft. Reduced storage and inflows have affected lake water quality. For instance, salinity has increased from about 3,500 mg/l historically to over 5,400 mg/l in 1991. Substantial increases in total dissolved solids above 5,900 mg/l may cause significant degradation of the food chain in Pyramid Lake (DWR, 1991a). However, the more important ramification of reduced storage and inflows is the reduced opportunities for Cui-ui spawning runs into the lower Truckee River.

2.1.2 Carson River System

The Carson River flows unimpeded from its source to Lahontan Reservoir. Some reaches of the river are classified as Super Fund sites because of mercury contamination from mining activity last century. Thus, the quality of inflows to Stillwater National Wildlife Refuge (NWR) are a concern (DWR, 1991a) because of potential effects on water fowl..

Lahontan Reservoir

Lahontan Dam was constructed in 1915 by the USBR as part of the Newlands Project. It is owned by the USBR, but has been operated by the TCID since 1926, when control of the Newlands Project was ceded to the Irrigation District. Lahontan Reservoir

Figure 2.2 - Pyramid Lake Water Surface Elevations

has a storage capacity of 295,542 ac-ft (319,400 ac-ft with flashboards), and controls inflows from the Carson River as well as flows diverted from the Truckee River at the Derby Diversion Dam.

Newlands Project

The Newlands Project was the first project developed under the Reclamation Act of 1902. Although the initial estimate of potential irrigated acreage was 232,000 acres, approximately 73,000 acres in the Newlands Project have water rights, and only about 65,000 acres have been irrigated on average. Historically, water use efficiency, which has been has been about 60 percent, and land use classification have been contentious issues. Lands can be classified as bench, which are entitled to 4.5 ac-ft/ac of water annually; bottom lands which are entitled to 3.5 ac-ft/ac annually; or pastures, which receive 1.5 ac-ft/acre annually. TCID and USBR disagree on the classification of numerous parcels with TCID claiming more bench land, and thus entitlement to more water. The Project is divided into two divisions: the Truckee Division and the Carson Division. The Truckee Division, which consists of 5,900 acres of which 4,300 are cultivated, receives all water supplies directly from the Truckee Canal. The Carson Division consists of about 67,820 acres, of which roughly 52,800 acres are currently irrigated.

Lahontan Wetlands/Stillwater Wildlife Refuge

Prior to development of the Newlands Project, the Carson River naturally flowed to the Lahontan Valley wetlands, either to the Carson Lake Pasture or to the Carson Sink. It is estimated that approximately 85,000 acres of wetlands existed in the Lahontan Valley, forming an integral part of the Pacific Flyway. Since the advent of the Newlands Project, it is estimated that freshwater flows to the wetlands have decreased by 85%, and most inflows to the wetlands have been replaced by lower quality agriculture drainage water (EDF, 1990). Currently, there are 4,000 acres of viable wetland habitat in the Stillwater National Wildlife Refuge.

2.3 PARTIES IN CONFLICT

The major parties involved in the Truckee-Carson water use conflicts are the federal government, the Pyramid Lake Paiute Indian Tribe, the Truckee-Carson Irrigation District, Sierra Pacific Power Company, and the States of California and Nevada. These groups have been involved since the beginning. In recent decades several environmental groups have become important, and numerous other parties have less prominent issue-specific involvement. In addition, Truckee-Carson water conflicts are particularly complex because some of these groups have internally inconsistent views and objectives, with consequent internal conflicts, while others have not been well represented in previous resolution efforts and are less than willing participants in current negotiations. The parties involved in conflict are identified in Table 2.4. A brief discussion of the major parties follows.

Table 2.4 - Parties Involved in the Truckee-Carson Water Conflicts

United States Government
- Department of the Interior - Bureau of Reclamation, Bureau of Indian Affairs
- Department of Defense - Fallon Naval Air Station, U.S. Army Corps of Engineers
- Department of Justice
- Fish and Wildlife Service

State of California
- Department of Water Resources
- State Water Resources Control Board
- Department of Fish and Game

State of Nevada
- Department of Water Resources

Indian Tribes
- Pyramid Lake Paiute Indian Tribe
- Fallon Paiute-Shoshone Indian Tribe

Sierra Pacific Power Company

Environmental Interests
- Environmental Defense Fund
- Nature Conservancy
- Natural Heritage Foundation
- Wildlife Management Groups - Stillwater Wildlife Refuge, Fernley Wildlife Refuge

Agricultural Interests
- Truckee-Carson Irrigation District (Newlands Project)
- Truckee Meadows Farmers
- Lower Truckee River Farmers
- Upper Carson River Farmers

Municipalities
- Cities of Reno and Sparks
- Towns of Fallon and Fernley
- North Tahoe Public Utility District
- Tahoe City Public Utility District
- Sierra Valley Water Company
- Carson Truckee Water Conservancy District
- Washoe County Water Conservation District
- Washoe County, Nevada

United States Government

The multiple and often conflicting interests of the federal government in the Truckee-Carson water disputes exemplifies the highly competitive nature of water use in the basin and the complexity of water management. The Departments of Interior (DOI), Justice (DOJ), and Defense (DOD) are all involved in basin issues and each has a stake in the outcome.

Several Bureaus within the DOI have a part in the conflict. The Bureau of Reclamation has been a major force behind water resources development in the Truckee-Carson basin, beginning with facilities constructed as part of the Newlands Project (Derby Dam, the Truckee Canal, and Lahontan Reservoir) and subsequently the Truckee Storage Project (Boca Reservoir) and the Washoe Storage Project (Stampede and Prosser Reservoirs) to supplement supplies to the Newlands project. USBR owns and operates several of the facilities on the Truckee-Carson system and maintains legislative control over operations of the Newlands Project, although day-to-day management of the Project was turned over to the Truckee-Carson Irrigation District (TCID) in 1926. USBR's primary water use interest is preserving adequate supplies of irrigation water for the Project.

The Bureau of Indian Affairs (BIA) is trustee for the Pyramid Lake Paiute Indian Tribe and must protect the tribe's interests. As such, their primary water use interest is securing sufficient water for protecting the endangered Cui-ui fish and for irrigation within the reservation. Other DOI agencies involved are the Fish and Wildlife Service, which upholds the Endangered Species and Migratory Bird Acts, and the United States Geologic Survey (USGS), which is developing a detailed hydrologic model of the Truckee and Carson River basins.

The DOJ has the role of protecting vested interests in Indian water rights. They are attempting to balance interests of all water users in the basin. DOD, through the Corps of Engineers, has flood control responsibilities for most reservoirs in the system.

State of California

Several agencies from the State of California are involved, including the Department of Water Resources, the State Water Resources Control Board (SWRCB), and the Department of Fish and Game (DFG). Water use interests include preserving in-stream flows in the Truckee River from Lake Tahoe to the stateline at Farad for environmental and fish and wildlife purposes; maintaining water surface elevations in Lake Tahoe for recreation, erosion control, and aesthetics; municipal and industrial (M&I) water supply to Lake Tahoe communities; dam safety responsibilities for reservoirs in California; and recreation in California reservoirs.

State of Nevada

Similarly, several agencies from the State of Nevada are involved, including the Department of Water Resources and the Department of Conservation of Natural Resources. Water use interests include preserving in-stream flow in the Truckee River from the stateline to Pyramid Lake; M&I water supply to cities, towns and irrigation districts along the river; river and reservoir recreation; and maintaining water quality in the Truckee and Carson Rivers.

Pyramid Lake Paiute Indian Tribe

The Tribe's principal water use interest is restoration of flows in the lower Truckee River to levels that will ensure survival of the endangered Cui-ui and threatened Lahontan cutthroat trout. The Tribe seeks to reclaim approximately one million acre-feet of water which allegedly have been diverted illegally from the Truckee River for use by TCID since implementation of the operating criteria and procedures (OCAP) for the Newlands Project in 1973. Through court victories, the Tribe has become a prominent force in negotiations for conflict resolution.

Sierra Pacific Power Company (Reno/Sparks)

Through a subsidiary, the SPPC is responsible for M&I water supply to sections of the Reno-Sparks metropolitan area. SPPC also operates four run-of-rive hydropower plants on the Truckee River. SPPC is actively pursuing the acquisition of water rights from agricultural interests in the Truckee Meadows basin. SPPC has entered into agreements with other water users for the coordinated operation and use of upstream facilities and water supplies to increase water supply reliability.

Truckee-Carson Irrigation District (TCID)

TCID assumed control of the Newlands Project in 1926 and has been at odds with the Bureau of Reclamation over operation of the Project and other issues, such as land classification, water duty, and operating efficiency. Though TCID farmers are intimately involved in the fray over water since TCID is the largest water user in the basin, they frequently are absent from negotiations, and seem reluctant to fully participate in the resolution process. TCID is primarily interested in maintaining a consistent supply of water for irrigation.

2.4 LEGISLATION PERTINENT TO SYSTEM OPERATION

Operation of the Truckee-Carson System is highly constrained by legislation, from the Reclamation Act of 1902 to the 1990 Settlement Act. The following items of legislation are integral to current system operation. A detailed review of the legislative history of the Truckee River Basin is provided in Kramer (1988).

Truckee River General Electric Decree (1915)

The Truckee River General Electric Agreement specified the terms under which Tahoe Dam was to be operated when ownership was transferred from the Truckee River Electric Company to the federal government. Most important of these terms was recognition of Floriston Rates established in 1908 when Tahoe Dam was purchased by the Electric Company from the Donner Lumber Company. Floriston Rates were meant to ensure sufficient flow for hydropower production at the run-of-river facilities on the Truckee River.

Truckee River Agreement (1935)

The Truckee River Agreement (TRA) is a complex legal document that includes several major stipulations concerning system operation. These include appointment of a federal watermaster to oversee daily operations of the Truckee River reservoirs; allowances for reductions in Floriston Rates under specified storage conditions Lake Tahoe; specification of reservoir storage priorities and rules for reservoir operations; and, specification of maximum water surface elevation for Lake Tahoe of 6229.1 ft. The TRA also provides for water classification based on ownership and intended purpose. Parties to the TRA are SPPC, TCID, the Bureau of Reclamation, the Washoe County Water Conservation District (WCWCD), and individual Truckee Meadows water rights holders.

Orr Ditch Decree (1944)

Adjudication of Truckee River water rights was finalized in the Orr Ditch Decree, 31 years after the proceedings were initiated. The federal Decree prioritized water use priorities for all diverters in the basin. As it turns out, one of the most lasting and damaging effects of the Orr Ditch Decree to the Paiute Tribe is the surrender of reserved rights, or rather the limited definition and quantification that was attached to these rights. Water rights were reserved for irrigation on the Paiute Reservation, but no water was specified for maintaining lake fisheries (Cui-ui and Lahontan cutthroat trout). Thus, no water is legally available to protect fisheries in Pyramid Lake, save what has been guaranteed through the Endangered Species Act. Much of the current conflict stems from failed attempts to re-open the Orr Ditch Decree and reassess the reserved rights issue.

Tahoe-Prosser Exchange Agreement (1959)

Under specified conditions, the Truckee-Prosser Exchange Agreement allows for water to be stored in Prosser Reservoir but be classified as Lake Tahoe water for purposes of satisfying Floriston Rates. By not having to make releases from Lake Tahoe to satisfy Floriston Rates, water is kept in storage to satisfy minimum instream flow requirements for fisheries in the upper Truckee River. Major parties to the agreement are TCID, SPPC, the Bureau of Reclamation, and WCWCD.

Operating Criteria and Procedures (OCAP) for Newlands Project (1988)

The operating criteria and procedures (OCAP) developed by the Bureau of Reclamation for the Newlands Project are designed to promote water use efficiency in the Project, maximize use of Carson River supplies, while reducing diversions from the Truckee River. The Paiute Tribe challenged initial OCAPs claiming that Truckee River diversions permitted by OCAP were in excess of legally entitled amounts. "Interim" OCAP have been developed each year since the Tribe challenge in 1973, while a final OCAP is developed. Developing a final OCAP involves resolving numerous issues, including the number of acres eligible to receive Project water, water duty on these lands, water requirements for Stillwater NWR, and operation of Lahontan reservoir for Project purposes versus recreational demands.

Truckee-Carson-Pyramid Lake Water Rights Settlement Act , PL 101-618 (1990)

Public Law 101-618 is a comprehensive attempt to improve operation of the Truckee-Carson system to satisfy all water interests in the basin and resolve long-standing disputes. Major provisions in the Act include development of a Truckee River Operating Agreement (TROA); establishment of a fund for the acquisition of water rights for protection of Lahontan Valley wetlands and Pyramid Lake to assist in the restoration of Cui-ui; reauthorization of the Newlands Project to serve additional purposes including recreation and fish and wildlife habitat; interstate allocation of water between California and Nevada. PL 101-618 is the motivating force for current negotiation activity.

Table 4.5 in Chapter 4 provides a summary of operating priorities as specified by the above documents. The list does not reflect many of the complex storage exchange and storage credit arrangements and the conditions under which they can be implemented, nor does it reflect the complicated water accounting system used to keep track of water ownership. Also discussed in Chapter 4 are modeling activities pertinent to system operation and current negotiations for conflict resolution.

2.5 CONFLICT IN THE TRUCKEE-CARSON BASIN

"Competition for water is often resolved only after costly and protracted legal battles, begun with considerable uncertainty about the outcome" (Frederick, 1986). Litigation has had a prominent role in conflict resolution and water resources development in the Truckee-Carson system. This section presents an overview of conflict in the basin and the efforts undertaken to resolve these conflicts. Some impediments or limitations to the successful resolutions of these conflicts are discussed.

2.5.1 Overview of Water Development and Conflict

The development of water resources in a basin can be analyzed from several perspectives. One perspective which seems appropriate for discussing development in the Truckee-Carson system draws a distinction between expansion and mature phases of development (Randall, 1981). Characteristics of the two phases are listed in Table 2.6. Basically, in an expansion phase things are good, there are ample supplies of adequate quality water, the physical infrastructure is in good shape, and competition for water is minimal although demands are increasing. In a mature phase, although demands may be growing less quickly, there is increased competition for increasingly scarce supplies, and externalities associated with water use, such as ground water overdraft or contamination from municipal and agricultural return flows become more problematic.

Table 2.6 - Expansion and Mature Phases of Water Resource Systems

Characteristics	Expansion Phase	Mature Phase
Water Supply	Elastic	Inelastic
Demand for Water	Expanding rapidly; mostly quantity	Expanding more slowly; quantity demands increase
Physical Condition of Water System	New	Older Facilities, Maintenance Problems
Competition for Water	Low	High
Externality Problems	Drainage	Ground Water Overdraft; Surface water pollution
Social Cost of Subsidy for Increased Water Use	Low	Rising

Source: Nickum and Easter (1991); adapted from Randall (1981).

"Because of the "lumpiness" of supply shifts and major institutional changes, the historical development of most water systems shows a sort of cyclical movement from an expansion phase to a mature phase and on to a new expansion phase" (Nickum and Easter, 1991). Historically, the transition from a mature phase to a new expansion phase has been principally through structural measures. But, as Nickum and Easter (1991) note "what seems to be unique about the present is the relative universality of moving beyond the present mature stage through capacity expansion." As the mature phase "matures" and solutions cannot be found easily, competition and conflict among water users intensifies.

Water resources development in the Truckee-Carson basin somewhat reflects these two phases. A chronology of water resources development and legislative action in the basin is shown in Figure 2.3. The "structural" development of the basin is traced along the bottom of the figure, while the upper portion identifies highlights of the legal and institutional development, including key events such as the listing of the Cui-ui as an endangered species.

The standard response to a maturing phase was capacity expansion through the construction of reservoirs. In fact, the basin has undergone three expansion phases, as shown on Figure 2.3. The first in response to development of the Newlands Project with construction of Derby Dam, Lahontan Reservoir, and the dam at Lake Tahoe; the second in the 1930s with the construction of Boca Reservoir and the dams at Independence and Donner Lakes; and the most recent, in the 1960s and early 1970s with construction of Prosser Creek, Stampede, and Martis Creek Reservoirs. Though new facilities did not always solve the root cause of conflict, they did ameliorate the situation for a while. Nonetheless, litigation has been a constant presence in the basin, as have federal and state legislation.

A summary of the major water management issues characterizing the latest mature phase is presented in Table 2.7. Responses have focused on demand management and institutional aspects, including water marketing activity and numerous storage credits and storage exchange schemes. Also, in the current version of the Negotiated Settlement Model being used to prepare the Environmental Impact Statement for the Truckee River Operating Agreement, a hypothetical reservoir is included in the analysis. However, there is no indication that a new reservoir is even a feasible alternative.

2.5.2 Impediments to Resolution

It is generally recognized that the recent advances in resolving water problems in the Truckee-Carson basin through multi-party negotiations owe much to earlier litigated victories by the Pyramid Lake Paiute Indian Tribe (NRC, 1992). It is unlikely that negotiations would have progressed as far or as quickly were it not for the standing and recognition gained by the Paiute Tribe from these court rulings. In essence, litigation has forced negotiation. This is true despite recent federal government initiatives to negotiate rather than litigate Indian claims. However, there are several potential impediments to the long-term success of negotiated solutions, or even to the likelihood of reaching agreement strictly through negotiation.

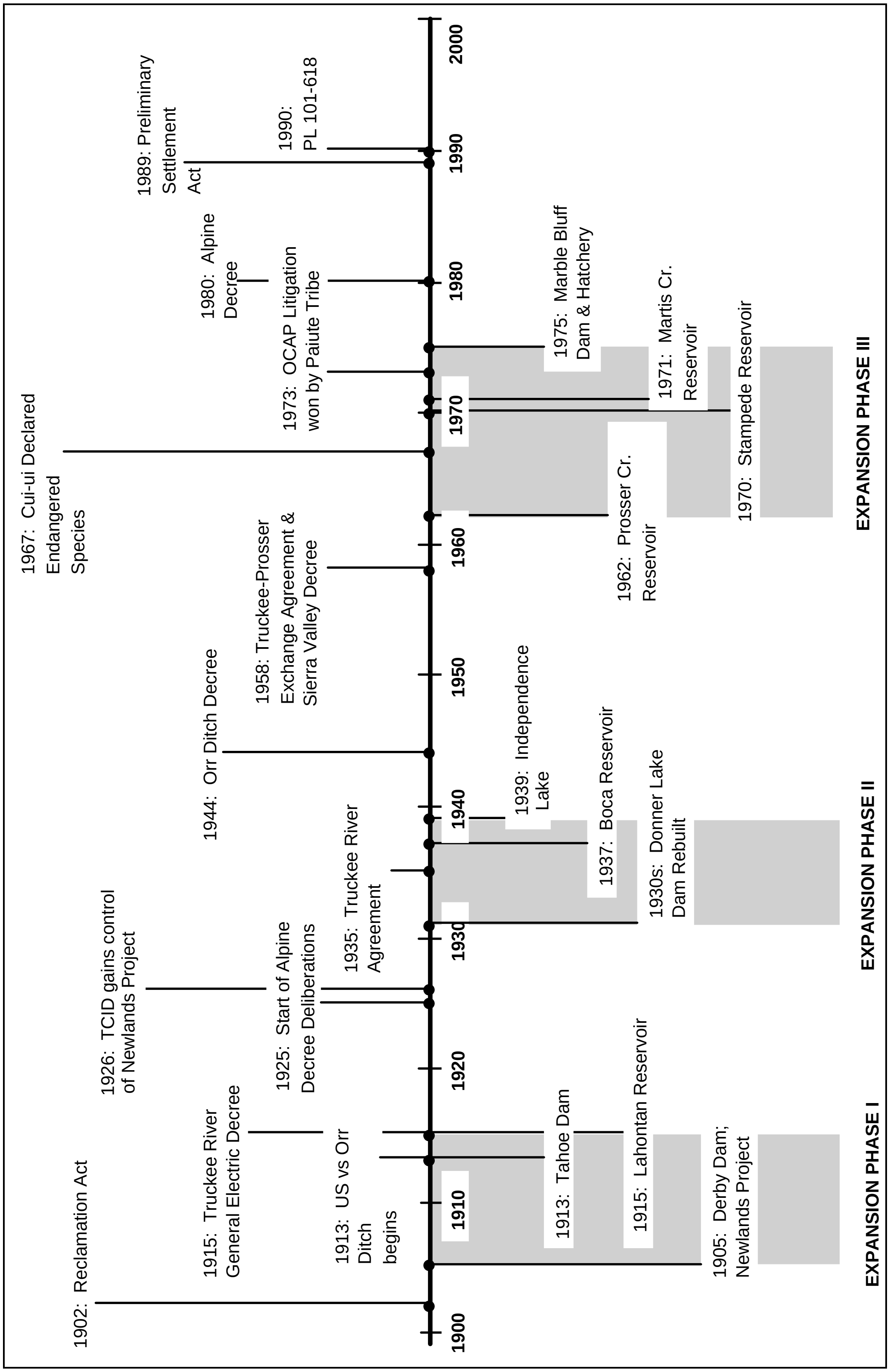

Figure 2.3 - Chronology of Water Resources Development

Table 2.7 - Water Management Issues in the Truckee-Carson Basin

- Interstate allocation of water between California and Nevada: a) different water laws, b) political boundaries, c) management philosophies, and d) basin geography.
- Maintenance of water levels in Lake Tahoe and of water rights in the Tahoe area.
- Protection of fisheries and water rights in the Upper Truckee River.
- Maintenance of specified flow rates at Farad for hydroelectric power production. Floriston Rates are defined by court decree.
- M&I water supply to Reno-Sparks area, including source of emergency supplies for use during drought periods.
- Provision of adequate flows to Pyramid Lake to maintain water levels and for the protection of endangered (Cui-ui) and threatened (Lahontan cutthroat trout) species.
- Maintenance of adequate flows in the Lower Truckee River to allow upstream spawning runs for the Cui-ui and trout. Required from January to May.
- Flow diversions at Derby Dam sufficient to meet irrigation and wetland demands.
- Maintenance of adequate storage in Lahontan Reservoir for irrigation and recreation purposes.
- Provision of adequate irrigation water for the Fallon Indian Tribe.
- Provision of adequate flows to maintain Lahontan Valley wetlands (Stillwater).
- M&I water supply to Carson City, Lyon and Douglas Counties and other communities along the Carson River.
- Agriculture water supply to Carson Valley farmers.
- M&I water supply for the towns of Fernley and Fallon

The aim of negotiation is to turn a win-lose situation (i.e., a zero-sum game such as litigation) into a win-win situation. Negotiation has numerous advantages over litigation (McCool, 1993a). However, for negotiation to be successful several conditions must be satisfied (McCool, 1993b; Burton, 1991), including participation of all parties involved in conflict and certainty or relative certainty about the pros and cons of potential alternatives. These conditions have not existed in the Truckee-Carson Basin. For example, negotiations have not always included all parties, while some, such as TCID, have, at times, refused to participate (Kramer, 1988). Also, possible outcomes of alternatives involving the marketing of Indian water rights are uncertain due to improperly defined water rights. As such, it is unlikely that the negotiation process alone (without further litigation) will be sufficient to resolve the water management problems in the basin, or in any such basin that has a protracted history of conflict and litigation.

Additional potential impediments to successful negotiations are discussed below. One is simply the long history of conflict and animosity that exists among principal parties and the institutional and legal constraints that this acrimonious history imposes on current negotiations. A second potential impediment is that the economic value of water to the different users is not considered explicitly in the negotiations. A third is the lack of a basin-wide systems perspective to the current negotiations.

The possible success of negotiation alone is further constrained due to the legislative history in the basin (e.g., Orr Ditch and Alpine Decrees). In essence, all planned modifications to the manner in which the basin's water resources are managed must conform to the prevailing court-ordered methodology. Negotiations that take place within the context of existing legislation can offer feasible, but limited solutions to the existing water problems. Litigation may be required to motivate progress in negotiations, and systems analysis, particularly simulation modeling, may be required to provide a means for developing and evaluating alternatives as part of negotiation.

Currently, the economic value of water to different parties is not incorporated in the conflict resolution process (in the evaluation of alternatives). It is implicitly assumed that all parties place the same value on water; that a ten percent shortage to the City of Reno has the same cost as a ten percent shortage to the Pyramid Lake Tribe or to the farmers at TCID. By not accounting for this difference in value and how shortages are allocated internally by each user group, the range of possible solutions is restricted. Solutions that address the inherent differences in the value placed on water use will more accurately reflect conditions in the basin and provide additional flexibility in managing the basin's water resources.

Previous attempts to reach consensus in water management in the Truckee-Carson basin, either by litigation or negotiation, have failed or yielded incomplete solutions in part because of an inadequate systems perspective by planners, managers, legislators, and politicians. This lack of system-wide perspective is best exemplified in the Truckee-Carson basin by the complex set of reservoir operating rules resulting from numerous local, state, and federal legislation and bi- and multi-party agreements. This piece-meal development of reservoir operations reveals a myopic and special (local)-interest perspective and may result in distinctly inferior outcomes. Even current negotiations on the Truckee River Operating Agreement are not approaching the problem from a system's analysis perspective. TROA is concerned only with problems on the Truckee River basin. It considers the Carson River basin only through operation of Lahontan Reservoir.

2.6 CONCLUSIONS

Kramer (1988) concluded that the best hope for resolution of conflict in the Truckee-Carson basin lay with equitable apportionment through a negotiated settlement. "Equitable apportionment has long been used in western water disputes to allocate water resources. Under this apportionment method, the strict rules of priority are largely disregarded in favor of allocation that will be *fair* to all water users [emphasis added]" (Littleworth and Gardner, 1995). There is precedent for "wiping the slate clean" in reallocating a basin's water resources.

Whereas current modeling efforts for TROA incorporate many of the historic institutional constraints (as legally required), the modeling analysis presented in Chapters 4 and 5 evaluates system operation without these constraints. The entire Truckee-Carson basin is modeled, and several of the institutional constraints restricting system operation are relaxed, including many on reservoir operation. This analysis may be analogous to the concept of equitable apportionment in that the institutional constraints are "disregarded in favor of allocations that will be fair."

Though not pursued in this research, several possibilities exist for analyzing further the impact of historical conflicts on current processes. For example, Howitt and Vaux (1995) examined the evolution of coalition formation in California water development history and related it to the prevailing economic environment. They assessed how the changing economic incentives and public attitudes towards water use in recent years have begun to force a change in the make-up of the coalitions. This type of detailed analysis of the motivating factors driving the formation of coalitions may be of value in explaining the nature of conflict in the basin and potentially suggesting new alternatives for resolution.

Chapter 3

Priority Preserving Unit Penalties in Network Flow Modeling

3.1 Introduction

As competition for scarce water resources increases and pressure to reallocate existing water supplies among diverse users rises, so does the need to include in the modeling effort a representation of the institutional framework governing regional water allocation. Primarily, the "institutional framework" refers to water use priorities as specified by the existing water rights structure, such as the prior appropriation doctrine. However, water rights are not necessarily the only "prioritized" water uses in a system. Often, because of historical precedent, force of habit, or judicial or legislative action, non-water righted purposes, such as environmental or recreational uses, gain stature and must be incorporated in system operation plans. Incorporating such institutional constraints in technical analyses is fundamental for reaching a compromise solution in conflict situations. This is particularly so in systems in which institutional criteria may be more influential than physical or economic factors in determining flow allocation among multiple and diverse uses, as is the case in over or fully appropriated basins.

Network flow programming (NFP) models have been used to some extent to model water rights and water use priorities (Labadie, 1995; Andrews et al., 1992; Graham et al., 1986). However, no systematic approach for determining unit cost coefficients which guarantees proper representation of water right priorities is available. In this chapter, a general algorithm for determining unit cost coefficients to reflect water use priorities in a network flow programming framework developed as part of this research is presented. HEC-PRM, a network flow optimization model developed by the U.S. Army Corps of Engineers Hydrologic Engineering Center (HEC, 1994) was used to develop and test the algorithm. However, the algorithm is valid for any network flow or linear programming based model.

In section 3.2, a description of network flow programming is provided, including a brief discussion on the choice between priority-based and economically-based cost coefficients. An overview of recent efforts to incorporate water use priorities in system models is presented in section 3.3. The algorithm for establishing cost coefficients to properly represent water use priorities follows in section 3.4, as a set of rules. In section 3.5, the algorithm is recast as a linear program. The chapter concludes with some observations on the choice between economic- and priority-based analyses.

3.2 Cost Coefficients for Network Flow Programming

Network flow programming can be used to model situations in which a resource, such as water, must be moved through a system from one or more source(s) to one or more point(s) of use (Jensen and Barnes, 1980). The water resource system is represented as a series of nodes and arcs, in which the nodes can represent reservoirs, diversion points, inflow or return flow points, stream junctions, and other control points. Arcs connect nodes and can represent river reaches, channels, or pipelines. The arcs can have upper and lower capacity constraints, as well as a flow multiplier coefficient for incorporating linear gains and losses. Unit cost coefficients ck are used to assign penalties for flow through the arcs. Arc flows qk representing changes reservoir storage, reservoir releases, and flows at selected points in the system are the decision variables. The network flow model can be represented by the following set of equations, in which the objective function (equation 1) is to minimize total costs of flow in the system:

Minimize Z = − I− SU(k=1,K,) ckqk (1)

subject to

1) mass balance at each node

− i− su(kiÎKin, ,) qk - − i− su(koÎKon, ,) akqk = 0 for all nodes n=1,2,É,N (2)

2) upper and lower capacity constraints for each arc

0 ² lk ² qk ² uk for all arcs k = 1,2,É,K (3)

where,

Z = total system cost (penalty)
N = number of nodes (e.g., demand points, reservoirs)
K = number of arcs (e.g., river reaches, canals)
qk = flow in arc k
ck = cost or penalty per unit flow in arc k
ak = flow multiplier for arc k, 0 ² ak ² 1, (e.g., canal losses)
Kin= subset of arcs flowing into node n
Kon= subset of arcs flowing out of node n
lk = lower bound flow for arc k
uk = upper bound flow for arc k

Since NFP is a minimal cost algorithm in which water is allocated first to those uses with the lowest unit cost coefficient, the selection of proper cost coefficients is an essential part of the analysis. Assigning increasing unit costs to water uses as their priority decreases assures that the highest priority demands are satisfied first in the cost minimization problem. As noted by Andrews et al. (1992), the network flow model of equations (1)-(3) lends itself to both optimization and simulation analyses of water resource systems, depending on how the cost coefficients ck are defined. If realistic economic values are used to characterize the penalty functions, the network flow model can be used to optimize system operation to minimize costs. However, if cost coefficients reflecting flow priorities (i.e., pseudo-costs) are used to represent operational priorities, then the network flow solution would reflect flow allocation under the predetermined operating scenarios. Different management alternatives can be represented simply by changing priorities on the various water uses.

Analyses undertaken with economically-based penalty functions are useful from a social welfare perspective in that by allocating water to the highest valued uses, they suggest strategies for system-wide minimum cost operation. This solution serves as a bound for the "implementable" solution, which is subject to institutional, political, and social constraints. Allocation determined by strict adherence to economic penalty functions could be quite different than what may be stipulated by an underlying water rights priority system. For instance, in many regions agricultural water rights are senior to urban water rights, yet the economic value of agricultural water is typically much less than urban water.

Analyses based on pseudo-costs to reflect water use priorities are motivated largely by the need in many situations to represent components of the institutional system, but also by the difficulty associated with developing realistic economically-based penalty functions for all water uses of interest. Often, representative and well-behaved, but hypothetical penalty functions are used as surrogates for realistic cost information (Karamouz et al., 1992). Yet, the accuracy of these hypothetical functions is always suspect. Indeed, developing economically-based penalty functions, whether real or hypothetical, can often be the most time-consuming and laborious part of an analysis and also the greatest source of controversy and disagreements over the results.

There are several other limitations to analyses based on economically derived penalty functions. As just mentioned, economically-based penalty functions may provide little representation of the underlying water rights system or of other institutional constraints which can be prioritized. Implementing alternatives suggested by such an analysis may be difficult since they must overcome institutional impediments associated with water rights. They can, however, serve as the justification for seeking to change or modify the institutional criteria (Vaux and Howitt, 1984). A major drawback to the use of economically-based penalty functions in multi-purpose project analysis is development of economic functions to represent the value of non-economic water uses, such as instream flow, recreation, or preservation of fish and wildlife. Efforts to derive economic value functions for these non-market uses has been a fertile field of research, but often has not provided widely accepted economic values.

Regardless of the basis for the penalty functions Ð real economic costs or pseudo-costs Ð the network flow algorithm requires greater simplifications in representing the system than would be required by linear or nonlinear programming models. These simplifications can limit the accuracy with which system penalties and priorities are represented in the model. Since all system constraints in NFP models must be represented as a function of a single network variable (e.g., arc flow) and no interaction among system components is possible, contingent constraints cannot be modeled. For example, for most NFP algorithms, off-stream diversions cannot be based on streamflow at a certain point in the system, nor can reservoir releases be dependent on reservoir storage or on releases in a previous time step. However, specialized algorithms have been developed and incorporated in some NFP models which allow reservoir storage-release and some non-linear relationships. Examples are the hydropower algorithm developed for HEC-PRM (HEC, 1994) and the algorithm developed by Sun et al. (1995) to incorporate non-linear reservoir evaporation loss functions. A final point about NFP is that water uses with very high priority may be best represented by upper or lower bound constraints on flow in the appropriate arc. Minimum instream flow requirements below a reservoir, for instance, can be incorporated as a fixed lower bound constraint on reservoir releases.

3.3 A Review of Water Rights and Priority Modeling

Attempts to model water rights and other "prioritized" institutional constraints explicitly are fairly recent. With few exceptions, most efforts to represent water use priority have employed simulation models or have used some form of network flow programming to optimize flow allocation at each time step in the simulation. However, as is apparent from the following review, there is no systematic approach for determining the unit cost coefficients for NFP applications which preserve water use priority ranking.

Wurbs and Walls (1989) presented a simulation model that captures water right seniority for various uses. In the model TAMUWRAP, water rights are represented by priority number based on date of water right acquisition, annual diversion amount, type of use (used to determine monthly demand factors), point of diversion, return flow factor, and reservoir storage capacity (if applicable). The primary purpose of the model is to determine the amount of unappropriated streamflow given demands exercised by existing water rights holders. The approach typically used in simulation models to represent water rights priority systems is based on knowing the cumulative entitlement for all priorities higher than the one being considered. Then, if streamflow at the point of interest is less then this cumulative amount, no diversions are permitted. Otherwise, the full entitlement up to the streamflow amount is diverted. As noted earlier, this type of conditional constraint cannot be represented in a network flow formulation because penalty information is limited to one arc.

Shafer et al. (1981) were the first to use a network flow model, MODSIM, to model water rights and water transfer opportunities. They evaluated the long-term effects of alternative water management policies, including changes in water rights and water use priorities, on water availability. By altering storage priorities, i.e., the pseudo-costs or unit cost coefficients, describing the penalty function, Shafer et al. were able to calibrate their model to historic operation (from Andrews, 1989:40). Trial and error was used to determine the proper pseudo-costs for each alternative analyzed.

Building on the work of Shafer et al., Graham et al. (1986) also incorporated water use priorities in a network flow model (MODSIMR). Each water use in their model is ranked according to its legal priority. This ranking was then transformed into a negative cost, i.e., a benefit, for use in the model. The transformation equation is rank-preserving:

$$cij = -(1000 - 10\ Rij) \qquad (4)$$

where cij is the unit cost associated with flow in the arc from node i to node j and corresponds to ck in equation (1). Rij is the rank (priority) placed on flow in this arc and ranges from 0 to 99, with the lower values reflecting higher priorities. There is nothing magical about this transformation, and, in fact, the authors and Labadie (1995) note that any rank preserving transformation can be used. The transformation of equation (4) implies that a difference of at least ten between unit cost coefficients is sufficient to preserve rank in the network flow analysis (e.g., priority 1 and priority 2 will have cost coefficients of -990 and -980, respectively). As discussed below, water allocation based on this approach may not always be rank-preserving.

Brendecke et al. (1989) used a similar approach in applying a network flow model, CRAM, to simulate system operation while optimizing water allocation at each time step. Unit cost coefficients on demand arcs were assigned to represent water right priority, and arc constraints were set equal to the water entitlement. Since the intent of the modeling exercise was to determine the yield of water righted diversions for a municipal user, other water righted withdrawals on the river were represented with demand arcs whose upper and lower bounds were set to the historical diversion amount. No information was provided on how the cost coefficients were derived and what their relative magnitudes were.

Chung et al. (1989) described the incorporation of a NFP algorithm in an existing simulation model for the vast California water supply system. The NFP was added to increase modeling flexibility by permitting managers to simulate varied operating criteria. The criteria are represented by varying the priority factors on different demands. Priority factors, however, are assigned arbitrarily and adjusted by trial and error.

By incorporating a sequential flow allocation technique to a network flow base model for the Kern Water Bank, Andrews et al. (1992) were able to extend the representation of water rights to include multiple supply sources and priorities which varied by source for each user. Previous efforts had either assumed single source supply, or in the event of multiple sources, that the same set of priorities applied equally to all supply sources for a given user. A system of layers representing different supply sources was devised and the NFP model was solved sequentially for each layer. Users were allocated water only from the layer(s) to which they had rights or authorization. Authorization patterns were permitted to vary by supply source to provide a more realistic representation of the Kern County water supply system. Nonetheless, "Écost assignments [i.e., unit cost coefficients]Éwere arbitrarily limited to a range of -100 to +100" and arbitrarily selected within this range.

While the above uses of NFP are in essence simulation studies using static optimization to allocate flows at each time step, Martin (1992) used HEC-PRM to optimize system operation for the full period of record. Martin (1992) used unit cost coefficients to represent reservoir operating policy priorities. The system evaluated by Martin (1992) consists of five reservoirs in series with storage penalties on each and flow penalties on reservoir releases and river flow at selected control points in the system. A trial and error approach was used to derive penalty functions to adequately represent the policy objectives. The penalty functions were also used to relate release rules to reservoir storage.

3.4 Algorithm for Developing Priority-Based Penalties

The studies cited in the previous section incorporate water use priorities in some form or another. However, no general method for determining the proper unit cost coefficients appears to exist. Rather, trial and error and intuition are used. In this section a generalized algorithm for determining unit cost coefficients which preserve water use priorities for use in NFP is presented.

3.4.1 Priority-Based Penalties

The prior appropriation doctrine used extensively in the western United States is founded on the principle of "first in time, first in right." Water right seniority and use priority are established by the date a user first appropriated water. This priority system dictates that in periods of reduced water supplies, users are shorted according to their seniority, with the most junior users shorted first. To mimic the water rights structure using a network flow formulation, it is necessary to assign decreasing unit costs to water uses as their priority increases to ensure that the demands of the most senior rights holders are fully satisfied before other more junior demands are met (Andrews et al., 1992), (i.e., the highest priority water use would have the lowest unit cost coefficient in equation (1)). In other words, the assignment of cost coefficients must guarantee that senior rights holders are not penalized or shorted until all junior rights holders have sacrificed their full entitlement. However, strict enforcement of the prior appropriation doctrine is rare. More often, diversions to senior water rights holders are reduced and the shortage is allocated among all water users. This issue is taken up again later in the chapter.

Prioritization of water rights also can be mandated by judicial or legislative action. For instance, under the federal endangered species act, water supply necessary to aid the recovery or delisting of a threatened or endangered species can be accorded the highest priority in the system. Young (1995:784) makes a similar case in reference to the operation of the Colorado River: "Although the Law of the River [Colorado River] is not technically a priority system, either expressed or implied priorities are created among those legally entitled to use water by the compacts, court decisions, statutes, and operating regulations that comprise the Law...[and] these priorities would presumably govern allocations in a severe drought situation."

In simple systems with few water users, assigning unit cost coefficients that preserve priority rank may appear to be a relatively straightforward task. However, even in these simple systems, the unit cost coefficients ck for water use k must satisfy several conditions if true system priorities are to be guaranteed under a variety of system configurations and flow conditions. Intuitive rules such as c1Ê<<Êc2Ê<< c3 may not always work. How is one to interpret "much less than"? Also, selecting arbitrarily large values, potentially resulting in a large range in the unit cost coefficients, may induce scaling problems in some optimization algorithms. Other rules such as the total penalty incurred by a water use with senior priority must be less than the sum of penalties incurred by all water uses with lower priorities also may not always provide the desired result.

Complications and difficulties with the use of these intuitive rules typically arise if return flows are incorporated in the NFP formulation. When return flows are modeled, the relative location of prioritized water uses is significant because it matters if the diversion and/or return flow points are upstream or downstream of senior or junior priorities. The studies cited in the previous section did not incorporate return flows, which may have facilitated the use of trial and error procedures or intuitive rules. The interaction between flow and storage penalties also is difficult to capture with intuitive rules. The following sections present an algorithm for assigning unit cost coefficients for flow and storage related penalties that guarantees that water use priorities are preserved.

3.4.2 Flow Related Penalties

Some guidelines, presented as rules, for determining a priority-preserving set of unit cost coefficients for flow related penalties are presented below. The guidelines embody the basic concept that until diverted from the stream, a unit of water released from storage can satisfy multiple non-consumptive instream demands, neglecting evaporation and seepage. However, once water is diverted from the stream, it is lost unless there is a return flow component. The interest in establishing the proper unit cost coefficients lies with the penalty incurred by the next unit of water to be allocated, i.e., the marginal penalty. Thus, the actual water right entitlement (or demand quantity) is not important. Priorities can be correctly represented so long as the unit cost coefficients, or slopes of the penalty functions, satisfy the conditions specified below.

The cost coefficient for the most junior rights holder, i.e., the lowest priority on the system, is used as the baseline measure and unit penalties are established for other users by applying the following Rules 1-4 sequentially in order of increasing use priority. The unit penalty for the most senior rights holder is determined last. The priority system can be verified by examining actual penalties incurred by the various water users. A senior priority should not incur penalties, that is, be deprived water, until all junior priorities have suffered the maximum penalty or shortage. Users having water rights with several priorities can be represented by a piece-wise linear penalty function in which each segment represents demand of a different priority, with the break points corresponding to the various entitlement levels. In this case, the appropriate unit cost is applied to each segment of the curve.

The following rules are described in terms of the penalty avoided for satisfying demands. The algorithm yields the absolute value of the unit cost coefficient. In implementing the algorithm care must be taken to provide the proper sign for the unit cost coefficients, which represent the actual slope of the penalty function (see Figure 3.1). Also, in the following, the term "unit penalty" refers to unit coefficients based on priority ranking and "unit cost coefficients" to unit coefficients based on economic criteria, though in the formulation of equation (1) they are analogous. Lastly, in the example accompanying each of the following rules, it is assumed for now that there are no storage related penalties and that each demand is equal to 10 units, which is also the entering flow rate for the single time period considered.

.c1.Figure 3.1 - Typical Flow and Storage Penalty Functions with Sign of Unit Cost Coefficient

Rule 1: Upstream Senior without Return Flows and Downstream Juniors

The unit penalty, Ps, on a diversion with senior priority and no return flow must be greater than the sum of unit penalties, Pj, on all junior priorities (N) located downstream, including both instream uses and diversions:

Ps > − i− su(j=1,N,) Pj (5a)

A simple example is illustrated in Figure 3.2. The highest priority water use, Ps, is also the most upstream diverter, and several junior rights holders, P1-P4, are situated downstream. P1, P2, and P4 are instream uses, and P3 is an off-stream diversion. There is no return flow from the diversion associated with the most senior rights holder (asÊ=Ê0). If water were allocated according to the unit penalty coefficients shown in Figure 3.2 (PsÊ=Ê80, P1Ê=Ê40, P2Ê=Ê30, P3Ê=Ê20, P4Ê=Ê10), the most senior rights holder would be shorted even though it has the largest unit penalty coefficient. To see this, note that by not diverting to Ps, a penalty of 900 is incurred (80 times 10 units demand for Ps plus 10 times 10 unit demand for P4; water would be diverted to use P3), but a penalty of 1000 for shorting all junior priorities is avoided. (P4 is shorted in both cases.) Therefore, to ensure that demands with the highest priority are satisfied first, the total penalty incurred for diverting must be less than the total penalty incurred for not diverting. Thus, in the example Ps must be greater than 100 (=Ê40Ê+ 30 + 20 + 10).

A more rigorous, but also more difficult to implement, version of Rule 1 addresses the existence of branches and multiple diversions downstream of the senior water use. The modified rule is presented in equation (5b), in which i represents the stream paths between the senior water use and the flow sink:

Ps > Maxi {− i− su(j=1,N,) Pij} for all stream paths i (5b)

In Figure 3.2, the two possible stream path alternatives to diverting to Ps are {P1,P2,P3} and {P1,P2,P4}, with penalties of 90 and 80, respectively. Thus, in this example, Ps would have to be greater than 90. Equation (5a) is a sufficient condition, and equation (5b) a necessary condition for determining Ps.

.c1.Figure 3.2 - Schematic for Rules 1 and 2

Rule 2: Upstream Senior with Return Flows and Downstream Juniors

The unit penalty, Ps, on a diversion with senior priority and return flow fraction as (0 < as <1) must be greater than (1 - as) times the sum of unit penalties, Pdj, on all junior priorities (N) downstream of the return flow point plus the sum of unit penalties, Puj, for all junior priorities (M) situated between the senior diversion point and the return flow point:

Ps > (1 - as) − i− su(j=1,N,) Pdj + − i− su(j=1,M,) Puj. (6)

Again referring to Figure 3.2, but now considering a return flow component, as, from the diversion of the most senior priority. The condition asÊ=Ê1 in which all diverted flow is returned to the river is equivalent to an instream use by the senior rights holder, and only those uses, Puj, situated between the senior diversion point and the return flow point are of concern. For asÊ=Ê0, equation (6) reduces to Rule 1. The condition with as > 0 is less stringent than that of Rule 1 because the return flow component reduces storages and penalties to junior rights holders. Using the unit penalty coefficients of the example in Rule 1 and a return flow of 30 percent (asÊ=Ê0.3), Ps would have to be greater than 82Ê(=Ê0.7(30Ê+Ê20Ê+Ê10)Ê+Ê40). Ironically, this rule could give rise to a situation in which Ps is less than some of the Pj and still be priority preserving.

Rule 3: Downstream Senior with Upstream Junior Return Flows

The unit penalty, Ps, on a diversion with senior priority located downstream of a diversion with junior priority and return flow fraction aj must be greater than the unit penalty, Pj, of the junior priority divided by (1 - aj).

Ps > − f(Pj ,1-aj) for aj - 1(7)

If several junior water rights holders divert upstream of the senior priority each with a different return flow component, only the highest of the junior priorities must be considered. In other words, if a senior user with priority n is located downstream of several junior priority holders that divert from the main channel, only the junior with priority n - 1 must be considered. The others are dealt with earlier in the sequential process of determining unit penalties.

A system in which the senior water use is located downstream of a junior priority with off-stream demand and return flow component aj is shown in Figure 3.3. The condition ajÊ=Ê0 represents a situation in which a water use with senior priority was located downstream of a water diverter with junior priority, but upstream of the spot where the junior's return flow re-enters the system. For ajÊ=Ê1, all water diverted by the junior rights holder is returned to the stream, and appears as an instream use to the senior rights holder. Thus, for ajÊ=Ê0 or 1, the situation is trivial in that so long as the unit penalty associated with the senior use is greater than that associated with the junior use, water rights priority will be preserved. (In fact, for ajÊ=Ê1, Ps can equal Pj because Pj would be a non-consumptive use.) To prevent the senior water user from being shorted when 0Ê<ÊajÊ<Ê1, the penalty on the senior water use associated with the amount of water available from the return flow must be greater than the unit penalty on the junior priority. That is, if all flow is diverted by the junior user and eighty percent is returned to the river and thus is available for the senior user, then the penalty on the senior for satisfying only eighty percent of demand must be greater than the unit penalty on the junior priority.

For example, the off-stream demand could be for a power plant that has junior rights for cooling water. Assume that 80 percent of the diverted flow is returned to the river, ajÊ=Ê0.8, and the unit costs for the senior and junior priorities are PsÊ=Ê100 and PjÊ=Ê50, respectively (see Figure 3.3). Under these conditions, the network flow

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.c1.Figure 3.3 - Schematic for Rule 3

algorithm would divert water for the junior rights holder at the expense of the senior. The total penalty for diverting to the junior user will be 200 (twenty percent unsatisfied demands for the senior) which is less then the penalty of 500 that would be incurred for fully shorting the junior priority. This condition would not satisfy the stated priorities because a senior is shorted while a junior receives full allotment. To be correct, PsÊ>Ê250Ê(=Ê50/(1-0.8)).

Rule 4: General Flow-based Seniority Penalty

If the point of diversion for the senior rights holder is such that junior rights holders are both upstream and downstream, the unit penalty for the senior priority, Ps, must be greater than the larger of the upstream (Rules 1 and 2) and the downstream condition values (Rule 3),

Ps > max {((1 - as) − i− su(j=1,N,) Pdj + − i− su(j=1,M,) Puj), − f(Pj ,1-aj) }. (8)

In most river basins, water users of various priorities are interspersed along the length of the river in no particular order. In such cases, Rules 2 and 3 need to be considered together. If the conditions of Rules 2 and 3 as shown in Figures 2 and 3 are combined as shown in Figure 3.4, the unit penalty, Ps, for the senior water use would have to be greater than 250. The conditions identified by the example accompanying Rule 2 result in a unit penalty coefficient of 100, while those of Rule 3, require a unit penalty coefficient of 250 for the senior water use.

Impure Priority Rules

In shortage situations, rarely will the prior appropriation doctrine or other rank-specifying mechanisms be strictly enforced to the extent that some users receive no water. Water conservation or some type of water rationing or water reallocation program would be implemented to avoid 100 percent shortages for many users. Economic based penalties can reflect the decreasing marginal benefit of water as supplies approach the demand level. Similarly, priority based penalty functions can be used to represent the reduced priority to the user for these last units of water.

Figure 3.5 represents the penalty function for a water user with two water claims of different priority. Claim 1 provides Q1 and Claim 2 provides D - Q1, where D is total demand. If ten percent water conservation were an option in dry years, this could be represented by reducing the priority on the last portion of Claim 2 water, as shown by the dashed line in Figure 3.5. The unit penalty on the segment 0.9D to D is set such that some or all junior water right holders receive water before the senior receives the full entitlement. In wet years, all demands would be satisfied and this additional priority would be inconsequential.

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.c1.Figure 3.4 - Schematic for Rule 4

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.c1.Figure 3.5 - Water Use with Varying Priorities

3.4.3 Storage Related Penalties

Wurbs and Walls (1989) note that in the modified Texas Water Code rights for reservoir storage were granted along with flow and diversion rights. More typically, however, prioritized storage uses, such as flood control, recreation, and minimum storage, are identified in authorizing legislation, judicial decisions, and in operating plans, not by water rights such as the prior appropriation doctrine. Nonetheless, storage rights and priorities are extremely important in system operation and legal judgments, and must be correctly accounted for because they can have tremendous influence on the analysis.

Reservoir storage is by far the most dynamic and complex arc in the network flow formulation. Unlike diversion, return flow, or flow-through arcs which are independent in time, reservoir storage arcs are linked in time by carry-over storage. Moreover, in addition to upper and lower bound constraints on storage capacity, storage arcs are bounded for the period of analysis by initial conditions and end-of-period target specifications. Also, reservoir storage is subject to evaporative losses, which vary by reservoir and are non-linear functions of storage. Evaporative losses are not considered in the following formulation. (Sun et al. (1995) developed an algorithm to incorporate such losses.) Following presentation of the rules for establishing unit penalty coefficients for storage, the influence of initial and end-of-period target conditions on system operation is addressed.

Rule 5: Storage vs. Storage Priorities

The unit penalty for a storage use of higher priority Pss must be greater than the unit penalty for a storage use with the next highest priority Psj:

$$Pss > Psj. \quad (9)$$

This rule would consider, for example, competing recreation uses at different reservoirs or different uses within the same reservoir, as specified by reservoir operation rules. For instance, to balance percentage storage in various reservoirs, Martin (1992) used storage penalty functions having approximately equal unit penalty coefficients at the same percentage of total capacity in each reservoir. To prioritize the order in which different reservoirs fill and draw down, the associated unit costs would be established according to the desired ranking, with the reservoir to be emptied last (highest priority storage) having the largest penalty. Storage penalties within the same reservoir are represented by a piece-wise linear penalty function. Kirby (1994) developed a "relative unit cost" method for establishing penalties for various storage related uses in a single reservoir.

The following rules apply to systems with mixed storage and release priorities.

Rule 6: Senior Storage with Downstream Junior Flow Priorities

The unit penalty, Pss, incurred at a storage arc with senior priority must be greater than the penalty incurred by all downstream flow demand points (N) with lower priority multiplied by the total number of time steps in the period of analysis:

$$Pss > T \; - i- su(j=1,N,) \; Pj \qquad (10)$$

where TÊ=Ênumber of time steps. If the NFP is used to optimally allocate flows within each time step of a simulation run, TÊ=Ê1.

This rule also would be subject to the downstream branching and diversion considerations discussed for Rule 1 (Equation 5b). However, this simpler version of the rule will always work.

Rule 7: Senior Storage with Upstream Junior Flow Priorities

The unit penalty, Pss, incurred at a storage arc with senior priority must be greater than the penalty incurred by upstream flow demand (N) with lower priority multiplied by the total number of time steps in the period of analysis and divided by (1-aj) if a return flow is associated with the junior water use:

Pss > T − f(Pj ,1-aj) , (11)

where TÊ=Ênumber of time steps. If the NFP is used to optimally allocate flows within each time step of a simulation run, TÊ=Ê1.

Rule 8: Mixture of Storage and Release Priorities

The unit penalty, Pss, incurred at a storage arc with senior priority must exceed the maximum of the upstream (Rule 7), downstream (Rule 6), or in-reservoir storage (Rule 5) condition values (Figure 3.6):

Pss > Max (T − i− su(j=1,N,) Pj , T − f(Pj ,1-aj) , Psj). (12)

The total penalty incurred is important in establishing unit penalty coefficients to represent relative priorities between storage and flow allocations. This is the reason for incorporating the length of model run (T) in equations (10-12). One unit of water released from storage to satisfy downstream demands is a one time use of water (although it may serve several purposes as it passes through the network). However, if that same unit of water is stored in the reservoir it would yield storage benefits (or avoid costs) each time step until it is released, while downstream flow related penalties suffer shortages every time period. For example, assume a very simple case in which a reservoir currently has one unit

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.c1.Figure 3.6 - Schematic for Storage Rule 8

of storage and receives no additional inflow in the period of analysis. Assume further that an instream use downstream of the reservoir demands one unit of flow. Storage and flow penalties are \$10/unit of water shorted. If water is released for the downstream demand, penalties in the first time period will be \$10 for the reservoir and zero for the stream demand, but \$20 for every time period thereafter (\$10 each for the reservoir and the flow). On the other hand, if water is retained in the reservoir, the only penalty incurred in each time step is the \$10 for not satisfying the flow demand. Thus, both the magnitude of the demand and the length of time during which the demand is not satisfied play a part in determining the proper unit penalty coefficient values for storage uses. Worst case conditions, i.e., maximum shortage and full period of analysis, should be used to guarantee that priorities are properly represented for storage-related penalties.

Although the rules for storage related penalties appear to be straightforward, the priorities associated with storage penalties are the most difficult to represent accurately. As noted earlier, Martin (1992) and others resorted to a trial and error process to develop priority based penalty functions for storage penalties. The difficulties arise because of the temporal aspects, and also because of user-specified initial and end-of-period target storage conditions required by the network flow models. The effect that these two conditions can have on water allocation is sometimes difficult to predict.

There is a "warm up" period in which initial reservoir storage conditions are brought into balance with the range of storage related penalties. The time needed for "warm up" depends on the initial reservoir storage, penalties associated with reservoir storage, inflow hydrograph, and downstream demands and penalties. As penalties on storage increase, reservoir releases may be limited to allow storage to build up to avoid potentially large storage related penalties, at the expense of incurring downstream flow penalties. Operation during this "warm up" period may not be representative of long-term strategic operations.

Similarly, there is a "cool down" period during which reservoir storage begins to seek an end-of-period target condition. Often an end-of-period target storage is specified and treated as a rigid constraint that must be satisfied (HEC, 1993; 1994). Again, the time required for this "cool down" period depends on the relationship between the target storage and the average operating storage during the model run and on the inflow hydrograph. Fortunately, HEC-PRM permits the user to specify a penalty for satisfying the specified end-of-period target storage rather than make the end-of-period target a fixed constraint. Thus, the "cool down" period can be greatly reduced with a reasonable penalty on end-of-period storage. Or, if a realistic end-of-period penalty is used, the cool down period can provide significant results.

Regardless of user-specified priorities, the network flow algorithm, first and foremost, will internally seek to provide a feasible solution. Flows and reservoir storages will be allocated to avoid infeasibilities (e.g., negative storage) at the expense of suffering large penalties for not satisfying the user-specified priorities.

3.4.4 Persuasion Penalties

Operators of complex water resource systems must contend not only with primary project purposes (e.g., prioritized water uses and uses with high economic value), but also with a myriad of secondary operating criteria. These secondary criteria may represent the "philosophy" underlying operation of a particular system. They comprise the subtle rules that experienced operators have developed to answer questions such as "If there is excess water, where would we rather have it, in storage (if so, in which reservoir), in the stream, or at a specified diversion point?" In a network flow formulation, these criteria can be represented with "persuasion penalties", so called because of their secondary, low priority nature.

Persuasion penalties are used to nudge the optimization algorithm in the desired manner to more accurately represent secondary operating criteria. Persuasion penalties are applicable to both economic- and priority-based analyses so long as there is no chance of them interfering with the primary operating purposes. These penalties must have the lowest overall priority for priority-based analysis, or the lowest cost for economically-based analysis. In the event that persuasion penalties of varying priorities are needed, the ranking rules presented above in equations (5-12) can be used to properly set the penalty coefficients and ensure that persuasion penalties are low enough to not interfere with primary operating purposes.

Persuasion penalties are commonly used in reservoir optimization studies, although not always explicitly. For example, Martin (1992) used a penalty function with a unit cost of one to keep water in the desired reservoir. Similarly, HEC (1993:PR-21) used "...very minor non-economic penalties which encourage releases within the physical limits of the project." Insight on existing flexibility in system operation can be gained by systematically changing the magnitude of cost coefficients on the persuasion penalties.

Persuasion penalties also can be used to overcome some of the quirks of the network flow algorithm. For instance, if the unit cost coefficient ck is the same for two or more arcs, or if several arcs have no associated penalties, the NFP algorithm will internally allocate flow quantities through these arcs. The final allocation will depend to a large extent on how the network is defined in the input file, i.e., the order in which the arcs and nodes are specified. In such cases, including persuasion penalties on selected arcs can reduce or altogether eliminate this internal flexibility. In other words, persuasion penalties can be used to "tighten up" the system, and let the user, not the algorithm, guide allocation decisions.

3.5 Linear Program for Assigning Unit Penalties

Rules 1-8 (Equations 5-12) for determining unit penalty coefficients for priority-based penalty functions are linear. Therefore, the problem of assigning such coefficients can be formulated as a linear program, so long as the objective function is also linear. This section presents such a linear program (LP). As noted previously, unit cost coefficients can be determined by applying the above rules sequentially beginning with the lowest priority use.

One of the issues mentioned earlier with regard to the random or trial and error selection of unit penalty coefficients is the potential for scaling problems in the NFP solution algorithm which may arise if the final coefficients vary too greatly in magnitude. To avoid this problem, the objective function for the proposed linear program is to minimize the range of unit penalty coefficients. The mathematical model is formulated as follows:

Min Z = P1 - PN (13)

Subject to:

(i) Pp ³ Pp+1 + e "p = 1,...,N-1 (14)

(ii) Pp ³ (1 - ap)− i− su(− a(j>p),K,) P'j + − i− su(− a(j>p),L,) P"j + e "p = 1,É,N (15)

(iii) Pp ³ − f(1 ,1-ap-1) Pp-1 + e "p = 1,É,N (16)

(iv)Psp ³ Ps,p-1 + e (17)

(v) Psp ³ T − i− su(j=1,N,) Pj + e (18)

(vi)Psp ³ T − f(Pj ,1-aj) + e (19)

(vii) PN = Base (20)

(viii) Pp ³ e "p = 1,É,N (21)

where,

Pp = penalty coefficient on water use with priority p, for p = 1,É,N, where P1 has highest priority and PN the lowest,

ap = return flow fraction for water use with priority p,

P'j = penalty coefficient for water use with priority j located downstream of return flow confluence, for jÊ=Ê1,É,K,

P"j = penalty coefficient for water use with priority j located between point of diversion and return flow confluence, for jÊ=Ê1,É,L,

Pp-1 = penalty coefficient for upstream water use having the next lowest priority to water use with priority p,

Psp = penalty coefficient on storage with priority p,

e = an arbitrarily small positive number, e > 0.

Strictly speaking, constraint (i) is not necessary. Though it is counter-intuitive, a water use of higher priority can, in fact, have a unit penalty coefficient lower than that of a water use of lower priority, and the NFP algorithm will still preserve priority ranking in allocating flows. The constraint is included in the formulation to maintain the order between a prioritized water use and its unit penalty coefficient. In this formulation Pp can include true system penalties and persuasion penalties.

The LP can be used as a pre-processor to the NFP model or it can be embedded in the model to be solved as part of the NFP formulation. If used as a pre-processor, the LP is solved as a stand alone component and the resulting unit penalty coefficients are used to generate the necessary penalty functions for the NFP. If the LP is embedded in the NFP model, standard input for node and arc designations would have to be supplemented to include priority information. Also, since the rules depend not only on the priority of the water use, but also on its location relative to other water uses and whether it is an instream or off-stream use, the algorithm would need to communicate with the NFP node connectivity matrix to access this geometric information.

The node connectivity matrix is used to establish relative river location for all water use points, and, thus, the algorithm would be able to identify upstream and downstream water uses of higher or lower priority. The necessary penalty functions would be internally generated by combining the unit penalty coefficients and the demand for each prioritized water use. In this case, water use priority variables in the LP need to be double indexed; the first index reflecting system priority and the second identifying relative location in the system. The objective function remains unchanged.

A limitation of the algorithm and priority-based penalty functions, in general, is that it does not guarantee convex composite penalty functions, as required by network flow optimization programs. Convexity requires that the priority of water uses, as represented by the unit penalty coefficient, be monotonically increasing with increasing or decreasing streamflow for flow arcs, or with storage, for reservoir arcs. This is illustrated by the solid curve in Figure 3.7. However, since the algorithm and priority-based penalties do not intrinsically recognize flow or storage quantities for the prioritized uses, it is possible to generate a non-convex penalty function, as shown by the dashed line in Figure 3.7.

.c1.Figure 3.7 - Convex and Non-Convex Penalty Functions

3.6 The Choice of Penalty functions

Analysis using priority-based penalty functions can be extended easily beyond the realm of water rights institutions to incorporate "value" judgments regarding non-water righted and non-economic uses such as recreation, instream flow for fish and wildlife habitat, and other environmental purposes. Since the unit of analysis is priority, the problem of non-commensurate units is avoided. However, priorities associated with non-water righted uses are not so easily determined. Often there are strong feelings expressed by conflicting parties as to the priority or significance of environmental and other non-economic water uses. It is also difficult to determine who is to establish the priorities. Parametric studies in which the priorities of the non-economic water uses are systematically varied through a predetermined range can be used to assess the influence that these uses have on water availability to righted uses, and to identify a trade-offs among various non-economic and economic uses. This issue is pursued further in Chapter 5.

Priority-based penalty functions tend to have simpler forms than economic penalty functions. Typically, simple linear functions suffice to properly represent water use priorities. Although simple linear penalty functions can reduce problem size substantially (piece-wise linearization of complex economic penalty functions can result in larger problems), it may also result in a "looser", less constrained system. In less constrained systems, the solution space around the optimal solution will tend to be rather flat (Rogers and Fiering, 1986). This characteristic may cause the optimal solution to be more susceptible to slight modifications in penalty function parameters (e.g., persuasion penalties) and system configuration. Also the less constrained systems may have longer run times as the solution algorithm oscillates around the decision points.

When economically-based penalty functions are used, total penalty can be interpreted as the minimum economic cost of operation, and the difference in penalties among various alternatives as an increase or decrease in economic benefits of implementing the alternative. Because the economic value of water is excluded from the analysis, this type of interpretation is not possible when priority-based penalties are used. Since the penalty coefficients for priority based penalty functions are arbitrarily specified, so long as conditions (5)-(12) are satisfied, the information content of the results is quite limited. In this case, penalty information can be used for comparative purposes only. No economic interpretation can be made. This may be the greatest weakness of the priority-based approach.

3.7 Conclusions

An algorithm was presented to assign unit penalty coefficients for use within a network flow programming framework to properly represent water use priorities under most system configuration and flow conditions. It is impossible to foresee all possible system configurations, but the rules presented are general enough to cover many configurations. Special cases can be incorporated by modifying specific rules accordingly or by developing new rules. The algorithm, which is formulated as a linear program, accounts for both storage and flow penalties and incorporates the effects of return flows on flow allocation. If it were not for the influence of return flows and the relation between storage and flow priorities, simpler, possibly more intuitive approaches could be used to establish unit penalty coefficients.

This chapter also touched on the differences between the use of economic and priority based penalty functions for systems analysis. The merits and drawbacks of each were mentioned. The approach chosen should depend largely on the focus of the study. Economic based studies will provide insight on minimum cost operation, whereas priority based analyses often better represent institutional constraints and operating criteria.

Finally, it may be possible to implement a mix of priority-based and economically-based penalty functions. In a two-stage process, the priority based functions would be used to satisfy water rights first. Flows in excess of water entitlements would then be allocated according to the economically-based functions. In essence, economic penalty functions would be used to allocate surplus water. This combination of penalty function types also may be used to allocate water in shortage situations in which the priority system is not strictly enforced.

CHAPTER 4
ANALYSIS OF THE TRUCKEE-CARSON RIVER SYSTEM

4.1 INTRODUCTION

4.1.1 Purpose

The analysis presented in this chapter serves two purposes. First, it demonstrates an application of the algorithm developed in Chapter 3 for determining unit penalty coefficients. Second, the analysis uses a screening level priority-based optimization model to evaluate several management alternatives for the Truckee-Carson system.

Water allocation in the Truckee-Carson system has been a contentious issue for most of this century. Current system operating policy has evolved over the years in response to numerous conflicts and complicated agreements, compacts, and legislated requirements and mandates. The Negotiated Settlement Model (NSM) is the only model currently available to analyze system operation and evaluate management alternatives. The intricacies of this simulation model, with many of the operating policies embedded in the model's FORTRAN code often make it difficult to adequately test proposed management alternatives that involve changes to these policies. The priority-based optimization model presented in this chapter provides a screening level operational analysis of the Truckee-Carson system. The purpose of the analysis is not reservoir operation directly, but the impact on downstream demands of various management alternatives. The analysis assumes that all water in the system is available to satisfy any or all downstream demands, subject only to user priority, mass balance, and storage constraints. Complicated operating criteria such as storage exchanges and credit water accumulation stipulated in legal agreements are not represented.

By stripping away the complicated operating criteria and focusing primarily on the essentials of total water availability and water use priority, the analysis should indicate instances in which institutional requirements may inadvertently reduce system performance. Results of this analysis should point to promising avenues for further system evaluation, and possibly provide some motivation for revisiting the intricate legal requirements currently governing system operation.

Analysis of the Truckee-Carson basin is divided into two parts. In the first part, presented in this Chapter, existing operation based on satisfying the legally mandated Floriston Rates is compared to operation based solely on satisfying prioritized downstream water demands without having to satisfy Floriston Rates. Within this framework, the response of the system to relaxing existing maximum water surface elevation restrictions at Lake Tahoe and closing the Truckee Canal are evaluated. In this initial analysis, non-water righted uses, such as environmental demands and in-reservoir uses, are given low priority. In the second part of the analysis, presented in Chapter 5, priorities for environmental water uses are systematically increased and the effects on water allocation to the water-righted, prioritized uses and among the various environmental uses are evaluated.

4.1.2 Modeling of the Truckee-Carson System

Several simulation models exist for the Truckee-Carson system. The most widely used is a mass balance, water accounting model known as the Negotiated Settlement Model (NSM). The NSM was developed in the early 1970s by the Bureau of Reclamation and Sierra Pacific Power Company (Westpac, 1988). The model has been under continual revision and modification since its inception, primarily to incorporate new operating agreements or test proposed management alternatives. Although there are reservations about the model's accuracy and validity, it is reluctantly accepted by most parties involved in the ongoing studies in support of the Truckee River Operating

Agreement (TROA) simply because there is no better alternative. (The USGS is developing a daily simulation model of the system, but it is not expected to be ready for several years.) There are questions regarding NSM's representation of the physical system. But, more importantly, there are concerns that the model does not adequately represent the system's complex legal and operation requirements. Furthermore, because some features of current operating policy were perceived to be non-negotiable by model developers, they are "hard-wired" into the model code and cannot be changed easily. Thus, the NSM does not provide the flexibility to model many alternative operating scenarios. Presently, efforts are underway to document and substantiate the model; i.e., the model is undergoing an "institutional verification".

The NSM is one of a suite of models that work together to evaluate operations of the Truckee-Carson system. Other models include HAB14, developed by the U.S. Fish and Wildlife Service to simulate Cui-ui spawning behavior in Pyramid Lake and the Lower Truckee River (Buchanan and Streckal, 1988); the Below Lahontan Model, developed by the Environmental Defense Fund to model in more detail operation of the Carson Division of the Newlands Project and impacts on inflows to the Stillwater Wildlife Refuge (EDF, 1994); a water quality model, developed by Brock *et al.* (1989) to simulate water quality impacts in the Lower Truckee River of proposed management alternatives; and the Truckee-Meadows Model, developed by Sierra Pacific Power Company to forecast water demands and water depletion in the Reno-Sparks urban areas. The Truckee-Meadows Model provides input to the NSM. The other models require output from the NSM.

In addition, several models have been developed for simulating the impacts of different management alternatives on water quality in the Truckee River (Nowlin, 1987; Brock *et al.*, 1989). Warwick and Heim (1995) developed a hydrodynamic model of the Carson River system, including Lahontan Reservoir, to simulate sediment transport and ultimately the fate of mercury in the Carson River system. The USGS is developing a daily hydrodynamic model of the Truckee River system, including Lake Tahoe and all upper Truckee reservoirs. The USGS model is intended to be used for operation analysis.

The analysis presented here is the first application of an optimization model to the entire Truckee-Carson system. Previous optimization studies considered selected components of the system. For example, MacDiarmid (1988) used an optimization model to evaluate the economic impact of proposed target efficiency requirements on agricultural production in the Carson Division of the Newlands Projects.

4.1.3 Use of HEC-PRM

Typically, optimization models have been used to examine optimal operating policies for a water system given a set of economic penalty functions reflecting user values. The operating rules inferred from the optimization results are then verified and fine-tuned by simulation modeling (USACE, 1993, 1995; Lund and Ferreira, 1996). Optimization models also can be used in a comparative framework to evaluate "optimal" operation given different sets of penalty functions representing different implied operating strategies. By altering the relative weight of penalty functions for different uses, for instance, placing greater relative penalties on satisfying reservoir storage targets than satisfying various downstream demands, different operating conditions can be evaluated. Also, different management alternatives can be represented by changing the capacity of physical facilities and system constraints. As such, models like the U.S. Army Corps of Engineers' Prescriptive Reservoir Model (HEC-PRM) (HEC, 1994) can be used to preliminarily evaluate and refine planning and management alternatives. This is the purpose of the current application.

HEC-PRM has been used to evaluate the operation of several river-reservoir systems, including the Missouri River (Lund and Ferreira, 1996), the Columbia River (USACE, 1993; 1995; 1996), and the Alamo Reservoir in Arizona (Kirby, 1994).

While the Truckee-Carson system is smaller than most previous systems analyzed with HEC-PRM, the physical system presents some conditions not previously analyzed. First, a branching system with multiple diversions from a single node is represented; and, second, return flows are included for agricultural and municipal uses. In the Truckee-Carson system, return flows are a significant part of available water in the system's lower reaches. Another difference from previous HEC-PRM applications is that the analysis is formulated with priority-based penalty functions instead of economically-based functions. The optimization was performed using penalty functions that reflect the priority-based appropriative water rights system.

4.2 REPRESENTATION OF THE TRUCKEE-CARSON SYSTEM

4.2.1 Physical System

The network flow algorithm in HEC-PRM requires that the river-reservoir system be represented as a set of arcs and nodes, in which arcs represent flows in the system and nodes represent control points, including reservoirs, demand points, and points of diversion (see Section 4.2). Numerous simplifications are necessary to represent the system in a network flow framework. While few reservoir systems conform exactly to these simplifications, the model retains an ability to represent many of the most important aspects of reservoir problems and should be able to provide at least qualitative insight to the problem of optimizing reservoir operations (Lund, 1996).

The simplified network representation of the Truckee-Carson system is shown in Figure 4.1. For comparison, a schematic of the actual system is shown in Figure 4.2. The network consists of 27 nodes and 53 arcs per monthly time step. Six nodes represent storage reservoirs: Lake Tahoe, Pyramid Lake, and Prosser, Stampede, Boca, and Lahontan Reservoirs. Reservoir characteristics are presented in Table 4.1. The usable capacity of Lake Tahoe was modeled as 762,000 ac-ft (762 KAF) instead of the actual 732 KAF. This was done to evaluate the effects of increasing the maximum pool elevation from 6229.1 ft. msl to 6229.35 ft. msl. For alternatives which do not consider this possibility, an upper bound of 732 KAF was used. Modeling Lake Tahoe requires special consideration because the water level can fall below the lake's natural rim. The next section discusses modeling of Lake Tahoe in more detail.

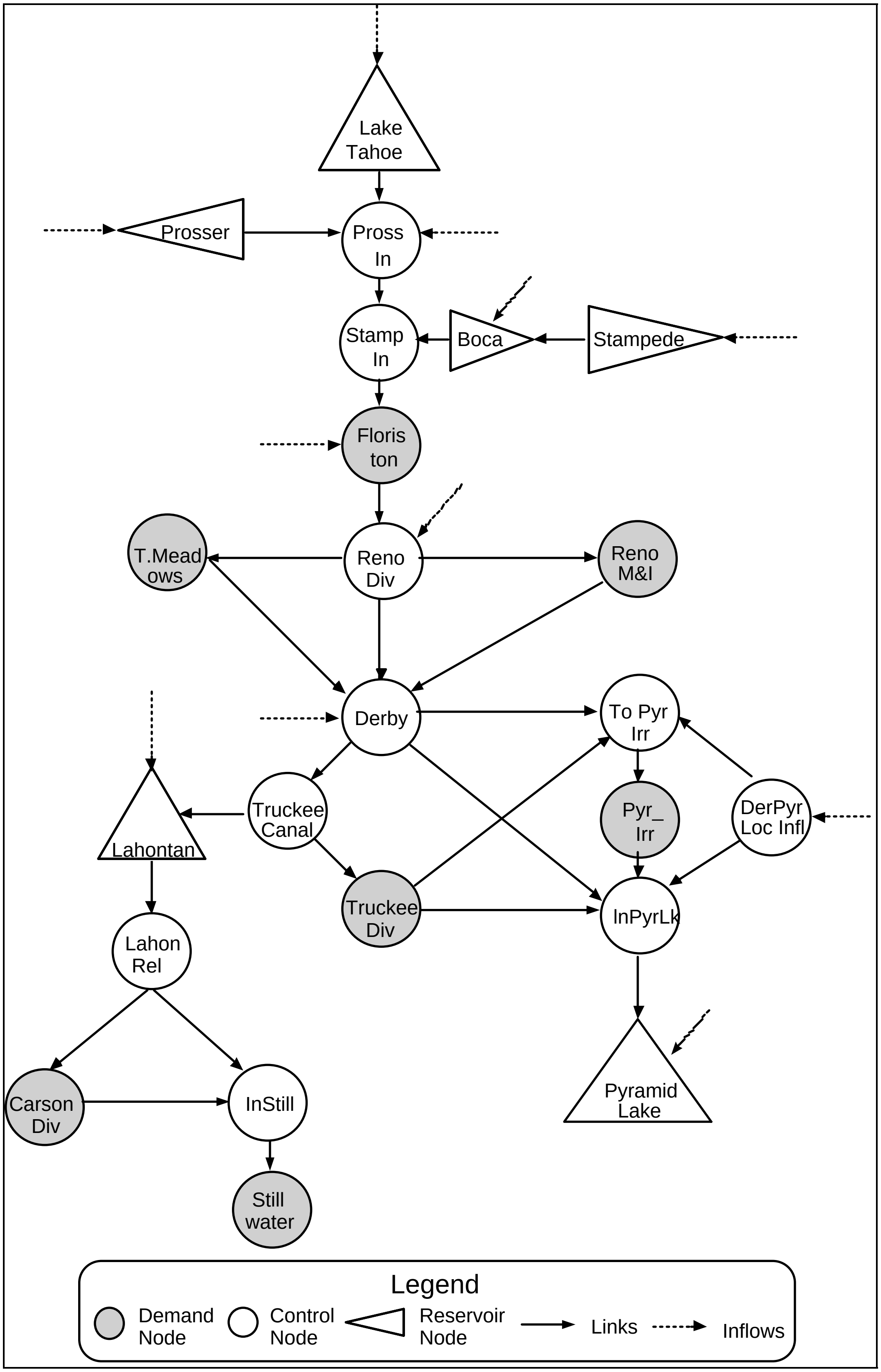


Figure 4.1 - Schematic of Truckee-Carson System Used in HEC-PRM

Pyramid Lake is modeled as a reservoir without releases, except evaporation. Maximum storage capacity for Pyramid Lake is set sufficiently large so it would not artificially limit inflows to the lake. Independence and Stampede Reservoirs on the Little Truckee River are combined in the model. Donner Lake and Martis Creek Reservoirs are not modeled because of their small contributions to overall system water supply and limited operational significance given the scope of this study. If a more detailed operational study of the Truckee-Carson system is required, Donner and Martis Creek Reservoirs can be incorporated and Stampede Reservoir can be disaggregated to reflect operation of Independence Lake. The remaining nodes, as shown in Figure 4.1, are demand and control points. Upper bounds on flow arcs were used to represent release capacities from all reservoirs, Truckee River channel capacity through Reno (6,000 cfs), and the Truckee Canal capacity (900 cfs).

Table 4.1 - Reservoir Node Characteristics

Reservoir Node	Minimum Storage (KAF)	Maximum Storage (KAF)	Release Capacity (KAF/mo.)
Lake Tahoe	0.0	762.0[1]	180.0
Prosser Reservoir	1.2	29.8	115.0
Stampede Reservoir	4.6	244.0[2]	163.0
Boca Reservoir	0.0	40.9	480.0
Pyramid Lake	0.0	29,170.0	N/A
Lahontan Reservoir	4.0	319.4[3]	121.0

1. Usable storage capacity in Lake Tahoe is 732 KAF at elevation 6229.1 ft. msl. It was modeled as 762 KAF (el. 6229.35 ft. msl) to incorporate flood damage and to evaluate alternatives involving higher lake levels.
2. The capacity of Stampede Reservoir is 226.5 KAF and of Independence Lake 17.5 KAF. Release capacity listed is for Stampede reservoir
3. Assumes 1.67 ft flashboards are in place; without flashboards, maximum storage is 295.0 KAF.

Additional simplifications to the physical system include the following:

- Diversions from the Lake Tahoe watershed or withdrawals from the lake other than releases to the Truckee River are excluded.
- Diversions from the Little Truckee River system to Sierra Valley are not modeled. These are relatively minor diversions and should not affect model results significantly.
- Ground water accretions to and seepage losses from the Truckee River are not modeled. Ground water accretions to the Truckee River below Derby Diversion Dam are assumed to be zero. These accretions are a function of diversions to the Truckee Canal; such a conditional constraint cannot be represented in HEC-PRM.
- Return flows from the Reno-Sparks wastewater treatment plant are assumed to be 56 percent of the amount diverted by Reno-Sparks for M&I use. This value is the average annual return flow computed from the input data for the NSM.
- Agricultural return flows from Truckee-Meadows and the Newlands Project are assumed to be an unlagged 30 percent of the amount diverted for irrigation. Half of the return flows from the Truckee Division of the Newlands Project are assumed to go for irrigation by the Pyramid Lake Paiute Indian Tribe and half are assumed to flow directly to Pyramid Lake.
- Seepage and evaporative losses in the Truckee Canal are assumed to be 15 percent of the flow diverted at Derby Dam. Actual losses are a seasonally-varying function of flow in the Canal and cannot be represented exactly in HEC-PRM. Thus, a linear loss function is assumed.

The arc amplitude factor (a_k in equation 2, Chapter 3) was used to model return flow as a percentage of diverted flow in every time step. The arc amplitude factor also was used to represent instream losses where applicable.

4.2.2 Modeling Lake Tahoe

Lake Tahoe is a natural lake with a controlled outlet. The outlet structure was constructed approximately 400 feet downstream of the lake's natural outfall. The dam controls the upper six feet of the lake, providing a usable storage capacity of roughly 732 KAF between the natural rim elevation of 6233.0 ft and elevation 6229.1 ft. However, when the lake's water surface falls below the natural rim, releases are not possible (see Figure 4.2). Although the dam is capable of providing additional storage, the lake’s maximum water surface elevation is stipulated by the Truckee River Agreement to be 6229.1 ft and this limit is strictly enforced in operations.

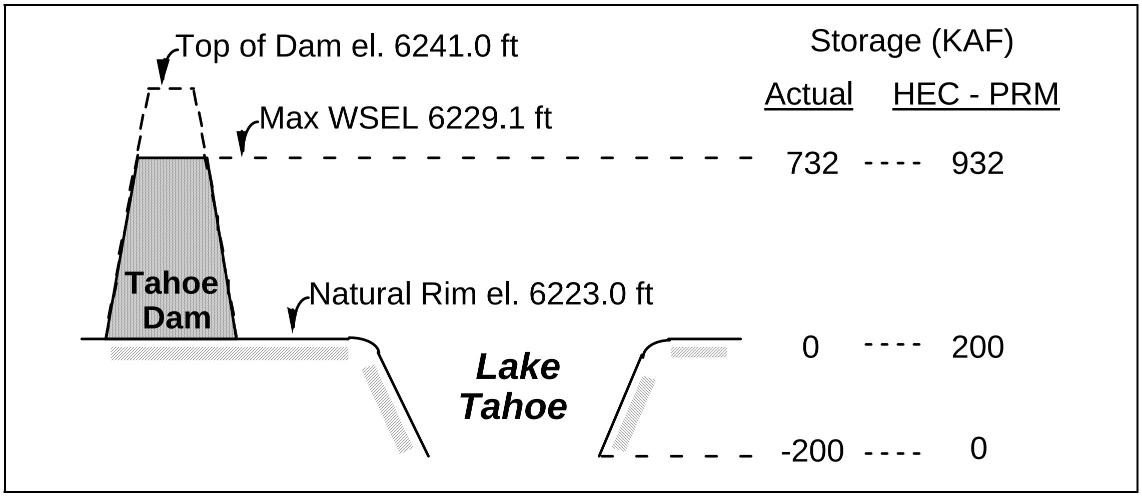


Figure 4.2 - Schematic of Lake Tahoe

Since HEC-PRM does not allow negative storages, considerable attention was given to representing Lake Tahoe. One option analyzed incorporated an inactive pool with very high penalties for encroachment. However, since the hydrologic data used for Lake Tahoe are net inflows, which can be negative because they include evaporation losses, significant negative inflows can "activate" the inactive pool regardless of the penalties. Furthermore, because reservoir releases cannot be conditioned on storage in a typical network flow formulation, even with the large penalties, it is impossible to restrict releases from the inactive pool. In fact, the penalties should be structured to prevent releases from the inactive pool, not to prevent encroachment into this area.

This type of penalty structure can be achieved with the hydropower algorithm developed for HEC-PRM (Martin, 1987; HEC, 1993). The algorithm uses the method of successive linear approximation to evaluate reservoir operation for hydropower generation. Nonlinear hydropower penalty functions are represented by a suite of piece-wise linear curves. Each curve represents a different level of storage and estimates hydropower penalties as functions of reservoir releases for that storage level (HEC, 1993). Typical hydropower penalties as functions of reservoir releases (or flow through the turbines) are somewhat U-shaped, with large penalties associated with releases below some target release level and possibly somewhat lower penalties for releases above the target level.

Lake Tahoe does not have hydropower facilities, but the algorithm can be used to restrict releases from the lake when the water surface is at or below the natural rim (storage of 200 KAF or less in Figure 4.2), while still allowing the water surface to fall below this level. For constant storage at or below the natural rim, a very high unit cost is applied for the full range of releases. This unit cost must be sufficiently large to overcome aggregated penalties incurred due to shortages at downstream demand points. For storage levels above the natural rim, (above 200 KAF in the model) the unit cost for any release is very small.

For the hydropower algorithm to function properly and to avoid negative storages, Lake Tahoe storage capacity was modeled as 932 KAF, with the natural rim elevation corresponding to a storage of 200 KAF. No releases were allowed for storage levels below 200 KAF. Usable storage is maintained at 732 KAF (or 762 KAF for the alternatives that consider higher water surface elevations). Lake Tahoe "hydropower" penalties are shown in Figure 4.3. Penalty functions for constant storages of 0, 190, 200, 210, 211, and 932 (or 762) KAF were used to improve the interpolation performed by the hydropower algorithm by reducing the discontinuity among penalty curves. Also, because the algorithm uses average monthly reservoir storage to determine releases, establishing a range of “no-release” storages (190-210 KAF) helps ensure that realistic conditions are represented.

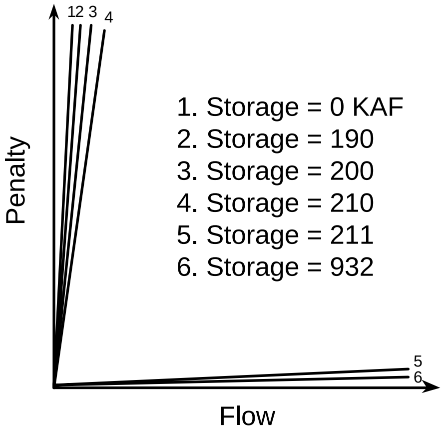


Figure 4.3 - Penalties on Releases from Lake Tahoe

Storage penalties for Lake Tahoe are shown in Figure 4.4. Persuasion penalties are used to dissuade storage from falling below 200 KAF. When maximum storage of 732 KAF is strictly enforced, penalties for storage above this level are very steep. For alternatives that consider additional storage capacity in Lake Tahoe, persuasion penalties are used to dissuade, but not restrict, use of the additional storage (dashed line in Figure 4.4).

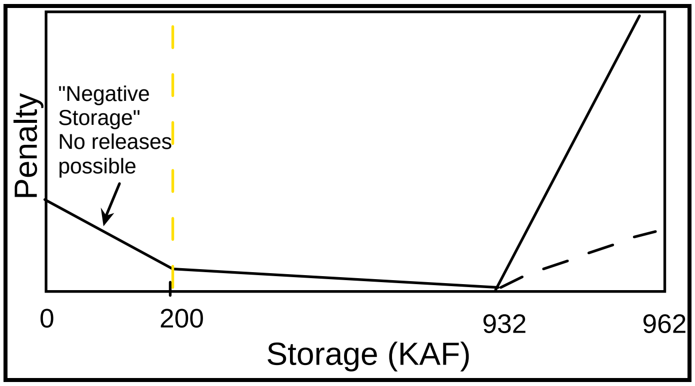


Figure 4.4 - Storage Penalties for Lake Tahoe

4.2.3 Hydrologic Data

Ninety-five years (1901-1995) of hydrologic data are available for the Truckee-Carson system. These data include reservoir inflow, reservoir evaporation, and local inflow at various points in the system. The hydrologic record is constructed from recorded and estimated monthly data. Gaps in the historic record were filled using various, and often unknown methods (Stetson Engineers, Inc., 1996). Also, there are some concerns about the stationarity and validity of the hydrologic data. The source of all hydrologic data is the NSM input files, a detailed description of which is provided in Stetson (1996). The recent drought of 1987-93 typically is used in water supply planning studies in the Truckee-Carson basin as the most severe drought of record. Additional drought periods of significance include the major 1929-34 drought, and the less severe droughts of 1958-1962 and 1976-1977.

The hydrologic data was modified as necessary to correspond with the simplified representation of the physical system (Figure 4.1). The following modifications and assumptions were necessary:

- Local inflow to Stampede Reservoir and Independence Lake are combined.
- Donner and Martis Creek inflows are combined and assumed to enter the system at the Prosser Creek confluence.
- Local inflows between Lake Tahoe and Farad are assumed to enter the system at Farad.
- Farad-Derby depletions and accretions are assumed to enter the system at Derby. Since, on average, depletions are larger than accretions, the amount of water available for Truckee Meadows demands tends to be over-estimated, while supplies to demands downstream of Derby are under-estimated.

- Inflows from Dog and Hunter Creeks were combined and assumed to enter the system at the diversion point for Reno and Truckee-Meadows. These inflows are available for diversions.
- Half of the local inflows between Derby Diversion Dam and Pyramid Lake are assumed to enter the system at Derby Dam and are available to meet Pyramid Lake irrigation demands. The balance is assumed to enter Pyramid Lake directly.

Evaporation from Lake Tahoe and Pyramid Lake constitutes a significant water loss from the system. Average annual evaporation from Lake Tahoe and Pyramid Lake is estimated at approximately 375 KAF and 440 KAF, respectively, compared to an average annual inflow of 1.055 million ac-ft (MAF) to the entire system. Evaporation from Lake Tahoe is incorporated in the inflow data, which defines net inflow to the lake. Average monthly evaporation data (reservoir loss data) for Boca, Prosser, Stampede, and Lahontan Reservoirs are taken from the NSM input data. Pyramid Lake average monthly losses were calculated from the time series of water surface elevation changes assuming no inflows to the lake. The average monthly values for the 95 year period were used. Evaporation coefficients for all reservoirs are listed in Table A.1 in Appendix A.

Evaporation calculations in HEC-PRM require that the area-storage relationship be approximated with a linear function. Simple linear regression of the area and storage values generated by the area-storage curves developed for the NSM was used to estimate the linear coefficient. To better balance the over- and under-estimation of evaporation, the linear regression was done for several ranges of reservoir storage. This places a higher weight on providing a better approximation of the area-storage curve for the higher storages when evaporation is more important, than for the lower storage levels when evaporation may be less significant. For example, it is unlikely that Pyramid Lake storage would fall below 15,000 KAF (the historic low is about 19,000 KAF). Therefore, the linear regression was performed for the area-storage curve above this point.

Although 95 years of hydrologic data are available, the period of record used for the HEC-PRM analysis was the 80 year period from 1915 to 1995. This was done primarily to reduce problem size and model run time. The 15 year reduction in period of record reduces the problem from one of 27,363 nodes and 60,232 arcs to one of 23,043 nodes and 50,722 arcs. Run time decreased by almost 20 percent in one case, from 12.1 hours to 9.71 hours. The first 15 years of record were fairly wet years, and, in fact, in initial runs made using the 95 year record, all reservoirs refill by 1915. Therefore, omitting the initial years should not significantly affect the results.

4.2.4 Water Demands

There are many and often conflicting water demands on the Truckee-Carson system, including municipal and industrial (M&I) uses, irrigation, reservoir and river recreation, run-of-the-river hydropower generation, environmental uses for instream flow and habitat preservation, and wastewater dilution. And, as with most water systems, there are discrepancies about demand estimates for the different uses. The water righted uses considered in this study are listed below and the average monthly demands for each are shown in Table 4.2. Average annual demand for these uses is 438.2 KAF. Estimated future demands from the NSM are used. All demands are assumed met with surface water since ground water supplies are not represented in the model. No reductions in demands were made for users known to use ground water or other supplemental supplies, such as the City of Reno. In order of priority, the water righted demands are

1) Pyramid Lake Paiute Indian Tribe irrigation water (Claims 1 and 2 of the Orr Ditch Decree),
2) Sierra Pacific Power Company's initial 40 cfs (2.4 KAF/month) for Reno M&I,
3) Truckee-Meadows irrigation (individual Truckee-Meadows ditch demands were aggregated into a regional demand for the Truckee-Meadows area),

4) Sierra Pacific Power Company's demand exceeding 40 cfs for Reno M&I, and

5) Irrigation in the Truckee and Carson Divisions of the Newlands Project.

Table 4.2 - Monthly Water Demands for Water Righted Uses (KAF/month)[1]

Month	Pyramid Lake Irrigation	Reno M&I	Truckee Meadows Irrigation	Carson Division[2]	Truckee Division
January	0.30	6.82	0.10	0	0
February	0.28	6.33	0.10	0	0
March	0.30	6.96	0.10	3.93	0.10
April	1.00	8.96	1.57	25.47	1.33
May	2.97	11.98	5.62	44.83	3.64
June	2.80	13.69	5.45	43.30	3.80
July	3.70	15.26	6.38	45.24	3.97
August	4.34	14.53	5.70	40.86	3.44
September	2.51	12.03	3.17	29.29	2.18
October	0.30	8.93	0.10	14.92	1.06
November	0.30	6.83	0.10	4.06	0.18
December	0.30	6.68	0.10	0	0
Annual Total	19.10	119.00	28.49	251.90	19.70

1. All demand data is from the "Future Without TROA" Negotiated Settlement Model input file NRUNDATA dated March 17, 1995.
2. Estimated future demands for the Truckee and Carson Divisions of the Newlands Project were recently modified. Annual demands for the Carson and Truckee Divisions increased to 264.5 KAF and 23.0 KAF, respectively. Monthly distribution remains unchanged. The values listed in the table were used in this study.

Non-water righted demands on the Truckee-Carson River system include minimum instream flow requirements below some of the reservoirs, inflow to Pyramid Lake, storage in Pyramid Lake, and inflow to the Stillwater National Wildlife Refuge. Average monthly demands are listed in Table 4.3.

Table 4.3 - Environmental Water Demands (Non-Water Righted Uses)

Month	Minimum Release Requirements[1] (KAF/month)			Pyramid Lake Inflow[2]	Stillwater Inflow[3]
	Lake Tahoe	Prosser	Stampede	(KAF/mo)	(KAF/mo)
January	3.02	0.30	1.81	60/ 150	0
February	3.02	0.30	1.81	60/ 150	0
March	3.02	0.30	1.81	60/ 150	16.66
April	4.23	0.30	1.81	60/ 150	16.66
May	4.23	0.30	1.81	60/ 150	16.66
June	4.23	0.30	1.81	60/ 150	16.66
July	4.23	0.30	1.81	0	16.66
August	4.23	0.30	1.81	0	10.42
September	4.23	0.30	1.81	0	10.42
October	3.02	0.30	1.81	0	10.42
November	3.02	0.30	1.81	0	10.42
December	3.02	0.30	1.81	0	0
Annual Total	43.50	3.60	21.72	360/900	124.98

1. Minimum instream flow (MIF) requirement downstream of Lake Tahoe is 50 cfs from October-March and 70 cfs from April-September; Stampede and Prosser Reservoirs have year round MIF requirements of 30 cfs and 5 cfs, respectively. Boca and Lahontan Reservoirs have no MIF requirements.
2. Data is from Cui-ui Recovery Plan (USFWS, 1992), that specifies a minimum attraction flow of 60 KAF and a preferred attraction flow of 150 KAF from January through June.
3. Desired inflow to Stillwater is assumed to be 5 ac-ft/ac annually for 25,000 acres of wetlands, for an annual water demand of 125 KAF. Demands coincide with the irrigation season. Two-thirds of the annual demand is distributed evenly during the period from March-July and the remaining third is distributed evenly from August-November. There are no demand requirements for December, January and February (Anglin 1995, personal communication).

4.2.5 System Operation

Operation of the Truckee-Carson system is highly regulated by a myriad of legal and legislative agreements. The most important of these are the 1935 Truckee River Agreement that establishes satisfying Floriston Rates as the primary operating criterion of the Truckee-Carson system, and the 1944 Orr Ditch Decree that prioritizes water use on the Truckee River. Floriston Rates specify seasonal flow requirements for the Truckee River at Farad, near the California-Nevada stateline. It is assumed that if Floriston Rates are satisfied, then the majority of downstream demands are also satisfied. If Floriston Rates cannot be met, shortages are allocated according to water right seniority as established by the 1944 Orr Ditch Decree. Floriston Rates are shown in Table 4.4. Reduced Floriston Rates, which attempt to preserve reservoir storage by reducing flow requirements when Lake Tahoe is low, were not modeled, because the model cannot represent such conditional constraints.

Table 4.4 - Floriston and Reduced Floriston Rates (cfs)

Lake Tahoe Elevation[1]	October	Nov.-Feb.	March	Apr.-Sept.
Less than 6225.25 ft. msl	400	400 (300)[2]	500 (300)	500
6225.25 to 6226.0 ft. msl	400	400 (350)	500 (350)	500
Over 6226.0 ft msl	400	400	500	500

1. Usable storage capacity in Lake Tahoe is between elevation 6223.0 and 6229.1 ft. msl.
2. Reduced Floriston Rates are in parentheses.

A hierarchy of decisions has been established to guide operation of the upper Truckee River reservoirs (Table 4.5). These criteria, which are based on storage and flow conditions throughout the system, establish the order in which reservoirs fill and release to best satisfy Floriston Rates and other downstream demands, including Cui-ui spawning. U.S. Army Corps of Engineers flood control requirements are incorporated in the operating criteria (USCOE, 1985). Many of the management criteria stipulated in the legal documents, such as storage credit and storage exchange arrangements, cannot be adequately represented in a network flow formulation, and neither can many of the conditional operating criteria. However, the gist of reservoir operations can be represented by the use of persuasion penalties, as discussed in the next section. These penalties can be used to capture, for example, the order in which reservoirs accumulate storage (e.g., Boca before Stampede before Prosser), but not necessarily the conditions under which they can, as just noted.

Table 4.5 - General Operating Criteria for the Truckee River System

1. To extent possible, use natural flow below Lake Tahoe to satisfy Floriston Rates, with the exception of California diversions between Lake Tahoe and the stateline. Storage of 9,500 ac-ft in Donner Lake and 3,000 ac-ft in Independence lake are senior to Floriston Rates.
2. Make releases from Boca, Prosser, or Lake Tahoe, as needed, to maintain Floriston Rates. Priority of releases is
   a) From Boca until storage is reduced to 15,000 ac-ft
   b) From Prosser until storage is reduced to 10,000 ac-ft
   c) From Lake Tahoe to extent possible
   d) From Boca, remaining active storage
   e) From Prosser, remaining active storage
3. Truckee Meadows diversion rights are considered met if Floriston Rates are maintained. Otherwise, water rights are filled as specified by the Orr Ditch Decree.
4. Store in Boca Reservoir up to 25,000 ac-ft if Floriston Rates are satisfied.
5. When Floriston Rates are being maintained and Pyramid Tribe irrigation demands are satisfied, diversion to the Truckee Canal for Newlands irrigation demands.
6. Store in Boca above 25,000 ac-ft if Floriston Rates are being met and Truckee Canal rights are satisfied.
7. Store water in Independence Lake if Floriston Rates are satisfied, storage in Boca is over 40,000 ac-ft or at flood control limit, and Truckee Canal demand is met.
8. Store in Stampede Reservoir if maintaining Floriston Rates, Truckee Canal demand is met, and storage in Boca is over 40,000 ac-ft or at flood control limit.
9. Store in Prosser if maintaining Floriston Rates, Truckee Canal demand is met, storage in Boca is over 40,000 ac-ft or at flood control limit, and Stampede is full or at flood control limit.
10. Release from Stampede if lower Truckee River flows are insufficient for Cui-ui spawning.
11. Enact Prosser-Tahoe Storage Exchange Agreement to maintain fishery flows below Lake Tahoe.

4.3 DEVELOPMENT OF PENALTY FUNCTIONS

In optimization models, penalty functions for reservoir storage, reservoir releases, water use, and river flows can represent various operating criteria and physical or institutional operating constraints. Priority-based penalty functions were used in this study instead of economically-based functions for several reasons. First, priority based penalty functions can represent many of the institutional constraints governing water allocation in the basin, such as water rights and other legislated or judicially mandated water use priorities, such as water for endangered species, which economically-based penalty functions are unable to capture. Second, priority-based penalty functions can be used to evaluate system operations considering all water uses, including environmental demands, whose use value cannot be expressed easily in monetary terms. In fact, data for developing economic penalty functions does not exist for many of the water uses in the Truckee-Carson basin. Some of the necessary economic data currently is being gathered as part of the environmental impact report for the proposed Truckee River Operation Agreement (USDOI, 1996). This section discusses formulation of priority based penalty functions and application of the algorithm presented in Chapter 3 for determining unit penalty coefficients.

Whereas economic penalty functions may be complex convex functions and require piece-wise linearization, priority based penalty functions have a simple structure. In most instances, one or two linear segments are sufficient to adequately represent a priority-based penalty. Additional segments can be incorporated to represent persuasion penalties or demands with multiple priorities. Figure 4.5 shows typical penalty functions for flow and storage uses. Flow persuasion penalties are used to dissuade releases or diversions in excess of demand, and storage persuasion penalties are used to keep water in storage if not needed to satisfy downstream demands. Demands for the flow penalties are listed in Table 4.2 and 4.3. Target storages correspond to either reservoir capacity or flood control requirements.

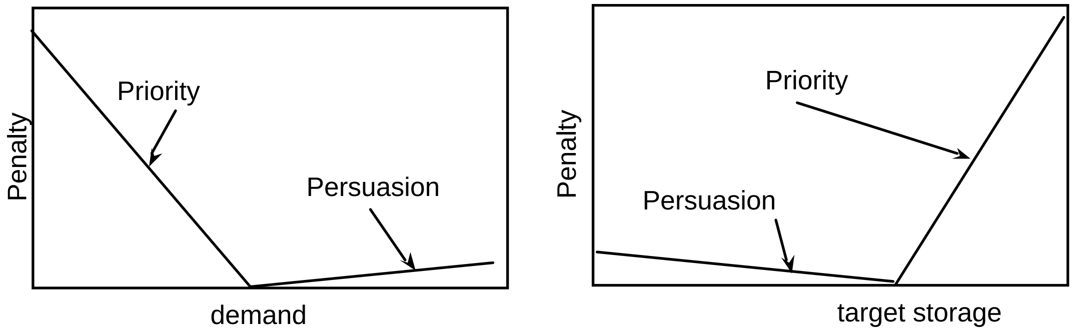


Figure 4.5 - Typical Flow (left) and Storage (right) Penalty Functions

4.3.1 Prioritized Penalties

The water righted uses on the Truckee-Carson system considered in this study are identified below in order of decreasing seniority. Average monthly demands for each are shown in Table 4.2 above.

1) Pyramid Lake Paiute Indian Tribe irrigation water,
2) Sierra Pacific Power Company's initial 40 cfs (for Reno M&I),
3) Truckee-Meadows irrigation,
4) Sierra Pacific Power Company's demand over 40 cfs (for Reno M&I), and
5) Irrigation in the Truckee and Carson Divisions of the Newlands Project.

Satisfying Floriston Rates is not a water right *per se*, but it is considered the highest operational priority on the system. Floriston Rates are an instream demand (see Figure 4.1). Thus, determination of its unit penalty coefficient is governed by Rule 2 in Chapter 3, or,

$$P_s > (1 - a_s) \sum_{j=1}^{N} P_{dj} + \sum_{j=1}^{M} P_{uj} \qquad (1)$$

where,

P_s = Unit penalty on the senior water demand

a_s = Return flow fraction from the senior diversion

P_{dj} = Unit penalty on junior priorities (N) located downstream of the point of senior return flow,

P_{uj} = Unit penalty on junior priorities (M) located between the senior diversion point and the point of return flow,

For instream demands, the return flow fraction a_s is 1 and the P_{uj} do not apply. Therefore, equation (1) reduces to $P_s > 0$, and the unit penalty coefficient is determined by $P_s > P_{s-1}$. Because Floriston Rates are not considered in all management alternatives analyzed, they are not incorporated in the algorithm. When required, the unit penalty coefficient for Floriston Rates is determined by $P_s > P_{s-1}$.

Also, the unit penalty coefficients for the hydropower penalties used to restrict releases from Lake Tahoe when storage drops below the natural rim are not included in the algorithm (see Section 4.2.2). These penalties reflect a physical constraint which should not be violated under any circumstance. Thus, the unit penalty coefficients are assigned the largest value allowed by HEC-PRM and remain unchanged throughout the analysis. Penalty functions for flood control operations, likewise, are excluded from the algorithm because they, too, represent strict operating policy that should not be violated. However, these types of penalties can be accommodated by the algorithm.

Although five prioritized uses are identified above, six are considered in the linear programming (LP) model because diversions for the Truckee and Carson Divisions of the Newlands Project occur at different points in the system and both must be accounted for. Diversions for the Truckee-Meadows irrigation (priority 3) and Reno M&I are made from the same node and the Reno M&I demand is composed of two parts (priorities 2 and 4).

4.3.2 Persuasion Penalties

As discussed in Section 4.4.4, persuasion penalties often are used in optimization modeling to represent secondary operating criteria. In the Truckee-Carson system, several such criteria exist. Persuasion penalties are used for the following purposes:

- To keep water in storage in the upper Truckee reservoirs rather than make releases in excess of downstream demands;
- To minimize diversions through the Truckee Canal, thereby directing excess Truckee River flows to Pyramid Lake;
- To minimize over-diversion at all withdrawal points, and;
- To specify end-of-period target reservoir storages. Persuasion penalties are used herein to avoid the "cool-down" effect often associated with fixed end-of-period target storages or with large penalties for not reaching the target (Lund and Ferreira, 1996). For the objectives of this analysis, end-of-period target storages (e.g., carry-over storage) are not very important.

The unit penalty coefficients for the persuasion penalties must be sufficiently small so they can be easily distinguished from the priority penalties, and not interfere with the system's major operating priorities. In the following formulation, for ease of interpretation, unit penalty coefficients for persuasion penalties are three orders of magnitude lower than the value of the lowest prioritized penalty.

4.3.3 Linear Program for Unit Penalty Coefficients

The linear program developed in Chapter 3 (equations 4-13 to 4-21) yields the following system of equations for the prioritized uses and persuasion penalties:

$$\text{Min } P_1 - P_6 \tag{2}$$

subject to

$$P_1 \geq P_2 + \varepsilon_1 \tag{3}$$

$$P_2 \geq P_3 + \varepsilon_1 \tag{4}$$

$$P_3 \geq P_4 + \varepsilon_1 \quad (5)$$

$$P_4 \geq P_5 + \varepsilon_1 \quad (6)$$

$$P_5 = P_6 \quad (7)$$

$$P_1 \geq P_5 + P_6 + \varepsilon_1 \quad (8)$$

$$P_1 \geq \frac{1}{(1 - 0.56)} P_2 + \varepsilon_1 \quad (9)$$

$$P_2 \geq \frac{1}{(1 - 0.56)} (P_5 + P_6) + P_3 + P_4 + \varepsilon_1 \quad (10)$$

$$P_3 \geq (1 - 0.3)(P_5 + P_6) + P_4 + \varepsilon_1 \quad (11)$$

$$P_4 \geq (1 - 0.56) P_5 + \varepsilon_1 \quad (12)$$

$$P_6 \geq 1000 P_7 \quad (13)$$

$$P_7 = P_8 = P_9 = P_{10} = P_{11} \quad (14)$$

$$P_{10} \geq T (P_{12} + P_{13} + \ldots + P_{17}) + \varepsilon_1 \quad (15)$$

$$P_{12} \geq \frac{1}{(1 - 0.56)} P_{13} + \varepsilon_1 \quad (16)$$

$$P_{13} = P_{14} = P_{15} = P_{16} = P_{17} \quad (17)$$

$$P_{13} = 0.1 \quad (18)$$

$$\varepsilon_1 = 0.10 \quad (19)$$

where,

P_1 = Pyramid Lake Irrigation

P_2 = Sierra Pacific Power Company initial 40 cfs

P_3 = Truckee Meadow Irrigation

P_4 = Sierra Pacific Power Company over 40 cfs

P_5 = Carson Division of the Newlands Project

P_6 = Truckee Division of the Newlands Project

P_7 to P_{11} = Persuasion penalties on reservoir storage

P_{12} = Persuasion penalty on diversion through the Truckee Canal

P_{13} to P_{17} = Persuasion penalties on over-diversion at the five demand points

0.56, 0.3 = return flow fractions from M&I and irrigation demands, respectively.

Equations 3-6 introduce redundant constraints to the LP and are not strictly required by the algorithm. They are included to maintain order between prioritized water uses and the unit penalty coefficients. Priority P_4 presents an example of a situation in which the algorithm would have determined a lower unit penalty coefficient for a higher priority use (equation 12) were it not for the constraint $P_4 > P_5$.

The unit penalty coefficients for the prioritized uses that result from this simple LP are (P_1, P_2, P_3, P_4, P_5, P_6) = (932, 428, 240, 110, 100, 100). For alternatives in which Floriston Rates are active, the associated unit penalty coefficient must be greater than 972. A value of 1000 is used. In Chapter 5, inflows to Pyramid Lake and Stillwater National Wildlife Refuge are considered prioritized water uses and the formulation presented above is adjusted accordingly.

4.4 OPERATION ANALYSIS

The purpose of this study is to provide a screening level evaluation of alternative options for managing the Truckee-Carson system to identify potential improvements to existing system operation. The analysis presented in this section assesses the ability of the Truckee-Carson system to satisfy only water righted priorities under several management alternatives. Environmental demands and other non-water righted uses were given low priority in these initial runs; persuasion penalties were used. In Chapter 5 environmental priorities are considered more fully. HEC-PRM was implemented in two "modes". First, system operation was optimized for the 80 year period of record (Section 4.4.2), and second, operation was optimized on an annual basis to partially overcome the bias introduced by the perfect hydrologic foresight of HEC-PRM (Section 4.4.3). A description of the management alternatives considered is provided in section 4.4.1.

4.4.1 Management Alternatives

Operation of the Truckee-Carson system is institutionally constrained in many respects, and often it is unclear how these constraints may hinder or impede potential improvements in system operation. Because of the complicated legal issues, historical resistance to change, and strong emotions involved in reversing or renewing some of the existing agreements, little serious consideration has previously been given to such analysis. Proposed solutions to water conflicts in the basin are constrained by and must be sought within the existing legal and legislative framework, e.g., including Floriston Rates, exchange agreements, storage credits, etc. In the following analysis, many of these institutional constraints are relaxed and potential improvements to system performance are evaluated. The three policy/institutional changes listed below are combined into eight alternatives for evaluation, as indicated in Table 4.6:

- Remove Floriston Rates requirements,
- Relax restrictions on maximum water surface elevation in Lake Tahoe (i.e., allow storages above 732 KAF), and
- Discontinue diversions through the Truckee Canal.

These institutional policy changes are illustrative of many that could be explored as part of a larger systems study.

Table 4.6 - Management Alternatives

Alternatives	Name	Floriston Rates	Max Tahoe Storage (KAF)	Truckee Canal
1 (Base Case)	y32o	yes	732	open
2	y62o	yes	762	open
3	y32c	yes	732	closed
4	y62c	yes	762	closed
5	n32o	no	732	open
6	n62o	no	762	open
7	n32c	no	732	closed
8	n62c	no	762	closed

The following naming convention for the alternatives is used: the first character is *y* or *n* depending on whether Floriston Rates are enforced or not; the second is either *32* or *62* depending on whether the storage capacity of Lake Tahoe is 732 KAF or 762 KAF; and the third character is *o* or *c*, depending on whether the Truckee Canal is open or closed. For example, Alternative y32o is the Base Case reflecting current operating conditions: Floriston Rates are enforced (y), usable storage capacity is 732 KAF (32) (i.e., maximum water surface elevation is 6229.1 ft. msl), and the Truckee Canal is open (o).

Relaxing Floriston Rates Requirements. Several studies have focused on the effects of reducing or eliminating Floriston Rates as the primary operating objective (EDF, 1987). The argument is that the system should be operated to satisfy downstream demands, not a seemingly arbitrary flow condition, even if the flow requirements provide a fair estimate of downstream demands. It has also been noted that Floriston Rates are an inefficient way to operate the system, particularly in winter months when downstream demands are low. The Pyramid Lake Paiute Indian Tribe has sought unsuccessfully to modify winter Floriston Rates to the amount needed for consumptive uses, foregoing winter releases for hydropower generation by Sierra Pacific Power Company.

Hydropower releases would be made in the spring to coincide with Cui-ui and Lahontan cutthroat trout spawning.

Relaxing Maximum Water Surface Elevation in Lake Tahoe. The Truckee River Agreement requires that the dam at Lake Tahoe be operated such that the maximum water surface will not exceed 6229.1 ft. Although there would be strong resistance from lake-side property owners and lake-based recreation interests to permitting increased water levels in Lake Tahoe, the alternative considered here is to allow the water surface elevation to increase by 0.25 feet, for a storage gain of approximately 30 KAF. Each additional foot of elevation in Lake Tahoe above 6229.1 ft. represents approximately 120,000 ac-ft of additional storage capacity.

Closing the Truckee Canal. The Truckee and Carson River basins were linked in 1905 with construction of Derby Diversion Dam and the Truckee Canal. Supplies from the Truckee River were crucial for development of the Newlands Project and continue to be an important supply source. Diversions to the Truckee Canal are on average one-third of the Truckee River flow. Closing the Truckee Canal or severely curtailing diversions is tantamount to eliminating the Truckee Division of the Newlands Project because all irrigation water for the Truckee Division is from the canal. Closing the canal would leave Lahontan Reservoir as the only supply for the Carson Division, which most likely would cause a reduction in the acreage that could reliably be irrigated. There is strong opposition to this option from the TCID farmers and also from some environmental interests protecting supplies for the Stillwater NWR.

These three options were selected because, on the surface, they appear to hold the most promise for improving performance of the Truckee-Carson system. Also, representing these options in HEC-PRM is fairly straightforward. As noted earlier, penalty functions can be used to turn these options on or off. For instance, very large unit penalty coefficients on flow through the Truckee Canal will, in essence, close the canal. These penalties represent physical constraints and, as such, are not included in the prioritization algorithm directly.

Flood control requirements on all reservoirs are incorporated. Other reservoir purposes, such as recreation and OCAP criteria for Lahontan Reservoir, are not included in these runs. Releases for maintaining minimum instream flow requirements below the appropriate reservoirs are also included. Minimum instream flow requirements may be incorporated by placing upper or lower bounds on the appropriate reservoir release or flow arc. However, in this study penalty functions were used instead to provide some flexibility in operation and to avoid infeasibility problems in the event that the constraints could not be satisfied.

4.4.2 Results

The eight alternatives were evaluated for their ability to satisfy downstream demands, including inflows to Pyramid Lake and Stillwater National Wildlife Refuge. The response of system reservoirs was also evaluated.

4.4.2.1 Effect of Maximum Storage Constraint on Lake Tahoe

The constraint on maximum storage capacity in Lake Tahoe was relaxed in some alternatives, but not entirely; a persuasion penalty was used to dissuade use of this additional storage (Figure 4.4). Varying the value of this penalty affects system operation, but not dramatically. The persuasion penalty can represent the reluctance or the limitations of using this additional storage (e.g., resistance from land owners).

Relaxing the maximum storage capacity constraint by itself does not seem have a tremendous effect on the operations of Lake Tahoe. Depending on the alternative and value of the persuasion penalty, storage exceeds 732 KAF in about three to five percent of the months, as reflected by the storage exceedence probability curves in Figure 4.6. Figure 4.6 shows results for alternatives n32o, n62o-10, n62o-1, and n92o-1, where the suffix indicates the value of the persuasion penalty coefficient. The flat segment on these curves correspond to storage of 732 KAF. The average excursion above 732 KAF was about 19 KAF (maximum is 30 KAF), or approximately 0.17 feet of elevation. The periods of storage excess occurred in months preceding large drought events to minimize impacts on lake operation and reduce the likelihood of storage falling below the natural rim. Use of the additional storage capacity reduced slightly the need for Lake Tahoe water surface to drop below the natural rim. Results for alternatives with Floriston Rates (yXXX) were similar.

To further assess the effect of increased storage capacity in Lake Tahoe, a run was made with maximum storage capacity of 792 KAF. The highest storage level attained in this run was 767 KAF, and only in three months did storage exceed 762 KAF (Figure 4.6). This reinforces the conclusion that increased storage capacity in Lake Tahoe is relatively unimportant for the runs that do not consider downstream environmental demands. The possible significance of increasing Lake Tahoe storage should become more apparent when environmental demands are considered in Chapter 5.

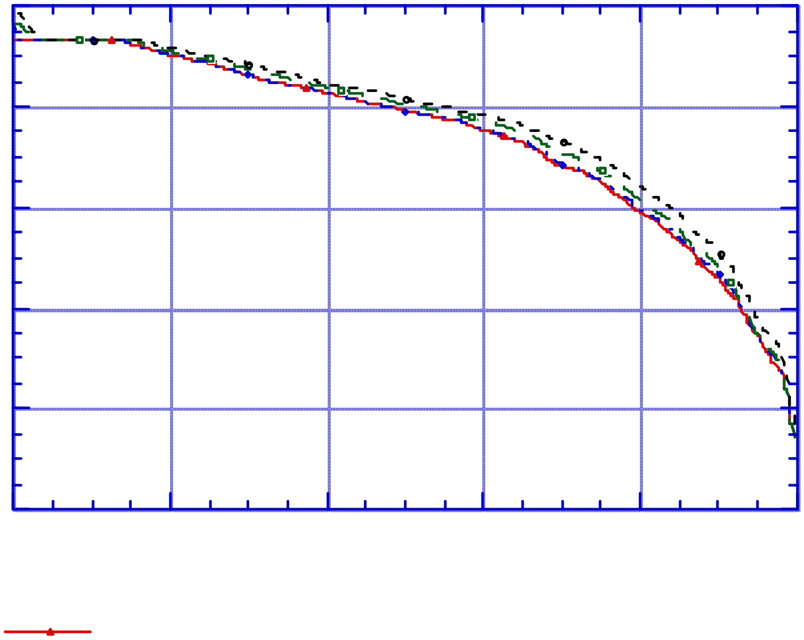


Figure 4.6 - Lake Tahoe Storage Exceedence Probabilities

The extra water stored in Lake Tahoe is done so at the expense of downstream environmental uses, as is to be expected since these are not considered prioritized demands in this set of runs. As the ability to store in Lake Tahoe increases, inflows to and storage in Pyramid Lake decrease. However, as discussed below, the effects are minor relative to those of varying Floriston Rates and closing the Truckee Canal.

Since relaxing water surface constraints in Lake Tahoe appears to have minimal effect on system operation and on the ability to satisfy downstream demands, further analysis will only consider the four alternatives that use storage of 732 KAF (y32o, y32c, n32o, and n32c).

4.4.2.2 Impact on Prioritized Demands

With the five prioritized demands identified in Table 4.2 and no major restrictions on the use reservoir storage (except for flood control requirements), the system is not stressed, as reflected by the results provided in Table 4.7. Table 4.7 lists the probability of shortage, i.e., probability of not fully satisfying demand in any month, the average magnitude of shortage, and the maximum shortage for the water righted demands. For comparison, results of a run using the Negotiated Settlement Model (NSM) are included in Table 4.7. To the extent possible, the NSM run reflects conditions represented by alternative y32o.

The results indicate that the top prioritized water uses - Pyramid Lake Irrigation, Reno M&I initial 40 cfs (2.14 KAF), and Truckee-Meadows irrigation - never suffer water shortages for optimal operations over the 80 year period. Reno M&I demands over the initial 40 cfs are shorted on average about two percent of the months when Floriston rates are in effect, and is not shorted at all when Floriston Rates are not enforced. Mandatory releases for Floriston Rates in winter months when consumptive uses are low, reduce storage availability to satisfy summer demands. The Carson and Truckee

Divisions of the Newlands Project suffer shortages of varying intensity depending on the alternative.

With the Truckee Canal open (n32o, y32o), the Carson Division suffers shortages roughly two percent of the time, with an average shortage of approximately 24-26 KAF. Eliminating Floriston Rates increases slightly the probability of shortages. When the Truckee Canal is closed, no water is delivered to the Truckee Division and the probability of shortage in the Carson Division increases to about fifteen percent. Average shortages decrease slightly, however.

For all water uses, alternatives that do not enforce Floriston Rates produce better results than those that consider satisfying Floriston Rates the primary operational criterion.

4.4.2.3 Impact on Environmental Demands

Environmental demands, i.e., inflows to Pyramid Lake and to Stillwater NWR, were not considered prioritized uses in the current analysis. The results discussed below can be considered “worst-case” conditions for the environmental demands. They provide a lower bound for the analysis presented in Chapter 5. Since these environmental demands are the most downstream water uses on the system (see Figure 4.1), a major supply source is from incidental flows, such as reservoir releases for maintaining minimum instream flow

requirements, reservoir releases to satisfy flood control criteria, and M&I and agricultural return flows.

Table 4.7 - Shortage Results for Prioritized Demands

Demand	Shortage Statistic (KAF/mo)	Alternative				
		y32o	n32o	y32c	n32c	NSM[1]
Pyramid Irr.	Prob. of Shortage	0	0	0	0	0
	Average Shortage	0	0	0	0	0
	Max. Shortage	0	0	0	0	0
Reno M&I	Prob. of Shortage	2.20	0	2.00	0	19.00
	Average Shortage	2.59	0	2.82	0	1.15
	Max. Shortage	8.68	0	8.68	0	11.37
Tr. Mead.	Prob. of Shortage	0	0	0	0	-
	Average Shortage	0	0	0	0	-
	Max. Shortage	0	0	0	0	-
Carson Div.	Prob. of Shortage	3.01	2.64	19.86	19.86	2.00
	Average Shortage	23.87	26.45	22.99	22.99	17.81
	Max. Shortage	45.24	45.24	45.24	45.24	45.24
Truck. Div	Prob. of Shortage	7.01	0	100.0	100.0	100.0
	Average Shortage	3.24	0	2.19	2.19	1.79
	Max. Shortage	3.97	0	3.97	3.97	3.97
Pyr. Inflow	Prob. of Shortage	75.20	71.00	73.80	67.20	64.00
	Average Shortage	40.64	43.65	32.87	38.28	33.78
	Max. Shortage	59.92	59.92	59.16	59.70	58.49
Still. Inflow	Prob. of Shortage	84.10	84.10	86.30	86.30	-
	Average Shortage	6.57	6.56	7.70	7.70	-
	Max. Shortage	16.66	16.66	16.66	16.66	-

1. Not all information is calculated in the Negotiated Settlement Model. NSM was run for conditions most closely reflecting Alternative y32o.

Attraction flows into Pyramid Lake for Cui-ui spawning are insufficient approximately 70 percent of the time, and inflows to Stillwater NWR are less than desired about 85 percent of the time, as indicated in Table 4.7. Alternatives that do not include Floriston Rates (n32o and n32c) perform somewhat better in satisfying attraction flow requirements for Cui-ui spawning than the equivalent alternatives with Floriston Rates (y32o and y32c). The No Floriston Rates alternatives yield a higher percentage of large flows, whereas the Floriston Rates alternatives provide slightly more constant inflows (Figure 4.7). Without having to release for Floriston Rates, Truckee River reservoirs can retain water in storage instead of making additional releases to satisfy Floriston Rates; that water is then available in the early spring for attraction flows. Relaxing Floriston Rates reduces slightly average inflows to Pyramid Lake.

Whether the Truckee Canal is operational or not appears to have a greater effect on Pyramid Lake storage than do Floriston Rates, as shown in Figure 4.8, because average are inflows are greater, as just noted.

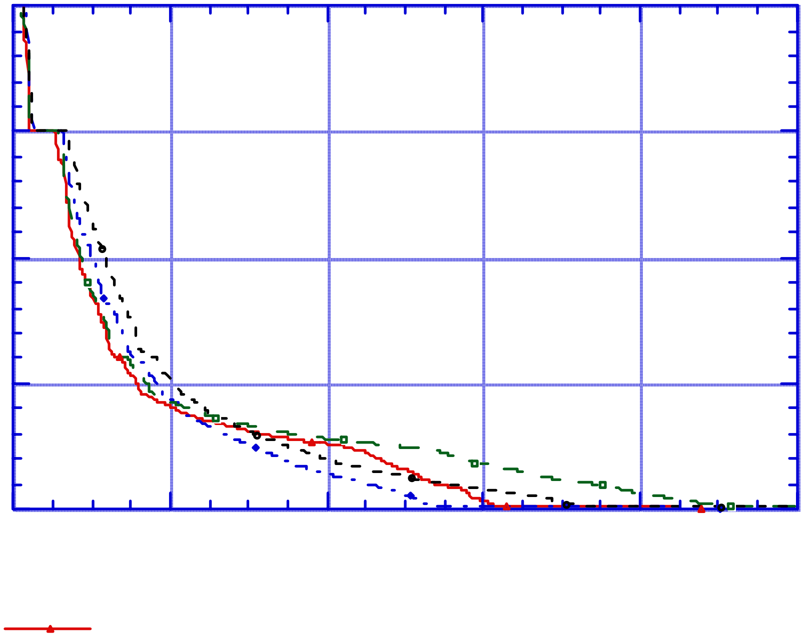


Figure 4.7 - Pyramid Lake Inflow Exceedence Probabilities

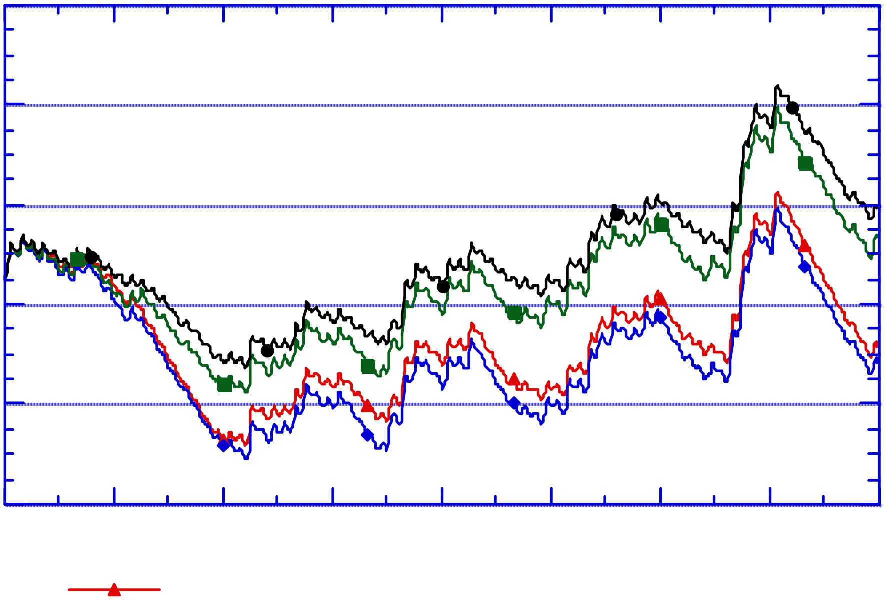


Figure 4.8 - Pyramid Lake Storage

Since the only sources of water for Stillwater NWR are return flows from the Carson Division and targeted releases from Lahontan Reservoir, closing the Truckee Canal has a substantial impact on Stillwater inflows. The stair-step pattern of the inflow exceedence probability curve (Figure 4.9) reflects this dependence on Carson Division return flows. Each step corresponds roughly to return flows from a monthly irrigation demand. In these runs, Floriston Rates had no impact on inflows to Stillwater because additional storage was not required in Lahontan Reservoir specifically for Stillwater demands. Lahontan Reservoir operation centered on satisfying demands of the Carson Division.

4.4.2.4 Analysis of Reservoir Operation

Although the Truckee-Carson system is not stressed in these runs, the proposed management alternatives do affect reservoir operation. In Section 4.4.2.1, relaxing maximum storage constraint in Lake Tahoe was shown to have minimal impact on

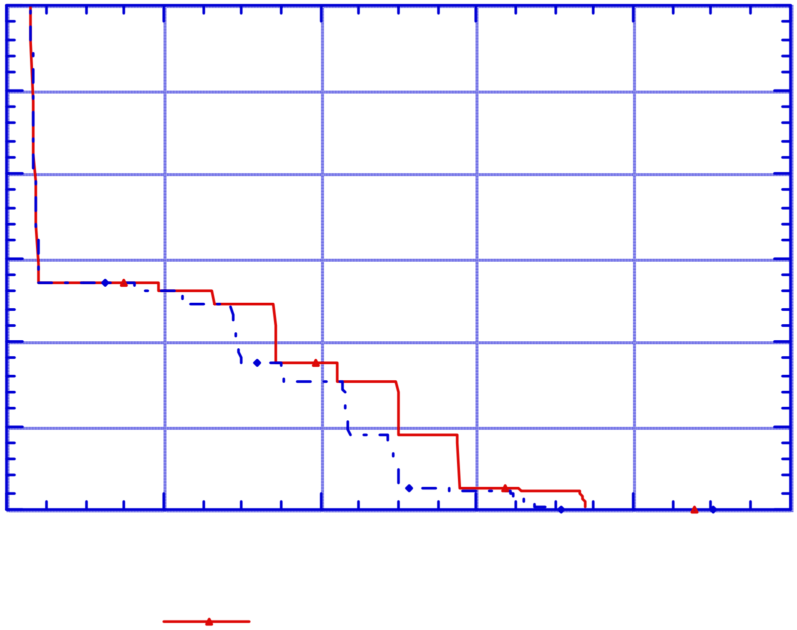


Figure 4.9 - Stillwater NWR Inflow Exceedence Probabilities

operation. Likewise, storage in Lake Tahoe is relatively insensitive to changes in Floriston Rates, as indicated by the storage exceedence probability curves in Figure 4.10. This would seem to indicate that existing Floriston Rates may be excessive since no shortages occur in the Truckee River under any of the eight alternatives. With Floriston Rates enforced, storage in Lake Tahoe falls below the natural rim (200 KAF in Figure 4.2) in about 4 percent of the months. Without Floriston Rates, encroachment below the natural rim are negligible. Whether the Truckee Canal is open or not appears to have minimal effect on Lake Tahoe storage when Floriston Rates are enforced and a slight impact when not enforced. Generally, storage levels in Lake Tahoe are higher when Floriston Rates are not enforced and the Truckee Canal is closed.

Stampede and Prosser Reservoirs are significantly affected by changes to Floriston Rates and operation of the Truckee Canal. Because reservoir release requirements are less without Floriston Rates, total system storage increases (Figures

4.11 and 4.12). The flat segment on the exceedence probability curves in these figures correspond to flood control pool levels (9.8 KAF for Prosser and 222.0 KAF for Stampede/Independence Reservoir). Closing the Truckee Canal has minimal impact on Stampede and Prosser storage when Floriston Rates are enforced. However, closing the canal has a substantial impact when Floriston Rates are not enforced.

The status of the Truckee Canal obviously impacts operation of Lahontan Reservoir because if it is closed, all Carson Division demands must be satisfied by Lahontan (Figure 4.13). The impact of closing the canal increases when inflows to Stillwater receive higher priority, as discussed in Chapter 5.

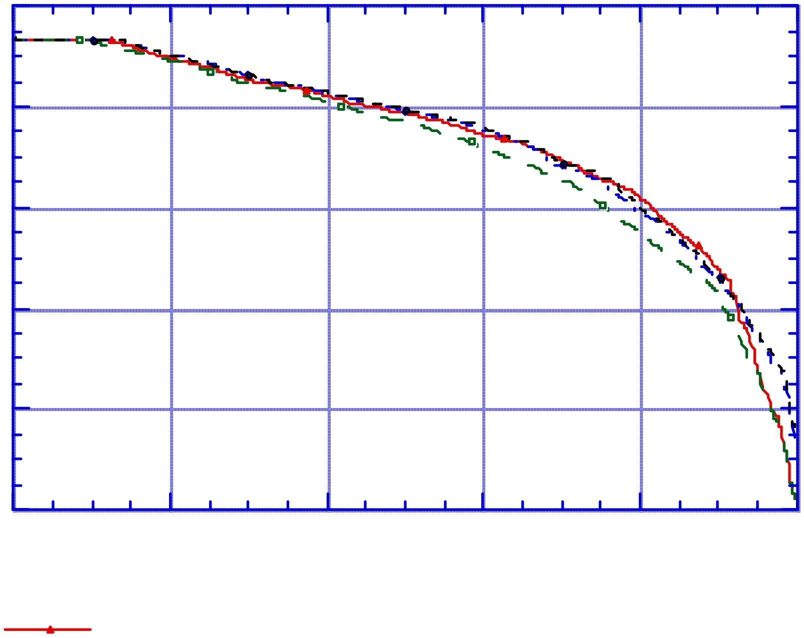


Figure 4.10 - Lake Tahoe Storage Exceedence Probabilities

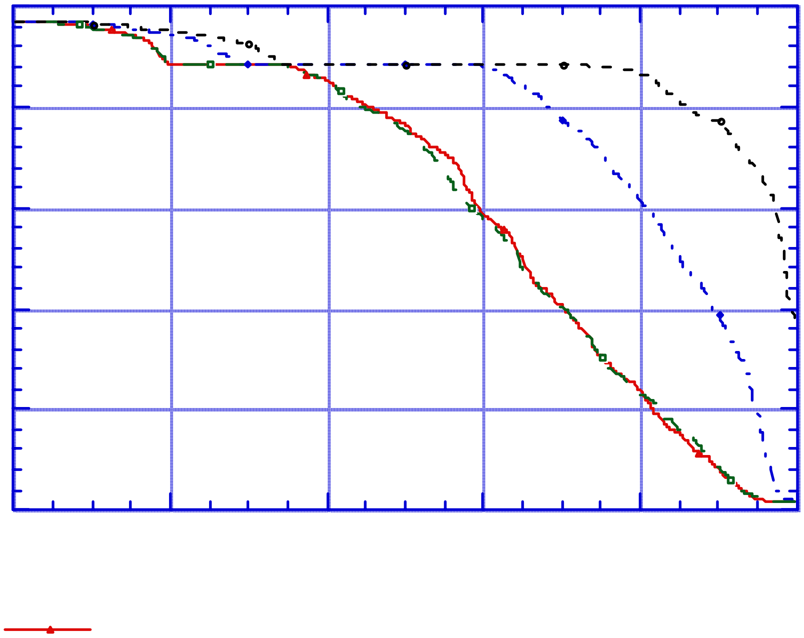


Figure 4.11 - Stampede Reservoir Storage Exceedence Probabilities

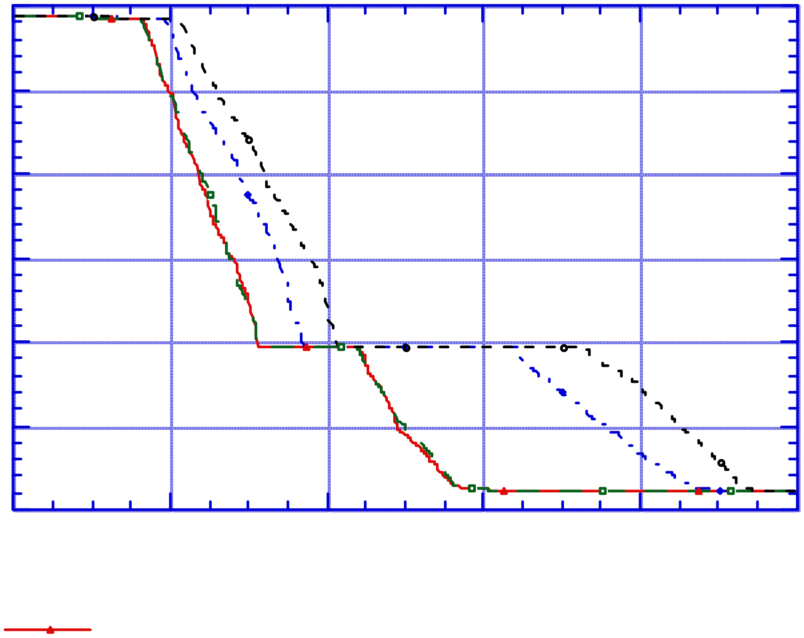


Figure 4.12 - Prosser Reservoir Storage Exceedence Probabilities

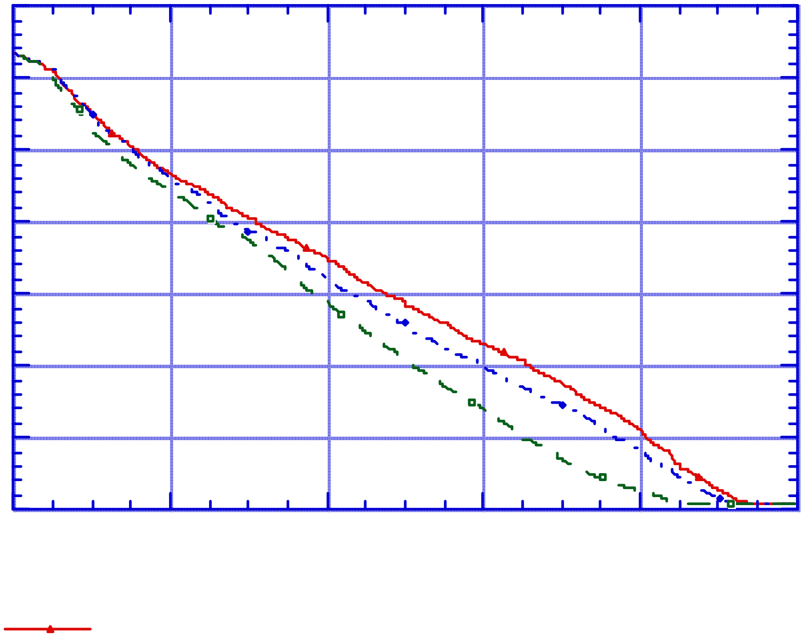


Figure 4.13 - Lahontan Reservoir Storage Exceedence Probabilities

4.4.3 Annual Optimization Analysis

A model such as HEC-PRM, with perfect hydrologic foresight, will optimally release water from storage in anticipation of large inflow events, and keep water back in perfect anticipation of shortages. Thus, there is some uneasiness associated with using results from deterministic optimization models to develop operating rules or suggest changes in operation. Often, these limitations can be corrected through subsequent simulation studies (Lund and Ferreira, 1996).

Sequential optimization also can be used to overcome the "limitations" of perfect foresight. In sequential optimization, the deterministic optimization model is run consecutively on a yearly basis (or other preferred time period) using the end-of-period results from the previous run as initial values for the current run. Although the model will still have perfect foresight for the period, this situation is more realistic since it is more in keeping with the knowledge from flow forecasts available to system operators.

In the limit, the time period for sequential analysis could be reduced to a single month, in which case the optimization model becomes a simulation model with optimal water allocation in each time period (Labadie, 1995; Wurbs, 1993; Chung *et al.*, 1989; WRMI, 1994).

In several alternatives evaluated above, the water surface of Lake Tahoe is permitted to encroach above elevation 6229.1 ft. msl. With perfect foresight for the 80 year period of record, HEC-PRM predicts that only in about three to five percent of the months would this elevation be exceeded, by an average of 0.17 ft. (section 4.4.2.1). Operators, of course, do not have perfect foresight and would not be able to operate the system as suggested by model results. The question arises, if it were possible to relax current restrictions on maximum water surface elevation, how often would this realistically happen given the information actually available to the operators, and what impact would this have on system operation? Running HEC-PRM sequentially with foresight for only one year may provide a better indication of the frequency with which the maximum elevation would be exceeded.

A similar condition exists at the other extreme, i.e., the water surface dropping below the natural rim, restricting releases from the lake. With perfect foresight of net inflows to Lake Tahoe, HEC-PRM minimizes the frequency of this happening. In no more than about four percent of the months did the water surface fall below the natural rim. The model is able to see a drought coming years before its arrival and operate the reservoirs accordingly. Again, sequential analysis with limited hydrologic foresight may provide a better indication of how often the lake's water surface will fall below the natural rim.

Initial runs of the sequential analysis using a negative storage of 200 KAF (Figure 4.2) yielded infeasible results. Large negative inflows associated with multi-year droughts coupled with HEC-PRM’s limited annual foresight tended to produce situations in which storage in Lake Tahoe would drop below the assumed zero storage level, creating the infeasibility. To overcome these infeasibilities, negative storage capacity was increased to 500 KAF, and very large penalties were placed on releases from storage less than 500 KAF (Figure 4.3).

Alternative y62o was re-evaluated by operating HEC-PRM sequentially with annual foresight. In the perfect foresight analyses, water surface excursions above elevation 6229.1 ft. msl or below the natural rim tended to occur in anticipation of or during severe drought events, respectively. Therefore, results of the sequential analysis are presented for the periods 1923-1943 and 1975-1995, which include the most severe droughts on record. Lake Tahoe storage for these two periods is shown on Figures 4.14 a-b. For comparative purposes, Lake Tahoe storage as determined by the NSM is also shown in these figures.

During normal years, results of the two analyses are quite comparable. However, they differ substantially during droughts. This is most apparent from reservoir operation during the drought of the 1930s shown on Figure 4.14a, in which operation with annual foresight draws down Lake Tahoe substantially more than in the case of perfect foresight. The probability of exceeding water surface elevation of 6229.1 ft. msl with limited hydrologic foresight is similar to that for the case of perfect foresight. However, the magnitude of exceedence is slightly larger with limited foresight.

Also, this analysis indicates that with optimal (i.e., perfect foresight) operation of all reservoirs in the system, it is possible to keep Lake Tahoe “active” more often, i.e., prevent Lake Tahoe water surface from falling below the natural rim. The ability to better use storage elsewhere in the system (Stampede, Prosser, and Boca Reservoirs) obviates the need for increased storage capacity in Lake Tahoe. This result is apparent from the exceedence probability curves for Lake Tahoe storage shown on Figure 4.15. The probability of exceeding storage of 732 KAF is roughly the same for the perfect and annual foresight runs, about three percent. However, the probability of the water surface dropping below the rim increases from about three percent with perfect foresight to about

12 percent with annual foresight. This is clearly indicated in Figures 4.14 and 4.15, in which runs with perfect hydrologic foresight drawdown Lake Tahoe substantially less than do runs with annual foresight.

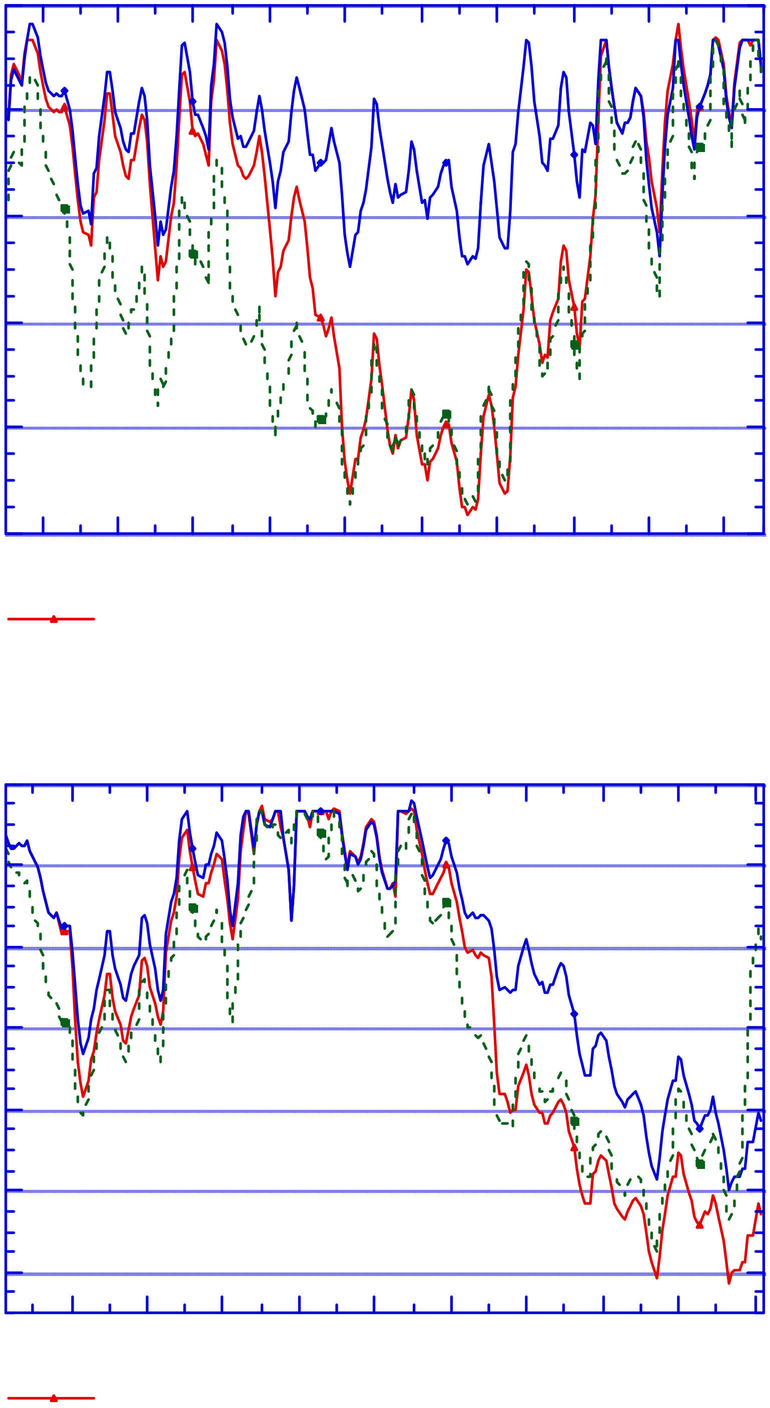


Figure 4.14 - Lake Tahoe Storage: Perfect Foresight vs. Annual Foresight (a) 1923-1943; (b) 1975-1995 [Alternative y62o]

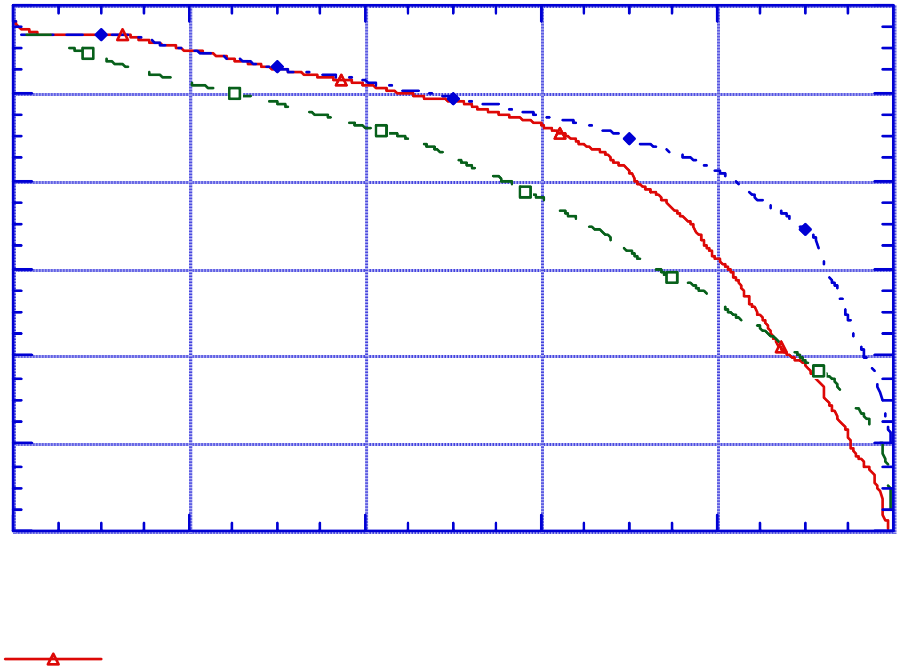


Figure 4.15 - Lake Tahoe Storage Exceedence Probability Curves

Performance in terms of demand shortages does not change significantly with limited hydrologic foresight, as indicated by the results shown in Table 4.8. A slight increase in the frequency of shortages for Reno M&I and Truckee Meadows occurs with the sequential runs. This is not surprising since satisfying these demands has highest priority on the system. The primary effect is noticeable in terms of reduced storage in Lake Tahoe and other reservoirs.

Determining proper end-of-period target storages is an important part of annual operational analysis (Lund, 1996; HEC, 1994), since it affects system operation for carry-over storage. Many seasonal optimization models add special end-of-period storage penalties to place a value on overyear storage. This was not done here because of the priority nature of the penalties. Perfect hydrologic foresight and adequate end-of-period target specifications are less critical limitations for systems with an annual drawdown-refill cycle because operating for carry-over storage is not a major concern, except during

Table 4.8 - Annual Foresight vs. Perfect Foresight Shortage Results

Demand	Shortage Statistic (KAF/mo)	Alternative[1]		
		Perfect Foresight	Annual Foresight	NSM
Pyramid Irr.	Prob. of Shortage	0	0.01	0
	Average Shortage	0	0.30	0
	Max. Shortage	0	0.30	0
Reno M&I	Prob. of Shortage	2.20	2.80	19.00
	Average Shortage	2.59	5.73	1.15
	Max. Shortage	8.68	12.84	11.37
Tr. Mead.	Prob. of Shortage	0	1.0	-
	Average Shortage	0	4.54	-
	Max. Shortage	0	6.38	-
Carson Div.	Prob. of Shortage	2.90	3.70	2.00
	Average Shortage	23.33	23.97	17.81
	Max. Shortage	45.24	45.24	45.24
Truck. Div	Prob. of Shortage	7.10	3.70	100.0
	Average Shortage	3.21	2.47	1.79
	Max. Shortage	3.97	3.97	3.97
Pyr. Inflow	Prob. of Shortage	75.40	74.60	64.00
	Average Shortage	40.56	38.71	33.78
	Max. Shortage	59.92	59.92	58.49
Still. Inflow	Prob. of Shortage	84.20	84.30	-
	Average Shortage	6.56	6.62	-
	Max. Shortage	16.66	16.66	-

1. Not all information is calculated in the Negotiated Settlement Model. All runs are for conditions most closely reflecting Alternative y32o.

prolonged droughts. The annual analysis presented here may have tended to draw down Lake Tahoe more than may have been expected because of the low persuasion penalty placed on end-of-period target storage. Had these penalties been higher, most likely the drawdown would have been less, as HEC-PRM attempts to keep water back to meet the end-of-period target.

Lastly, Figure 4.16 indicates that sequential analysis with annual foresight does a fair job of reproducing the operation of Lake Tahoe simulated with the Negotiated Settlement Model.

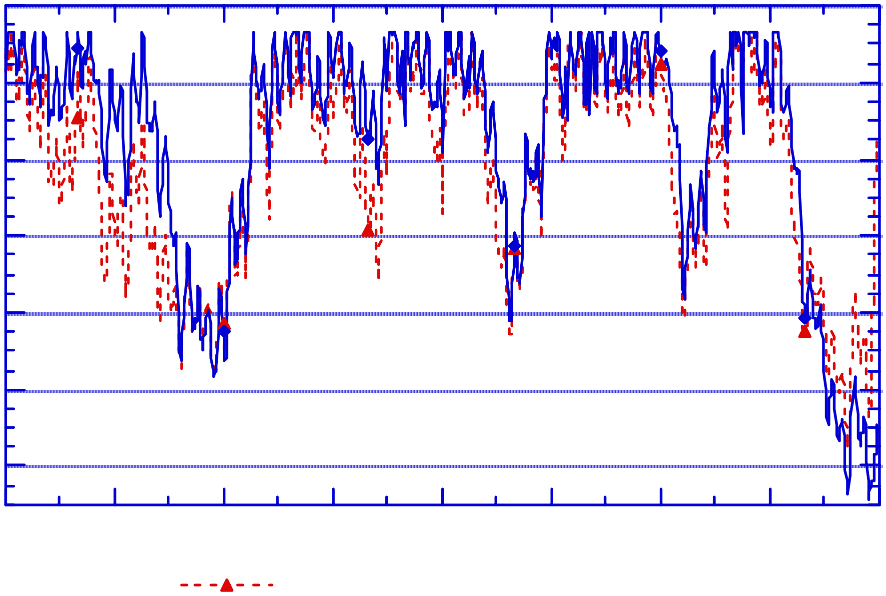


Figure 4.16 - Lake Tahoe Storage - NSM vs. Annual Foresight

4.5 CONCLUSIONS

Conclusions of this chapter are presented in three areas: technical aspects of modeling the Truckee-Carson system, policy implications of the modeling analysis, and limitations and possible extensions to the analysis.

4.5.1 Technical Conclusions

The foregoing analysis demonstrated use of the algorithm developed in Chapter 3 for determining unit penalty coefficients that preserve priority in water allocation. The unit penalty algorithm is sufficiently robust to handle various system configurations, including multiple diversions from a single node, combinations of storage and flow demands, instream demands, and persuasion penalties. The algorithm provides a rigorous alternative to trial and error determination of unit penalty coefficients. Furthermore, it is sufficiently simple in form to be solved using spreadsheet optimization functions.

Because of the simplifications incorporated in network flow models, reservoir releases typically cannot be conditioned on reservoir storage, as they could be in more general linear programming models. However, the hydropower algorithm developed for HEC-PRM was used successfully to represent Lake Tahoe, from which no releases are possible when the water surface falls below the lake's natural rim. Very high unit penalty coefficients were used for releases from storage levels corresponding to the natural rim or lower, while very low unit penalties were used for releases when storage was above the natural rim. The algorithm constrained Lake Tahoe operation to conform to realistic conditions and may be used more generally to govern reservoir releases limited by storage head.

To evaluate the effect of perfect hydrologic foresight on system performance, HEC-PRM was run sequentially, optimizing system operation on a yearly basis. Operation based on annual foresight more closely approximates the knowledge of system operators and could provide a better indication of actual system response. Optimizing system operation on an annual basis had little effect on the ability to satisfy water-righted demands. The main effect was on reservoir storage. In general, annual optimization reduces average reservoir storage, and, in the case of Lake Tahoe, increases the frequency with which the water surface elevation falls below the natural rim.

The results of optimization models of complex water resource systems should be considered preliminary for various reasons, including the many simplifications and assumptions required to represent the physical system; the likelihood of multiple near optima; the sensitivity of results to model parameters, including penalty functions, and;

for models such as HEC-PRM, the limitations introduced by perfect hydrologic foresight. Conceptually, however, the deterministic optimization model developed for the Truckee-Carson system can be used to evaluate numerous management alternatives and institutional policy changes, including some being considered for the Truckee River Operating Agreement environmental impact report.

4.5.2 Policy Implications

The principal policy/management conclusion from the foregoing analysis is that if environmental uses are given low priority in system operation, there are few problems in satisfying demands of the water righted uses. Furthermore, there appears to be a fair amount of flexibility in system operation, as indicated by the variability in reservoir storages and releases under the different alternatives and from slight modifications of the persuasion penalties without adversely affecting system demands. This condition usually indicates a fairly unconstrained system for which there may be multiple near optima with similar values of the objective function, but different values for the decision variables, i.e., streamflow, reservoir releases, etc. Sensitivity to alternative formulations and parameter values should be investigated, especially when the objective is to derive operating rules and total cost is of lesser importance.

Results of the analysis confirm general expectations of how the different management alternatives would affect system operation. Closing the Truckee Canal would improve storage conditions in Pyramid Lake, but would be detrimental for Stillwater NWR. Reducing or removing Floriston Rates would increase the probability of fully satisfying Cui-ui attraction flow requirements, but because average lake inflows are less under these alternatives, Pyramid Lake storage conditions do not benefit substantially. The analysis presented in Chapter 5 will further evaluate the impact of these management measures.

The use of optimization and simulation models addresses only part of the problem of establishing a "best" policy for resolving water conflicts. Solutions to a conflict situation that have been developed from a purely engineering perspective are not always implemented, and indeed may not even be feasible if one considers institutional or other "non-technical" factors. Though preliminary in many respects, results from the analysis presented in this Chapter provide sufficient support for pursuing some alternatives further. The results indicate that there are benefits to be gained in system operation if institutional constraints associated with relaxing Floriston Rates and closing the Truckee Canal can be overcome.

4.5.3 Limitations and Extensions

Without further refinement of the model and possible subsequent analysis with a simulation model, it is difficult to select a preferred operating strategy or to fully evaluate the impact of proposed policy changes. However, several extensions to the model are possible which would provide further insight to the operation of the Truckee-Carson system. For instance, system representation can be refined to perform a more detailed reservoir operation analysis, including recreation requirements and OCAP criteria at Lahontan Reservoir. Also, a systems analysis evaluation of the Truckee-Carson basin would require that upper Carson irrigation and municipal demands be incorporated.

The underlying assumption in this analysis is that all water supplies were available to satisfy all water demands, subject only to mass balance, reservoir storage, and water right priority constraints. However, to enable representation of water use priorities and source supply hierarchies that presently exist in the Truckee-Carson system, an approach similar to that of Andrews *et al.* (1992), in which certain water supplies were linked with specific water demands, could be implemented to the model presented here. For instance, Sierra Pacific Power Company has proprietary use of

Donner Lake supplies. Similarly, other demands are subject to priority and proprietary use of supplies from the various reservoirs.

It is anticipated that by considering the economic value of water to each participant through the use of economically-based penalty functions, it may be possible to generate additional alternatives for managing the system's supplies, thereby, increasing operational flexibility in the basin. We should be able to determine trade-offs in water use between participants, beyond the purely hydrologic trade-offs now considered. For example, how does a reduction in water supplies to the cities of Reno and Sparks compare to an equivalent reduction in supplies to the TCID, or to Pyramid Lake, i.e., are the costs associated with these losses equivalent?

Simulations models often are used to verify and fine tune the results of optimization models. Simulation models are also necessary to analyze other impacts of proposed management alternatives, such as water quality impacts. HEC-PRM does not account for water quality considerations which are a major concern in the lower Truckee River and a primary focus of environmental impact studies.

In the next chapter, the analysis presented here is extended to include several environmental demands. Inflows to Pyramid Lake and to the Stillwater Wildlife Refuge are considered prioritized demands and the impact on other water demands is evaluated.

CHAPTER 5

AN EVALUATION OF COMPETING ENVIRONMENTAL DEMANDS

5.1 INTRODUCTION

5.1.1 Purpose

Environmental demands have been playing an increasingly important and influential role in the planning, management, and operation of water resource systems. Increasingly, the traditional water consuming sectors, e.g., urban (municipal and industrial) and agriculture, are being required, often through litigation or legislation, to surrender some of their water supply reliability to satisfy environmental demands. In the past two decades several court decisions and state and federal laws have been used to reallocate water between consumptive and environmental uses (Littleworth and Gardner, 1995). These include the public trust doctrine, legislation protecting wild and scenic rivers, the Endangered Species Act (ESA), National Environmental Policy Act (NEPA), and in California, the Central Valley Project Improvement Act (CVPIA). Littleworth and Gardner (1995) further note that "a satisfactory method for resolving the competing demands for water between consumptive and environmental users has not been found. Currently, these disputes are resolved through litigation."

Recently however, it has become apparent, particularly in the water-scarce western United States, that the urban and agricultural sectors alone are unable to provide sufficient water to satisfy environmental demands. Environmental purposes compete among themselves for water. Examples include competition among endangered and threatened species such as the fall run Chinook salmon in the Sacramento River versus Delta smelt in the Sacramento-San Joaquin Delta in California (DWR, 1994); bald eagle nesting around the Alamo Reservoir, Arizona versus riparian vegetation downstream of the reservoir (Kirby, 1996); protection of the littoral zone habitat in Lake Okechobee versus downstream biological integrity (Trimble and Marban, 1988); and instream versus in-reservoir fisheries in countless water systems. This competition has pitted environmental groups against one other and has resulted in the formation of coalitions among historic adversaries.

Given the level of water scarcity, over-appropriation, and conflict over water use, the need arises to address environmental versus environmental conflicts. However, this increasingly prominent issue in water resources management has received scant attention in the literature. In an extensive literature survey of trade-off analysis for environmental projects, Feather *et al.* (1995) note that "there were very few cases where several environmental aspects were traded-off against one another."

This is precisely the situation in the Truckee-Carson basin, where water managers must address competition between the endangered Cui-ui fish in Pyramid Lake and preserving wetland habitat in the Stillwater National Wildlife Refuge at the terminus of the Carson River. Proposed management alternatives for the Truckee-Carson basin must routinely evaluate the water needs of these environmental uses and ultimately may have to choose between them (New York Times, 1988; Lancaster, 1990; Yardas, 1987).

In this chapter, results are presented of an analysis in which the HEC-PRM optimization model introduced in Chapter 4 was used to assess the effect on water-righted demands of varying the priority associated with environmental uses. Changes in relative priority among the environmental purposes, as well as relative to other water righted users, are investigated. The algorithm developed in Chapter 3 was used to determine unit penalty coefficients for the prioritized demands. Varying demand priorities will impact deliveries to upstream water rights holders, but may also affect water allocation among the two environmental uses. Trade-offs in terms of demand shortages among the environmental uses are discussed. A review of current literature on valuing and comparing environmental demands for water is provided first, followed by background on environmental demands in the Truckee-Carson system.

5.1.2 Valuing Environmental Demands

Although it may not be readily apparent or explicit in operating policy, existing management of water resources systems is based on underlying values which guide decision-making regarding trade-offs among operating purposes. Existing projects are authorized for specific purposes, and often these purposes are prioritized in some way, e.g., the manner in which shortages are allocated. These priority rankings are ordinal in that the relative value among purposes frequently is not considered.

Choosing among environmental demands in the operation of water resource systems is particularly difficult because of the difficulty of quantifying the use value of individual demands. Resource economists, using a variety of tools (e.g., contingent valuation, travel cost, and hedonic pricing), have attempted to place values on non-marketed uses of water, such as recreation, instream flow, and environmental benefits (Freeman, 1993). Several studies address environmental uses of interest to the operation of the Truckee-Carson system.

Creel and Loomis (1992) note that "more efficient allocation of water might be facilitated if information on the economic value of water in environmental uses was available to decision makers. Although few estimates of the value of water in specific environmental uses are available, there is a general lack of information about the economic value of water for maintenance of wetlands for recreation uses. State agencies such as fish and game departments also need this information in forming wetland habitat acquisition and management strategies." The same holds for endangered and threatened species, for which there is lack of information about use value. Furthermore, unlike wetlands for which it may be possible to develop some general methods based on wetland type or use, endangered species are each unique.

Loomis *et al*. (1991) conducted a study of the public's willingness to pay to prevent a decrease in wetland acreage, to increase wetland acreage, and to protect fish and bird species in the San Joaquin Valley (SJV) wetlands in California. They concluded that Californians value clean and adequate water supplies for wildlife refuges at approximately $3 billion per year. In many respects conditions at the SJV wetlands are similar to the wetlands in the Carson River system. The SJV wetlands receive approximately 25 percent of the water required for optimal management and much of the source supply is contaminated agricultural drainage water. Loomis *et al*. conclude that "implicit in their results is that the first half million acre-feet (MAF) of water needed to protect wetlands and wildlife from contamination is worth more than the value that 0.5 MAF of water could provide in agricultural production." Direct comparisons are not entirely valid, of course, but this study provides some indication that the value society places on wetland preservation can be large and should be explicitly considered in management decisions.

Hardy (1995) notes that competition among environmental demands is often revealed in the preparation of environmental impact assessments of projects that would alter the natural flow regime of a stream. Different water allocation decisions will impact or benefit different resources in different ways. However, no suggestions for resolving these conflicts are provided. Even, the Endangered Species Act (ESA) does not provide clear guidelines on how to balance conflicting needs between listed species (Kirby, 1996). Kirby (1996) proposes a system of relative unit costs to represent the competition among environmental purposes within a single reservoir system. This approach is demonstrated in an application to the Alamo Reservoir in Arizona. Multi-objective trade-off analysis traditionally has been used to evaluate this class of problem (Cohon, 1978; Feather *et al.*, 1995).

5.1.3 Environmental Demands in the Truckee-Carson System

The principal environmental demands in the Truckee-Carson system are inflows to Pyramid Lake to support the threatened Lahontan cutthroat trout and endangered Cui-ui and inflows to the Stillwater National Wildlife Refuge (NWR) to maintain wetland habitat for migratory fowl. Both of these resources have been harmed by construction of the Newlands Project. Recent conflicts in the Truckee-Carson basin center on restoring these environmental uses of water.

Before the Truckee and Carson River systems were linked by the Truckee Canal, Pyramid Lake was the natural terminus of the Truckee River. Natural inflows to the lake and sustained lake levels provided suitable habitat for the Cui-ui. With development of the Newlands Project and construction of Lahontan Dam and the Truckee Canal, diversions from the Truckee River caused a large decline in Pyramid Lake water surface elevation (Figure 2.2). As a result, Lahontan cutthroat trout was listed as threatened and the Cui-ui as an endangered species. In addition, Lake Winnemucca, which was fed by overflow from Pyramid Lake, dried up completely.

Presently, the Endangered Species Act guarantees that inflows to Pyramid Lake receive high priority. Operation of the upstream reservoirs has been adjusted to reflect this change in water use priority. A Cui-ui recovery plan has been developed and recovery criteria have been incorporated in the operation of Stampede Reservoir and the Negotiated Settlement Model (NSM). Complex operating criteria have been implemented to accommodate Cui-ui attraction flows, including storage credit and exchange arrangements.

“The irrigation project [Newlands Project] has played havoc with the wetlands in and around the Stillwater NWR…that serve as a vital way station for some of the densest populations of migratory waterfowl in North America” (Lancaster, 1990). Wetlands in the Carson Sink area cover approximately one-tenth of the 100,000 acres they did before construction of the Newlands Project. Also, the quality of inflows to the wetlands is quite poor since it is primarily agricultural drainage from the Carson Division of the Newlands Project. Since construction of Lahontan Dam in 1911, the wetlands have relied exclusively on agricultural return flows and occasional reservoir spills for water supply. A significant portion of that supply has come at the of expense Pyramid Lake via Truckee River diversions through the Truckee Canal. Water demands of the Stillwater NWR are not considered explicitly in the operation of the Truckee River reservoirs. "In an ironic twist, the situation at Stillwater has been exacerbated by federal efforts to protect an endangered fish in Pyramid Lake northwest of the valley. More water for the sucker-like Cui-ui means less water for the refuge" (Lancaster, 1990).

In the Truckee-Carson system, the economic analysis for the Environmental Impact Report (EIR) of the Truckee River Operating Agreement (TROA) will consider the economic impact of various management strategies on recreation value in the upper Truckee River reservoirs. Also incorporated in the economic model are the secondary impacts associated with transferring water rights from irrigation to municipal uses. Preliminary estimates of recreation value in Pyramid Lake have been estimated (Shonkwiler, 1994), but are not being considered in the TROA EIR. However, there is still insufficient information to develop adequate economic-based penalty functions for most of the environmental uses in the Truckee-Carson system. As noted, a major obstacle to evaluating environmental uses in the traditional benefit-cost framework is that not all environmental use values can be expressed easily in monetary terms. The analysis presented here based on water use priorities obviates the need to develop economically-based penalty functions for all purposes.

Environmental demands in the Truckee-Carson system considered in this study are listed in Table 5.1. The Cui-ui Recovery Plan (USFWS, 1992) identifies a minimum attraction flow into Pyramid Lake of 60 KAF/month and a preferred attraction flow of 150 KAF/month from January through June as required for delisting the Cui-ui. Pyramid Lake levels are also an important component of the recovery plan. Lake storage must be sufficiently high (above elevation 3812 ft.)for the Cui-ui to have access to the lower Truckee River, over the natural delta. At lower elevations, but higher than 3784 ft., the fishway at Marble Bluff Dam can be used. In fact, it is a combination of attraction flow and storage level that determines the likelihood of a successful spawning run. Storage criteria were included in the model, but in modeling environmental demands, inflows to the lake were prioritized higher than lake level.

Desired inflows to Stillwater NWR for maintaining 25,000 acres of wetlands are assumed to be 5 ac-ft/ac annually, for an annual water demand of 125 KAF. Wetland demands coincide with the irrigation season, with two-thirds of the annual demand distributed evenly from March-July and the remaining third distributed evenly from August-November. There are no demand requirements for December, January and February (Anglin 1995, personal communication). In addition, minimum instream flow requirements exist for several reaches of the Truckee River and some of the tributaries. These also are noted in Table 5.1.

5.2 ANALYSIS

5.2.1 Selection of Alternatives

Based on the results of the analysis in Chapter 4, alternatives y32o, n62o, and n62c are considered here. Alternative y32o was selected because it represents existing conditions - Floriston rates enforced, maximum water surface elevation in Lake Tahoe restricted to 6229.1 ft., for a storage of 732 KAF, and the Truckee Canal is open. Alternative n62o was selected because it imposes the minimum institutional constraints on system operation - no Floriston Rates, no water surface restrictions on Lake Tahoe, and an open Truckee Canal. Both of these alternatives include operation of the Truckee Canal, and, thus, are suitable for evaluating impacts to the Stillwater NWR and quantifying trade-offs with Pyramid Lake inflow demands. Alternative n62c (closed Truckee Canal) was evaluated to assess the impacts on Lahontan Reservoir operation and Carson Division demands if Stillwater NWR demands are given high priority and additional supplies are not available from the Truckee River. Increased storage capacity in Lake Tahoe did not have much impact on system operation when environmental demands were not prioritized. Alternatives n62o and n62c also were selected to further evaluate the need for this extra storage when environmental demands are considered more significantly.

Table 5.1 - Environmental Water Demands (Non-Water Righted Uses)

Month	Minimum Release Requirements[1] (KAF/month)			Pyramid Lake Inflow[2]	Stillwater Inflow[3]
	Lake Tahoe	Prosser	Stampede	(KAF/mo)	(KAF/mo)
January	3.02	0.30	1.81	60/ 150	0
February	3.02	0.30	1.81	60/ 150	0
March	3.02	0.30	1.81	60/ 150	16.66
April	4.23	0.30	1.81	60/ 150	16.66
May	4.23	0.30	1.81	60/ 150	16.66
June	4.23	0.30	1.81	60/ 150	16.66
July	4.23	0.30	1.81	0	16.66
August	4.23	0.30	1.81	0	10.42
September	4.23	0.30	1.81	0	10.42
October	3.02	0.30	1.81	0	10.42
November	3.02	0.30	1.81	0	10.42
December	3.02	0.30	1.81	0	0
Annual Total	43.50	3.60	21.72	360/900	125.00

1. Minimum instream flow (MIF) requirement downstream of Lake Tahoe is 50 cfs from October-March and 70 cfs from April-September; Stampede and Prosser Reservoirs have year round MIF requirements of 30 cfs and 5 cfs, respectively. Boca and Lahontan Reservoirs have no MIF requirements.
2. Minimum/Preferred flows. From Cui-ui Recovery Plan (USFWS, 1992).
3. Personal Communication, Ron Anglin, 1995.

Runs for this analysis were made by operating HEC-PRM in sequential mode as described in Section 4.4.3. For annual optimization runs, problem size is reduced from 23,043 nodes and 50,722 arcs for the 80 year record to 291 nodes and 645 arcs. This greatly reduces run time since model run time for the annual optimization increases linearly with the number of years in the analysis period, not exponentially. For comparative purposes, alternative y32o also was evaluated with perfect foresight (alternative PFy32o), as in Chapter 4.

5.2.2 Relative Priorities and Unit Penalty Coefficients

In Chapter 4, system operation was evaluated with environmental demands having low priority relative to other system demands. In this chapter, the three alternatives were re-evaluated considering a range of relative priorities, as identified in Table 5.2. In Table 5.2, the notation pXsX refers to the priority given to each of the environmental demands: inflows to Pyramid Lake (pX) and inflows to Stillwater NWR (sX). These relative priority rankings were used to generate a range of "best-case" conditions for the environmental uses. The relative priorities of the five non-environmental demands from Chapter 4 are retained (Table 4.2). For instance, p1s2 implies that Pyramid Lake inflows are the top priority, inflows to Stillwater NWR are second, Pyramid Lake irrigation is third, and so forth. Case p7s7 represents conditions as modeled in Chapter 4.

Table 5.2 - Priorities for Environmental Demands

Case	Pyramid Lake Inflows	Stillwater NWR Inflows
p1s2	1	2
p2s1	2	1
p1s7	1	7
p7s1	7	1
p7s7	7	7

The algorithm developed in Chapter 3 was used to determine unit penalty coefficients for the different cases. An example of the linear program for Case p1s7 is provided below. Recall, that although Carson and Truckee Division demands have the same water right priority, they are considered separately in the algorithm because the points of diversion are different. The persuasion penalties used in the analysis of Chapter 4 were used for the analysis in this chapter. Also, the penalties used to limit releases from Lake Tahoe when storage is below the natural rim were incorporated as in Chapter 4, as were flood control criteria and minimum instream flow requirements. Constraints in equations 2-7 below are not necessary to the algorithm, but are included to maintain the order between a prioritized water use and its unit penalty coefficient. Otherwise, a water use of higher priority can have a unit penalty coefficient lower than that of a lower priority water use (constraint 14). Constraints 2-7 introduce redundant equations in the LP, but are retained below for completeness.

$$\text{Min } P_1 - P_8 \tag{1}$$

subject to

$$P_1 \geq P_2 + \varepsilon_1 \tag{2}$$

$$P_2 \geq P_3 + \varepsilon_1 \tag{3}$$

$$P_3 \geq P_4 + \varepsilon_1 \tag{4}$$

$$P_4 \geq P_5 + \varepsilon_1 \tag{5}$$

$$P_5 \geq P_6 + \varepsilon_1 \tag{6}$$

$$P_6 \geq P_8 + \varepsilon_1 \tag{7}$$

$$P_6 = P_7 \tag{8}$$

$$P_1 \geq \frac{1}{(1 - 0.56)} P_2 + \varepsilon_1 \tag{9}$$

$$P_2 \geq P_6 + P_7 + \varepsilon_1 \tag{10}$$

$$P_2 \geq \frac{1}{(1 - 0.56)} P_3 + \varepsilon_1 \tag{11}$$

$$P_4 \geq \frac{1}{(1 - 0.56)} (P_5 + P_6) + P_4 + P_5 + \varepsilon_1 \qquad (12)$$

$$P_4 \geq (1 - 0.3)(P_6 + P_7) + P_5 + \varepsilon_1 \qquad (13)$$

$$P_5 \geq (1 - 0.56) P_6 + \varepsilon_1 \qquad (14)$$

$$P_8 = 100 \qquad (15)$$

$$\varepsilon_1 = 0.1 \qquad (16)$$

where,

P_1 = Inflows to Pyramid Lake

P_2 = Pyramid Lake Irrigation

P_3 = Sierra Pacific Power Company initial 40 cfs

P_4 = Truckee Meadow Irrigation

P_5 = Sierra Pacific Power Company over 40 cfs

P_6 = Carson Division of the Newlands Project

P_7 = Truckee Division of the Newlands Project

P_8 = Inflows to Stillwater NWR

5.3 RESULTS

By varying the priority assigned to the different environmental uses relative to one another and to other water uses, it is possible to quantify trade-offs among uses. In Section 5.3.1, trade-off among environmental uses is analyzed. The impact of varying environmental priorities on water righted uses is discussed in Section 5.3.2, and the effect on reservoir operation is discussed in Section 5.3.3. Probability of shortage and the probability of exceeding shortages of various levels were used to evaluate the different alternatives. Ideally, more specific measures of performance would be used for each water use (e.g., Hashimoto *et al.*, 1982).

5.3.1 Environmental Trade-Off Analysis

Probabilities of shortage for inflows to Pyramid Lake and Stillwater NWR under the various alternatives are compared in Figure 5.1. This is the probability of not fully satisfying demand in any month. A trade-off frontier is generated for each alternative (y32o, n62o, and n62c) by plotting the probability of shortage for different combinations of environmental priorities (p1s7, p2s1, etc.). These curves are the non-dominated solutions for each alternative (Cohon, 1978). Any other combination of weights (relative priorities) for a given alternatives will produce less desirable results, i.e., larger probabilities of shortages for the environmental uses. The probability of fully satisfying demands improves to the upper right of the figure. Points in the lower left part of the figure represent the "worst-case" conditions in which environmental uses receive the lowest priorities in the system (p7s7 in Chapter 4). The origin represents 100 percent probability of some shortage, that is, demands will never be fully satisfied. Feasible solutions will lie between these points and the trade-off frontiers. Several observations can be made regarding Figure 5.1.

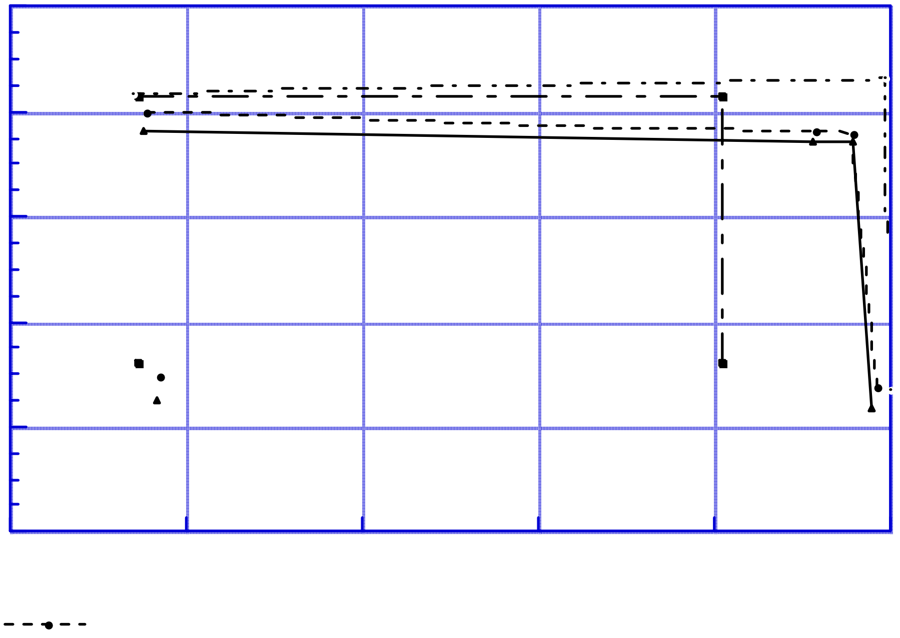


Figure 5.1 - Trade-off Curves for Probability of Shortage

The probability of shortage trade-off curve generated by evaluating alternative y32o with perfect hydrologic foresight (PFy32o) is the outer-most curve in Figure 5.1. These points represent the best that can be expected for the given institutional conditions because with perfect foresight, the model correctly anticipates droughts and floods and optimizes operation accordingly. The probability of shortage in any given month will be greater for any of the annual optimization runs. Perfect foresight for alternatives n62o and n62c would yield even better results because, based on the results of Chapter 4, these two alternatives relax institutional constraints that introduce some flexibility in system operation. However, for the purposes of this analysis, the actual values of probability of shortage are less important than the qualitative comparison among alternatives. Since the same general trends are produced by the perfect and annual foresight runs, only the annual runs were evaluated in detail.

Removing some of the institutional constraints can be advantageous for the environmental uses. The trade-off frontier for alternative n62o, which removes Floriston Rate requirements and relaxes water elevation constraints in Lake Tahoe dominates alternative y32o, which represents existing, institutionally constrained operations, i.e., the probability of fully satisfying demand is greater for n62o than for y32o. The improvement is more pronounced for inflows to Pyramid Lake than for inflows to Stillwater NWR.

Results for alternative n62c, in which the Truckee Canal is assumed closed, show further improvements in the probability of shortages of inflows to Pyramid Lake. However, closing the canal increases the probability of shortage for inflows to Stillwater NWR. With the canal closed, the probability of not fully satisfying demand in any month for which there is a demand at Stillwater increases to almost 20 percent. Alternative n62c produces the minimum probabilities of shortage for inflows to Pyramid Lake for all priority combinations.

A different, possibly more illustrative, representation of the trade-offs among the environmental demands is shown in Figure 5.2, which plots the probability of shortage for all water uses for alternative n62o. Concentrating only on the environmental demands to the right of the figure (other demands will be addressed in the next section), we see that when environmental demands are the highest prioritized uses (p1s2, p2s1), the tradeoff among the two is relatively minor because there are ample supplies for both. In fact, the probability of any shortage is unchanged for Pyramid Lake and improves slightly for Stillwater NWR. However, when the two environmental demands are considered to have low priority (p7s6, p6s7), the trade-off is more pronounced as competition for scarce supplies intensifies. With p7s6, Pyramid Lake inflow requirements are not fully satisfied about 72 percent of the months. The percentage falls to 22 percent with weights p6s7. For Stillwater NWR the reverse is true. With p7s6, the probability of shortage is about 6 percent, and increases to almost 85 percent for p6s7.

Figure 5.2 also reflects the relative dominance of Pyramid Lake inflow demand in water allocation. The probability of shortage to Stillwater inflows is less for p7s6 than for p1s2, even though the priority for Stillwater inflows is higher. Because of the large demand, a high priority on Pyramid Lake inflows overwhelms demands at Stillwater NWR.

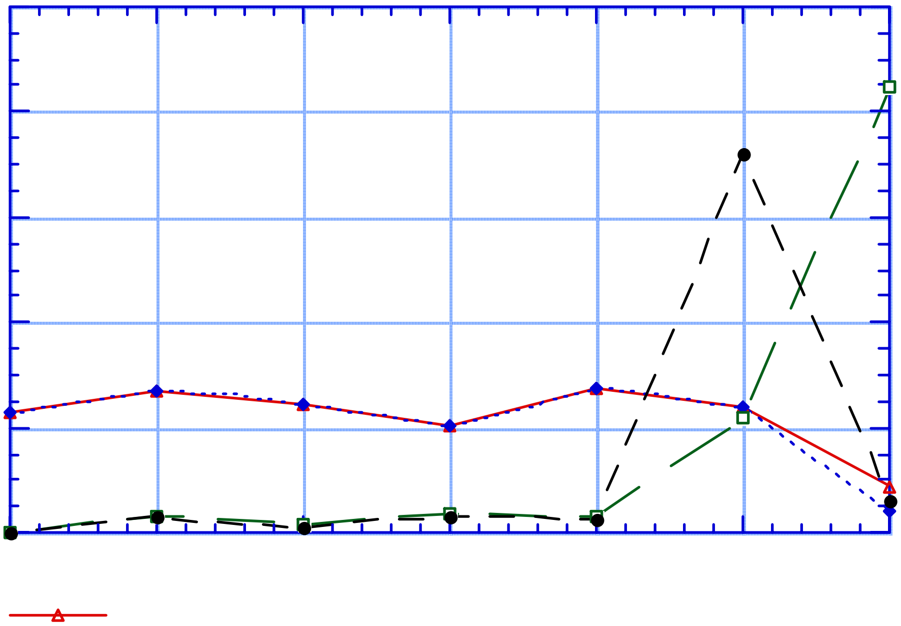


Figure 5.2 - Trade-off between Environmental Uses

Average magnitude of shortage for each of the runs is shown in Table 5.3. Results of the perfect foresight run (PFy32o) also are listed in Table 5.3. Pyramid Lake demand is 60 KAF/month. Therefore, the average shortages listed in Table 5.3 are between about 44 and 72 percent of demand. Stillwater NWR inflow demands are 10.42 and 16.66 KAF/month depending on the month. Thus, average shortage as a percent of average demand range from 47 to 70 percent.

Table 5.3 - Average Shortage (KAF/month)

Alternative	Demand	Priority				
		p1s7	p1s2	p2s1	p7s1	p7s7
y32o	Pyramid	35.89	36.23	39.13	41.60	38.47
	Stillwater	7.21	8.41	7.20	6.74	6.58
n62o	Pyramid	35.46	35.67	38.30	45.61	43.01
	Stillwater	7.14	8.29	6.97	7.15	6.52
n62c	Pyramid	33.16	32.90	32.90	38.58	38.58
	Stillwater	7.69	8.76	8.76	8.76	7.69
PFy32o	Pyramid	26.26	26.83	26.83	43.33	40.64
	Stillwater	7.32	9.58	9.58	0.0	6.57

When inflows to Pyramid Lake have high priority, not only does the probability of shortage decrease with alternatives n62o and n62c (Figure 5.1), so does the average magnitude of shortage. Without having to make releases for Floriston Rates, more water is available in storage to satisfy Pyramid Lake demands. With the Truckee Canal closed (n62c), average shortages of Stillwater NWR inflows are greater if these have a high priority relative to Carson Division demands than if they have lower priority, but the frequency is less.

Figure 5.1 identifies the probability of shortages of any amount, i.e., any time demand is not fully satisfied. However, the frequency with which shortages of different magnitudes occur (as a percent of monthly demand) also may be an important criterion for evaluating among competing alternatives. In analyzing these types of trade-offs, it may be important to know, for example, the probability of incurring large or small shortages. Depending on the use, it may be more desirable to have a greater number of smaller shortages than an increase in the magnitude of less frequent large shortages. This type of information is conveyed in Figures 5.3 and 5.4, which show the probability of exceeding shortages of different levels as a percent of demand for inflows to Pyramid Lake and

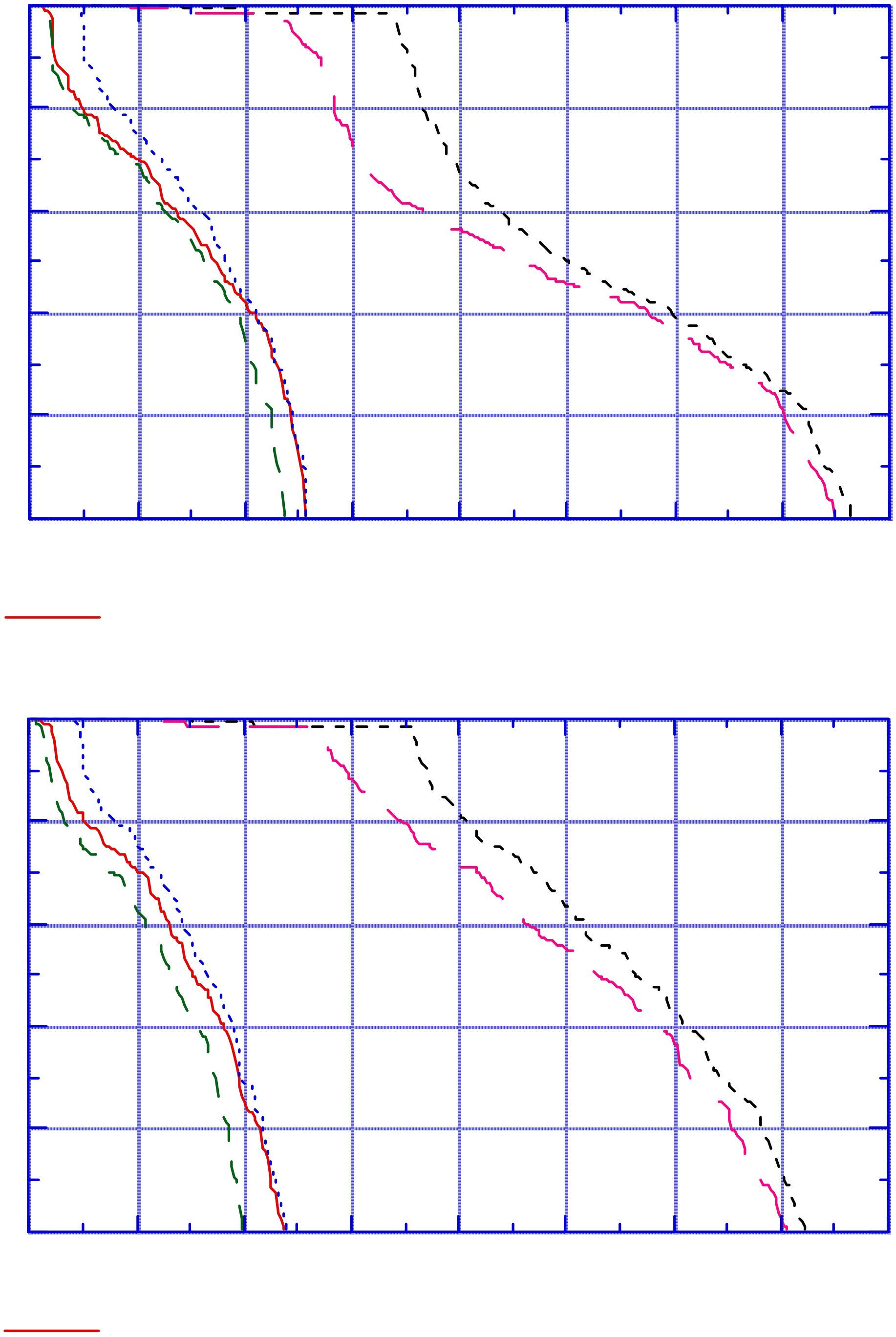


Figure 5.3 - Exceedence Probability for Shortages in Inflows to Pyramid Lake (a) Alternative y32o (b) Alternative n62o

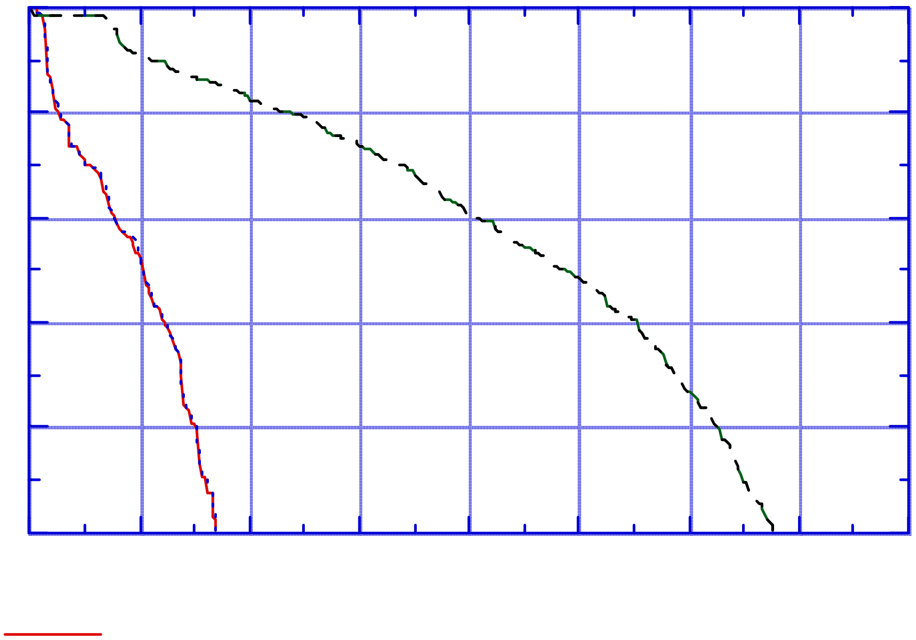


Figure 5.3 - Exceedence Probability for Shortages in Inflows to Pyramid Lake (c) Alternative n62c

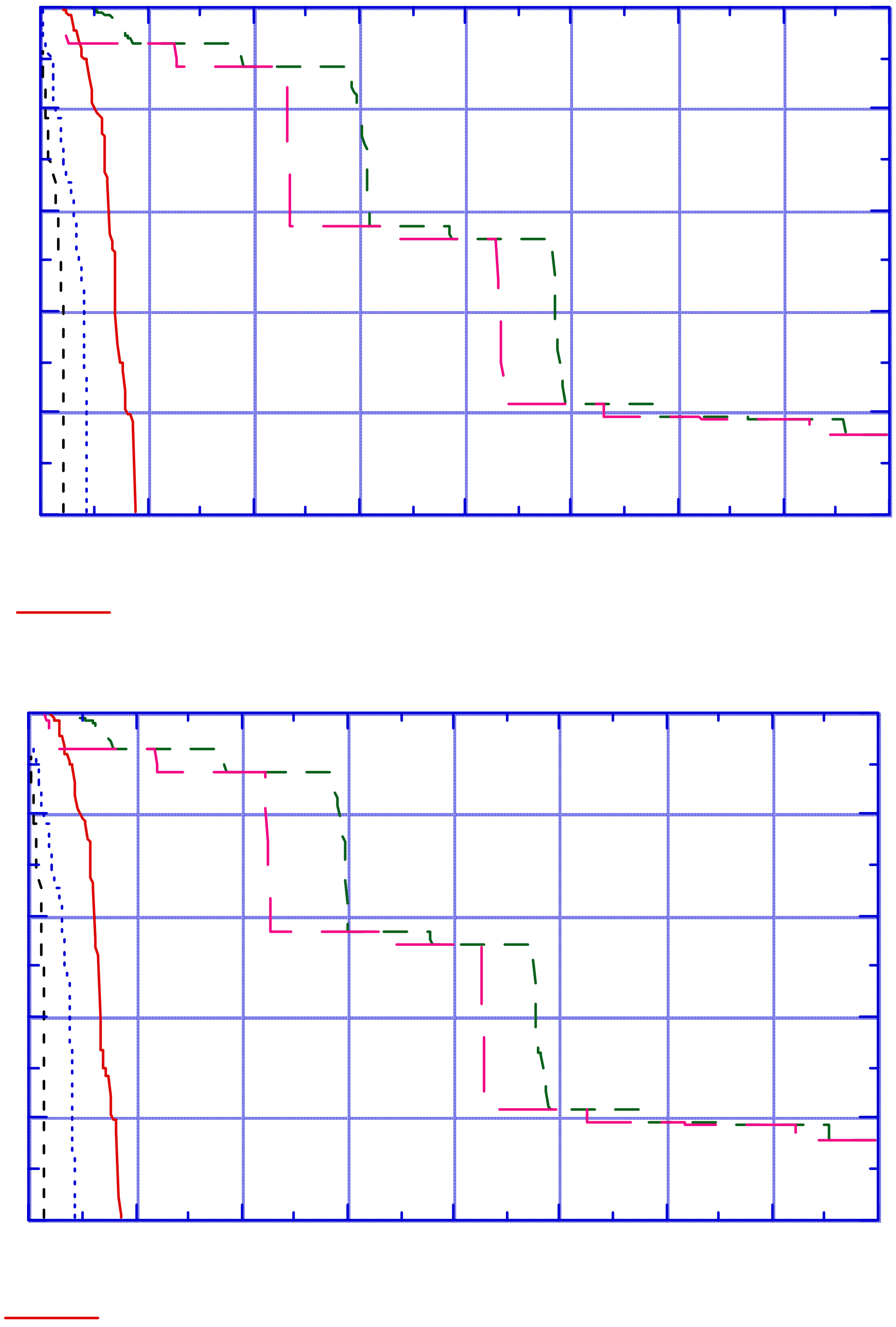


Figure 5.4 - Exceedence Probability for Shortages in Inflows to Stillwater NWR (a) Alternative y32o (b) n62o

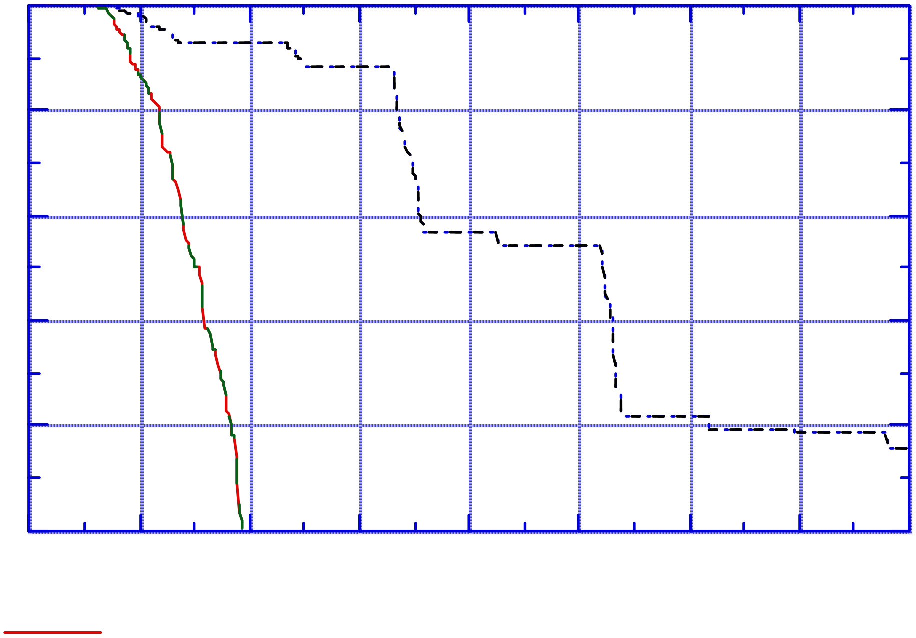


Figure 5.4 - Exceedence Probability for Shortages in Inflows to Stillwater NWR (c) Alternative n62c

Stillwater NWR, respectively. Conversely, these curves could be interpreted as the percent reduction in monthly demand. For example, a 50 percent exceedence probability for a 60 percent shortage implies that in 50 percent of the months, inflows will be only 40 percent of the required demand.

In Figures 5.4, the step shaped exceedence curves for priorities p1s7 and p7s7 highlight the reliance of inflows to Stillwater on agricultural drainage from the Carson Division. Since for these runs, inflows to Stillwater NWR receive low priority, each of the nine steps corresponds roughly to return flow from a monthly Carson Division demand. For alternative n62c, in which the Truckee Canal is closed and the two river systems are independent , the environmental demands also are independent. Thus, the five exceedence curves are reduced to two; one representing high priority and the other low priority for environmental demands on the individual rivers.

The most evident result from these figures is that, since the curves never cross, the higher the priority given to a demand, the lower will be the probability of shortage of any magnitude. For instance, under alternative y32o (Figure 5.3(a)), a shortage of 40 percent of demand is exceeded in roughly 58 percent of the months when priorities are p7s7. With priorities p1s7, this same shortage level is exceeded in only about 20 percent of the months. Figures 5.3 and 5.4 show the potential improvement afforded by the different combinations of priority weights for a given alternative, or, for a given priority weight, the potential improvement due to different management alternatives.

Considering inflows to Pyramid Lake and assuming p7s7 as the baseline, Figure 5.5 illustrates the change in exceedence probability for different shortage levels and environmental priority levels. When inflows to Pyramid Lake are given high priority, the probabilities of exceeding low level shortages improves by up to 50 percent. That is, there is a 50 percent reduction in the probability of shortage. In general, improvements are larger for low shortages as a percent of demand than for large shortages. The condition for shortages of up to 30 percent of demand improves by about 50 percent, whereas for shortages greater than 70 percent of demand, the improvement is only about 20 percent. Only p7s1 performs worse than the baseline. In this case, surplus water that would otherwise flow to Pyramid Lake is diverted to Stillwater NWR because it has highest priority. The probability of incurring larger shortages is slightly more than the probability of suffering smaller shortages.

In Figure 5.6 shortage exceedence probabilities for priority sets p1s7 and p7s1 are compared for the three alternatives. For p1s7, results are similar to those presented earlier, in that alternative n62c produces the lowest exceedence probabilities at all shortage levels, followed by n62o and y32o. However, the results are a bit different for priorities p7s1. Alternative n62c remains the best overall and performs especially well for shortages greater than approximately sixty percent of demand. But it is unclear whether n62o or y32o is better overall. Alternative n62o yields lower exceedence probabilities at low shortage

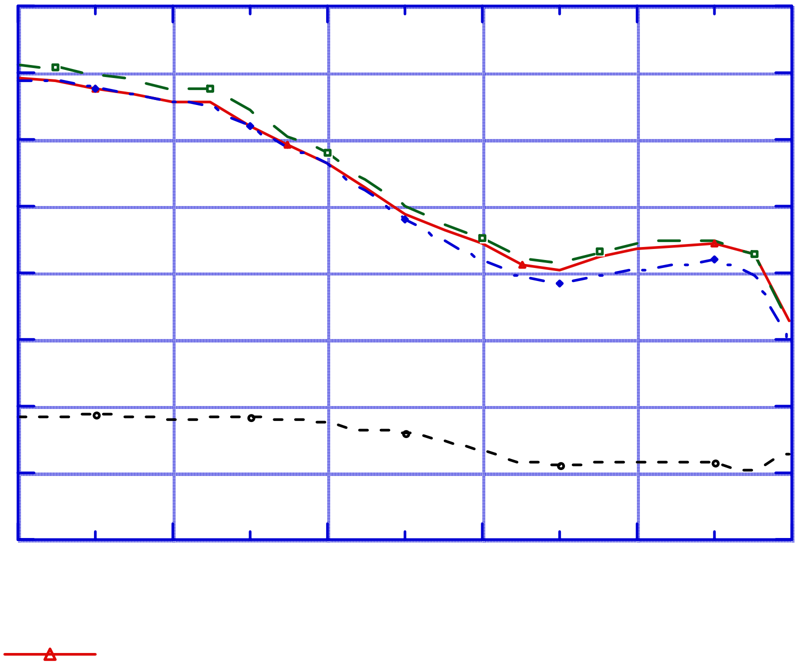


Figure 5.5 - Percent Change in Exceedence Probability for Shortages in Inflows to Pyramid Lake

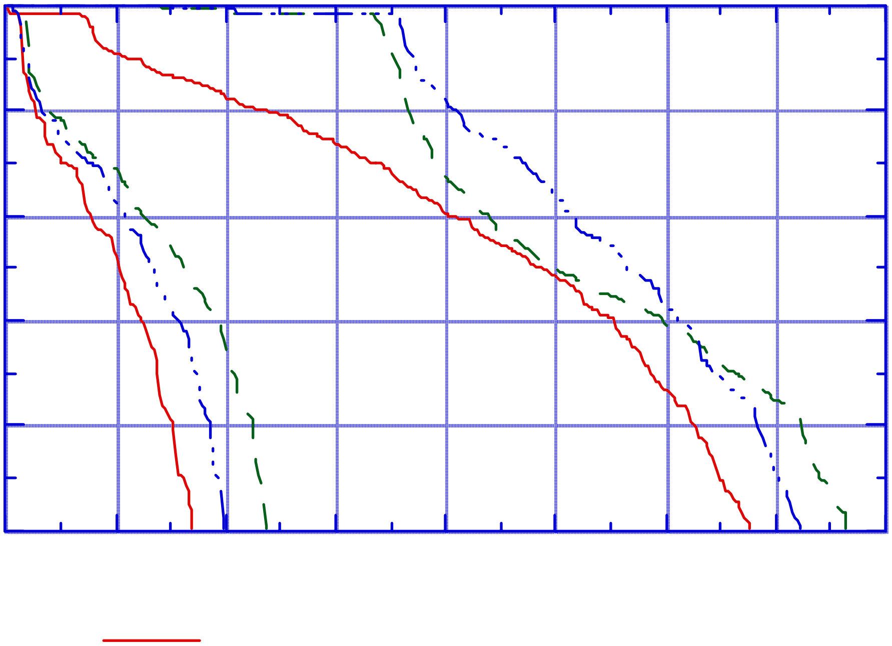


Figure 5.6 - Exceedence Probability for Shortages in Inflows to Pyramid Lake (p1s7 vs. p7s1)

levels, but is out performed by alternative y32o for shortages exceeding about 40 percent of demand. Similarly, for priorities p1s2 and p2s1 y32o is marginally better for shortages above 60 percent of demand. For smaller shortages, however, n62o is better. Alternative n62c out performs both. Results for other priority combinations and for inflows to Stillwater NWR are similar.

Although the two environmental demands compete against each other to some extent, as the above analysis has borne out, it is unlikely that the two would be considered true competitors, independent of one another, as represented by the corner points of Figure 5.1 (priorities p1s7 and p7s1). Though there is competition for water, the two demands most likely would be considered together in analysis or negotiations. Environmental groups would tend to push for increased supplies to both uses simultaneously. But even then, some trade-offs between the two would be necessary. Thus, the feasible region in Figure 5.1 most likely can be reduced to that region for which priorities on environmental demands are no more than one or two rank orders apart. And figures such as 5.6 provide upper bounds for likely alternative and priority combinations.

Moving along each of the trade-off curves in Figure 5.1 to points of different priority or from curve to curve has many implications for other water uses in the systems. The effect on other water uses and on reservoir operation must be considered in the decision-making process. These effects are discussed in the following sections.

5.3.2 Impact on Water Righted Demands

Since environmental demands are the most downstream uses on the system, a portion of the demand requirement can be met by incidental supplies (e.g., municipal and agricultural return flows, reservoir spills, and releases for minimum instream flow requirements). However, the timing and relative magnitude of environmental demands, particularly attraction flows to Pyramid Lake also need to be considered. Attraction flows are required early in the year, from January to July, whereas peak agricultural and M&I demands occur from April to September. From January to April reservoir releases for fish flow almost can be considered single source releases because of low demand levels elsewhere in the system. The decrease in reservoir storage due to these releases affects municipal and agricultural demands later in the year.

The effect of different alternatives and environmental priorities on the ability to satisfy demands of the five water righted uses is shown in Figures 5.7(a-c), in terms of probability of shortage. Also shown for comparison are the probabilities of shortage for the two environmental uses. From these figures it is possible to get a snapshot of the effect of different environmental priorities on all water righted demands at once. Generally, the higher the priorities given to the environmental demands, the greater the probability of shortage for the water righted uses. For example, priority weights p1s2 and p2s1 result in probability of shortage of about 20-30 percent for all uses under alternative y32o, and 15-25 percent for alternative n62o. Demands are fully satisfied 75-

85 percent of the time. The dip in probability of shortage for Carson Division demands is a result of Lahontan Reservoir supplies being available solely for Carson Division demands. The effect of closing the canal is apparent from the results of alternative n62o (Figure 5.7b) and n62c (Figure 5.7c). Truckee Division is shorted fully every month.

Although Carson and Truckee Division demands are assumed to have the same water use priority, and, thus, should have similar probabilities of shortage, this is not always the case. For low environmental priorities (p7s7), the probability of shortages for the two are roughly the same. However, as the priority of environmental demands increases, especially the priority of inflows to Pyramid Lake, less water is available for diversions to the Truckee Canal and shortages at the Truckee Division increase. The Carson Division is buffered from reduced Truckee Canal flows by Lahontan Reservoir. System configuration is an important factor in water allocation and may override allocation priorities specified through penalty functions.

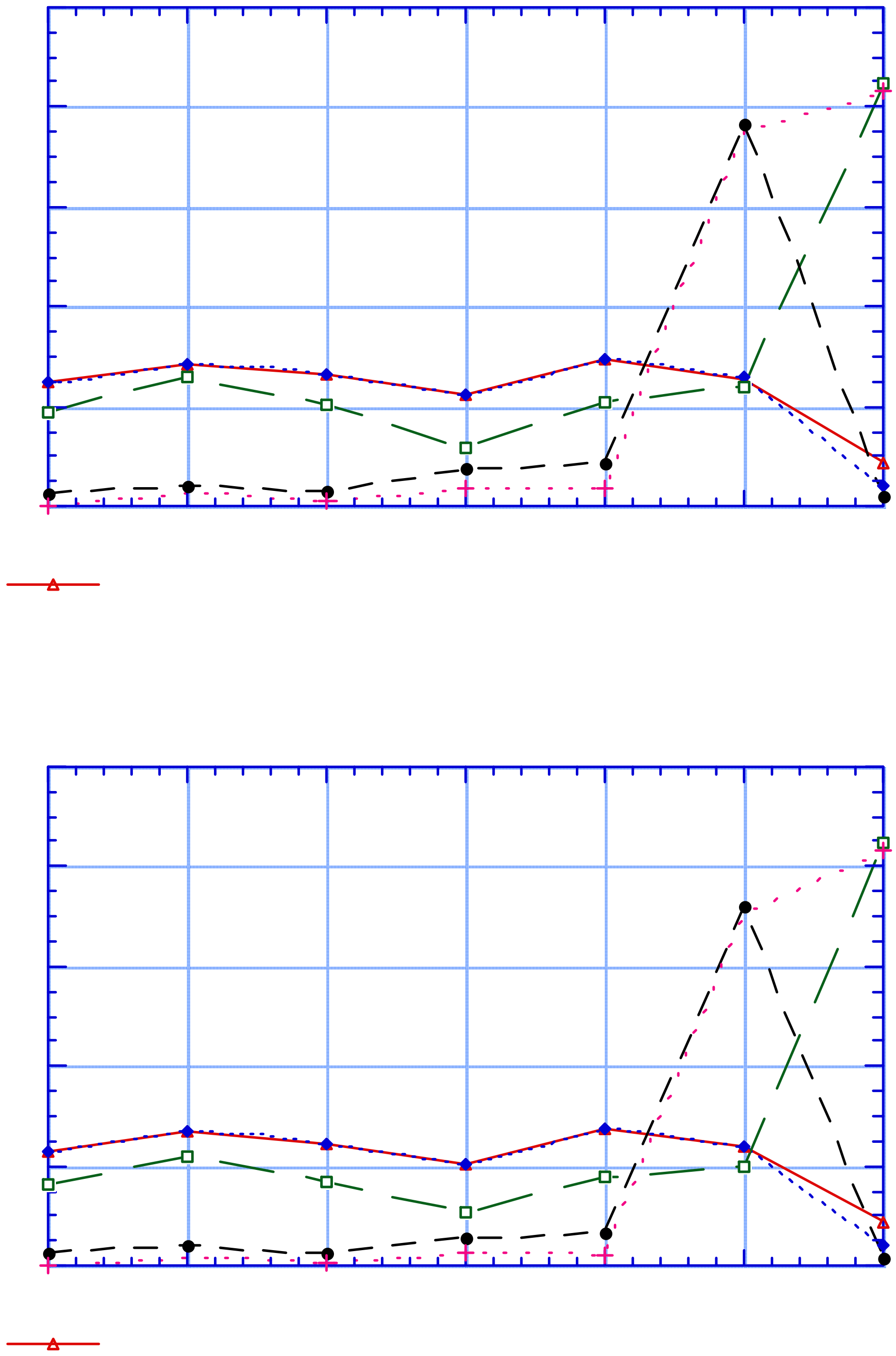


Figure 5.7 - Probability of Shortage for Water Righted Demands
(a) Alternative y32o (b) Alternative n62o

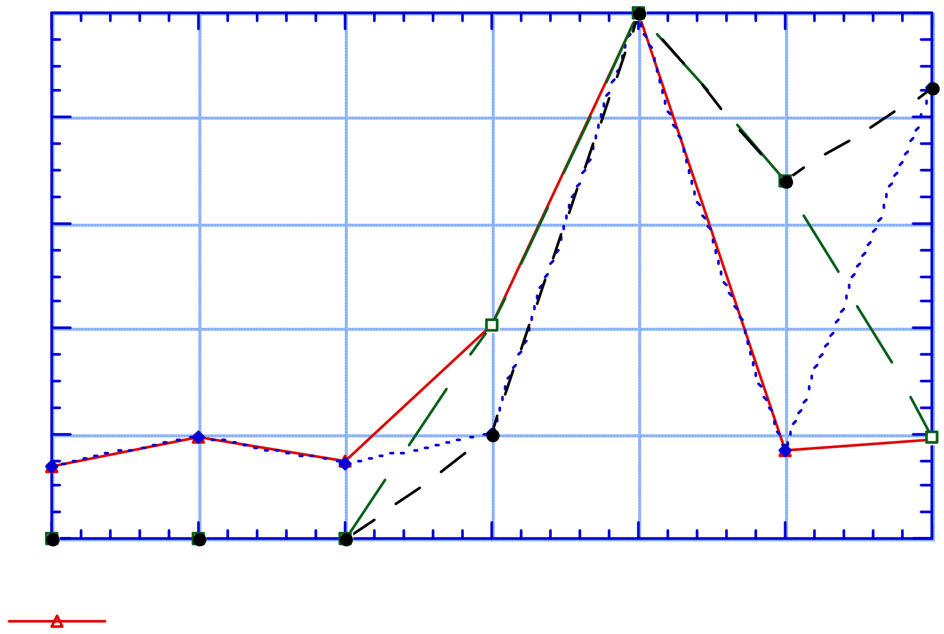


Figure 5.7(c) - Probability of Shortage for Water Righted Demands (Alternative n62c)

Shortage probabilities for priority weights p1s2 shown on Figure 5.8 indicate that when environmental demands have high priority, the probability of shortage for all uses is roughly the same under alternatives y32o and n62o. Water righted demands are fully satisfied in about 75-80 percent of the months under these conditions. When the Truckee Canal is closed (alternative n62c), the probability of shortage for irrigation at Pyramid Lake, Reno M&I demands, and Truckee Meadows demands decreases, while that for the Carson Division increases. Under this alternative, the Truckee Division receives no water. Figures for the other priority weights (p2s1, p1s7, p7s1, and p7s7) are similar.

As with the analysis of environmental trade-offs presented in the previous section, the probability of shortage alone does not provide sufficient information for decision-making. Additional information on the magnitude of shortages and the likelihood of their occurrence also is useful for comparing among alternatives. Figures 5.9a-e are probability

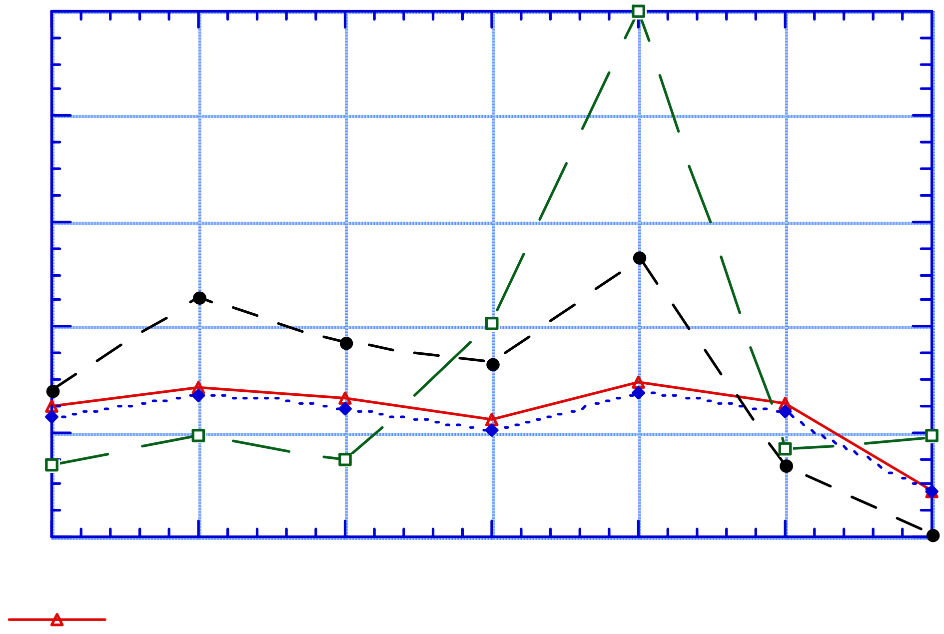
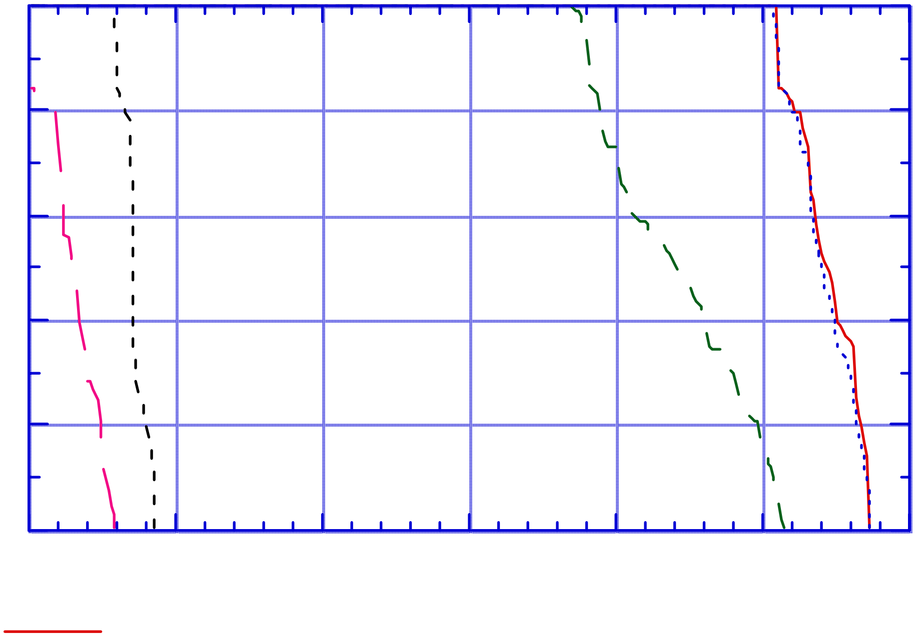


Figure 5.8 - Probability of Shortage for Water Righted Demands (p1s2)

exceedence curves for shortage levels as a percent of monthly demand for the five water righted uses. (Similar figures can be developed for the other alternatives.) Noteworthy in these figures is that the majority of the exceedence curves are vertical or nearly so, indicating that if a shortage occurs, it is most likely a complete shortage. In fact, average shortage as a percent of demand for these water uses is between 80 and 100 percent. This reflects strict adherence to the prioritization penalties developed for these runs. The magnitude of demand is not considered in determining water allocation. This somewhat unrealistic condition can be overcome by restructuring the penalty functions to incorporate a minimum water supply for each use, although this is not in keeping with the prior appropriation doctrine.

Shortage probabilities for Reno M&I under alternatives y32o and n62o are shown in Figure 5.10. Two conclusions can be drawn from Figures 5.9 and 5.10. First, the institutional conditions represented by alternative n62o consistently result in lower



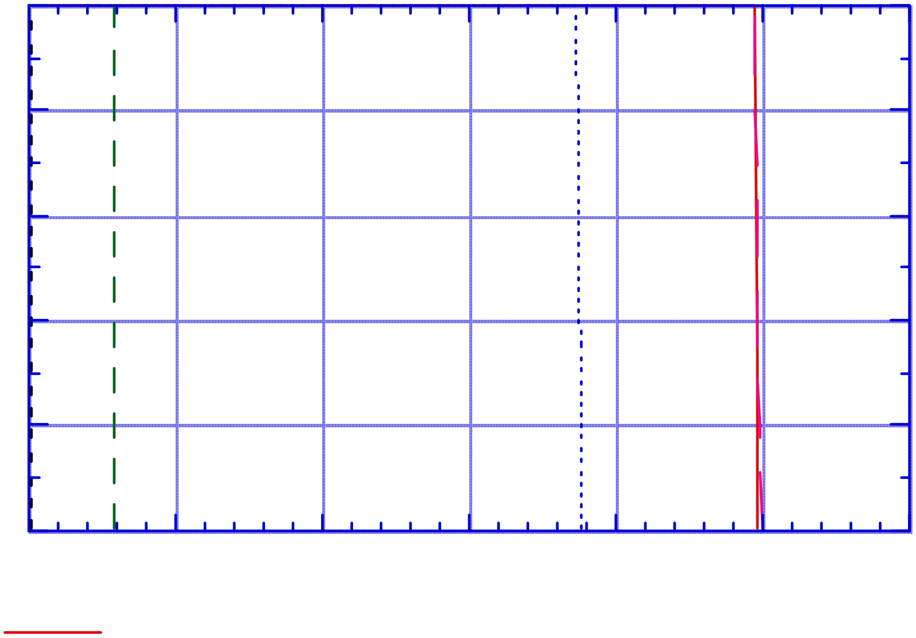


Figure 5.9 - Exceedence Probability of Shortage for Water Righted Demands (a) Pyramid Irrigation (b) Reno M&I

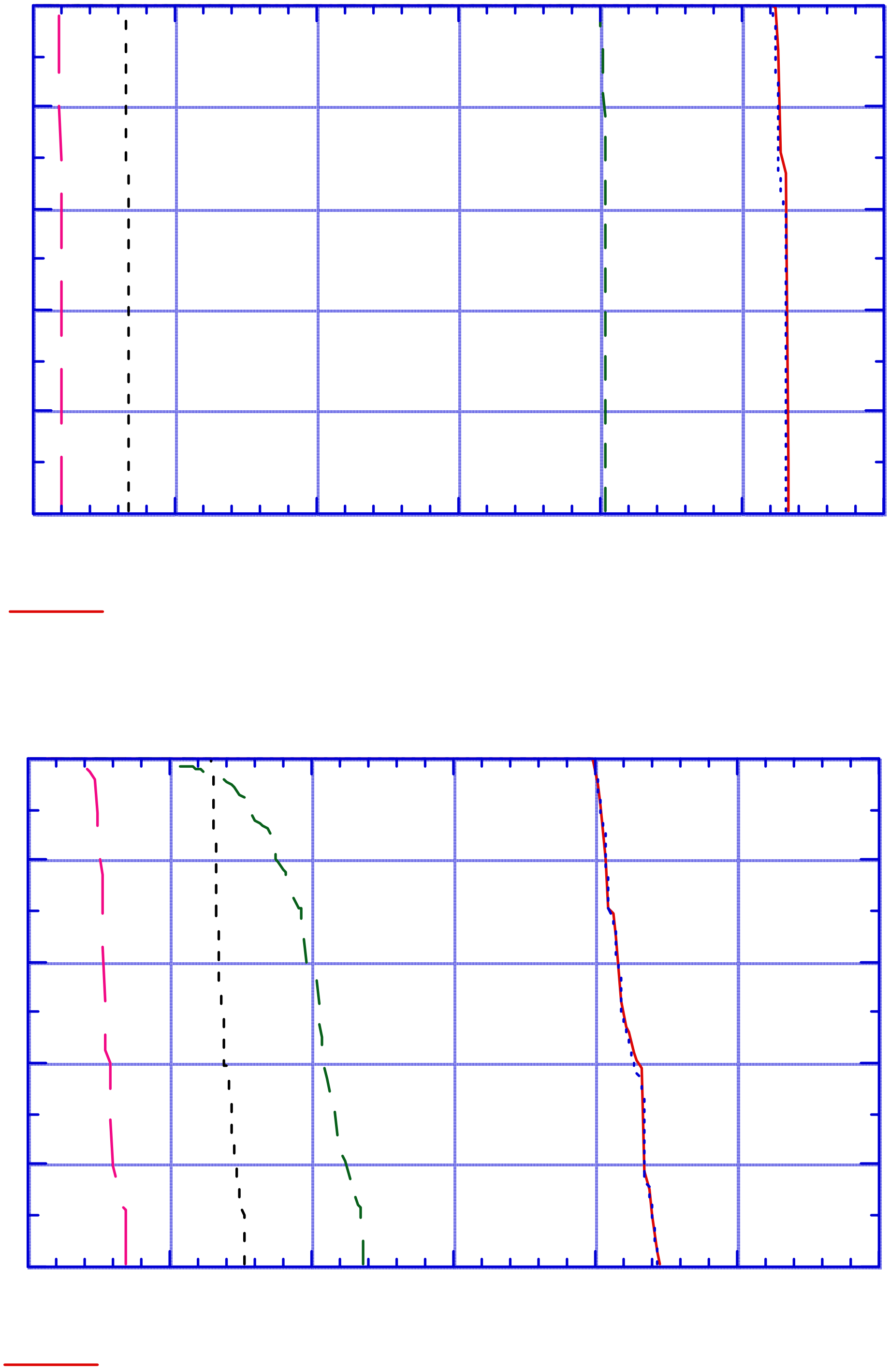


Figure 5.9 - Exceedence Probability of Shortage for Water Righted Demands (c) Truckee Meadows (d) Carson Division

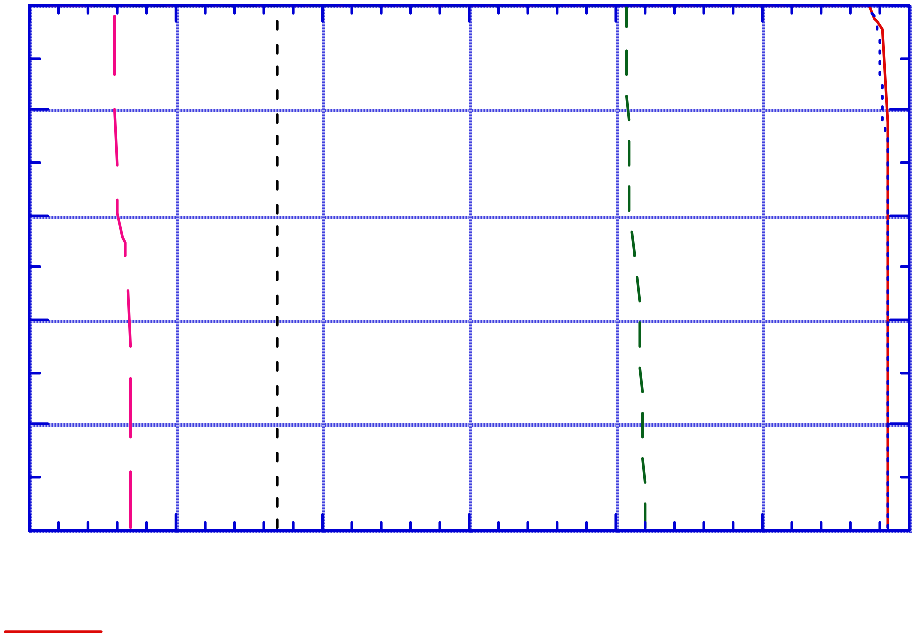


Figure 5.9 - Exceedence Probability of Shortage for Water Righted Demands (e) Truckee Division

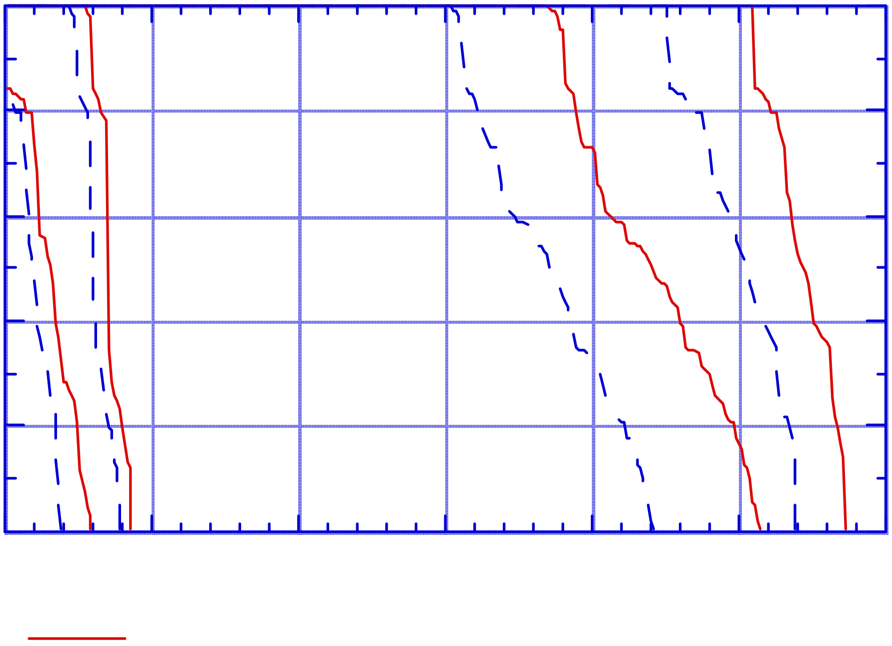


Figure 5.10 - Shortage Exceedence Probability for Reno M&I (y32o v. n62o)

probability of shortage for Reno M&I than alternative y32o. Second, the priority of Pyramid Lake inflows has a much greater influence on the water righted demands than the priority on Stillwater inflows. Because of the large Pyramid Lake demand, priority weights p1s7, p1s2, and p2s1, induce higher probabilities of shortage at Reno than priority weights p7s7 and p7s1, in which Stillwater inflows have priority. Results for other water uses are similar.

Up to now, water demands have been considered individually. In the following discussion the seven water uses are aggregated into two groups (Environmental and Water Righted) to evaluate trade-offs. For each group, an aggregated probability of shortage was calculated by averaging probabilities of shortage for the five water righted uses and two environmental uses. Results for all runs are presented in Figures 5.11a-b in terms of water supply reliability (i.e., the probability of fully satisfying demands). The curve shown is analogous to a "production possibilities frontier" in that it represents the maximum amount of Environmental supply reliability that can be attained for a given amount of Water Righted supply reliability, or vice-versa. Any point on this curve is Pareto optimal since water supply reliability to one group cannot be improved without reducing it for the other. Points above the curve are infeasible and those below the curve are dominated.

In Figure 5.11(a) all points on the curve are produced by alternative n62o, which dominates alternatives y32o and n62c. Results for runs in which Pyramid Lake inflows have highest priority (p1sX) are dominated because trying to fully satisfying Pyramid Lake demands induces too many shortages elsewhere in the system. Low priority on environmental demands generates points with high reliability of Water Righted uses and low reliability for the environmental. The opposite is true when high priority is given to the environmental demands.

The analysis was repeated considering only Truckee River demands in the Water Righted group (Pyramid Lake irrigation, Reno M&I, and Truckee Meadows irrigation);

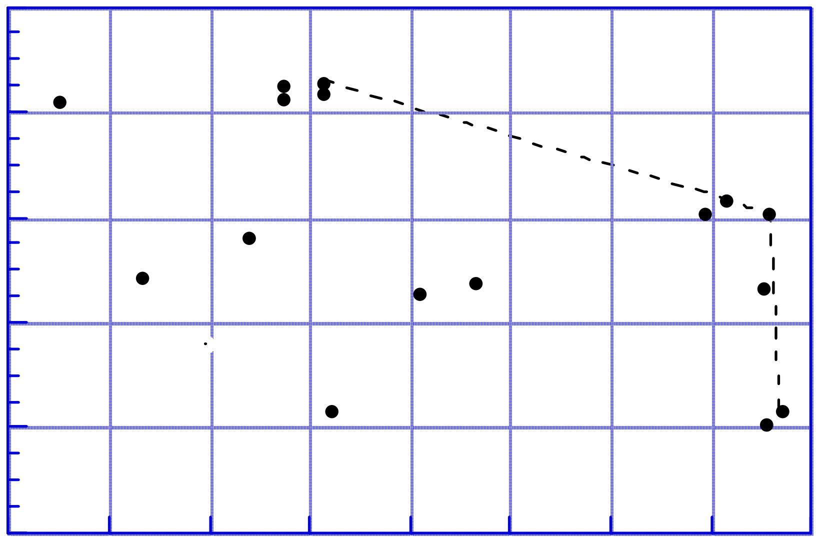
demands of the Newlands Project were excluded. Results for this case are more interesting because the curve is comprised of points generated by alternatives n62o and n62c (Figure 5.11(b)). In evaluating trade-offs in water supply reliability represented by moving along the curve, not only must priority weights be considered, as in Figure 5.11(a), but so must institutional and policy issues - status of the Truckee Canal.

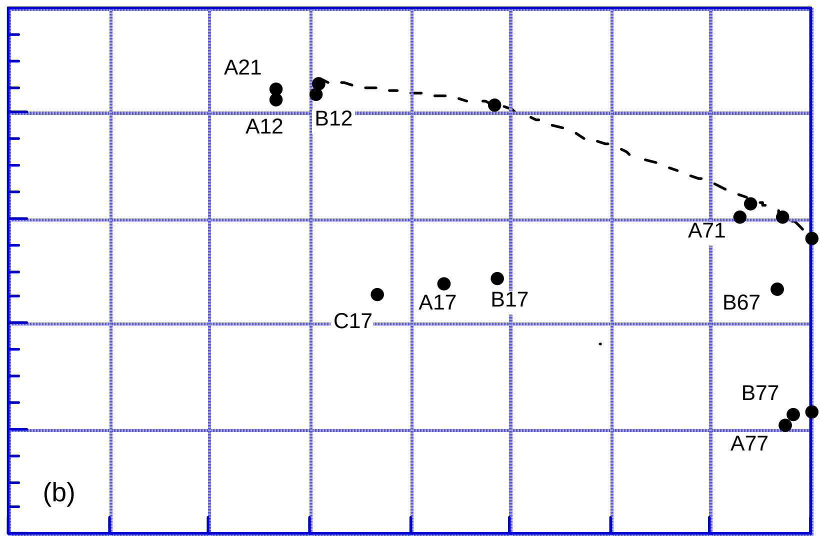
Also shown in Figures 5.11a-b are results from a run using the Negotiated Settlement Model. The NSM run approximates the conditions of the existing institutional environment represented by alternative y32o. Shortage probabilities for the various water demands generated by NSM are listed in Table 4.7. Since the NSM does not calculate shortage information for inflows to Stillwater NWR and for Truckee Meadows irrigation, the aggregated values are not directly comparable with HEC-PRM results. Nonetheless, it is apparent from these figures that the NSM values are dominated by several alternatives, indicating that there are opportunities for improving operation of the system to the benefit of all water users.

The next section discusses how Lake Tahoe and the Truckee River reservoirs respond to the different alternatives and priority weights.

5.3.3 Impact on Reservoir Operation

The priority of environmental demands relative to other system demands will affect how Lake Tahoe and the upper Truckee River reservoirs respond. Exceedence probability curves for storage in Lake Tahoe shown in Figure 5.12 are typical reservoir response in that storage levels tend to be lower as the priority of environmental demands increases. Results are shown for alternative y32o, but the same holds for alternatives n62o and n62c As noted previously, because of the buffering effect of Lahontan Reservoir as a dedicated supply source for Stillwater NWR and Carson Division demands, a high priority on inflows to Pyramid Lake (e.g., priority weights p1s7, p1s2) will impact operation of Lake Tahoe, Prosser Reservoir, and Stampede Reservoir much more than a high priority on inflows to Stillwater NWR (p7s1). A comparison of storage exceedence probability curves for priority weights p1s7 and p7s1 for alternatives n62o and n32o is shown in Figure 5.13.





A = y32o B = n62o C = n62c; p,s are relative priority on Pyramid and Stillwater inflows
A12 represents alternative y32o with Pyramid inflows top priority and Stillwater second priority

Figure 5.11 - Trade-offs between Environmental and Water Righted Uses

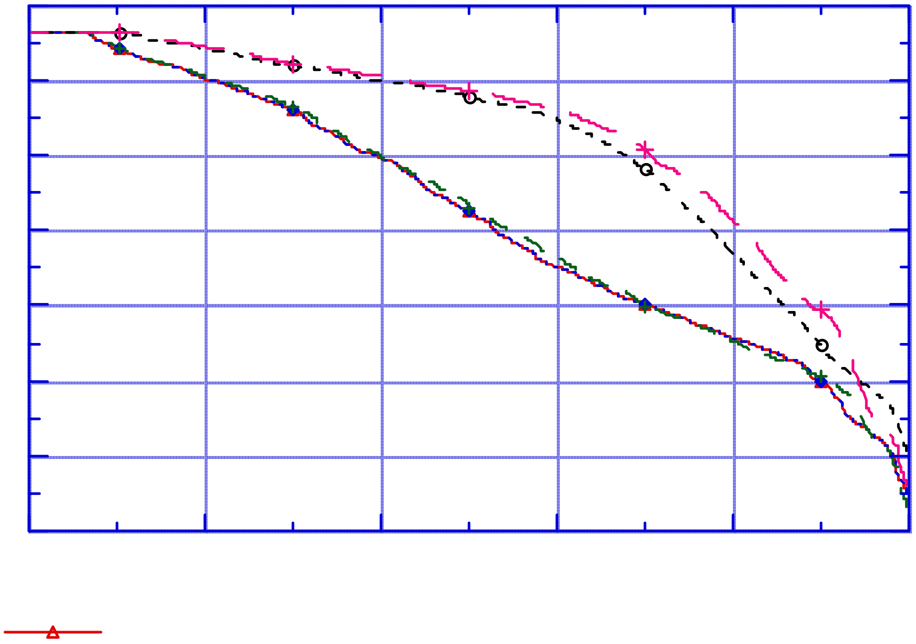


Figure 5.12 - Lake Tahoe Storage Exceedence Probabilities (y32o)

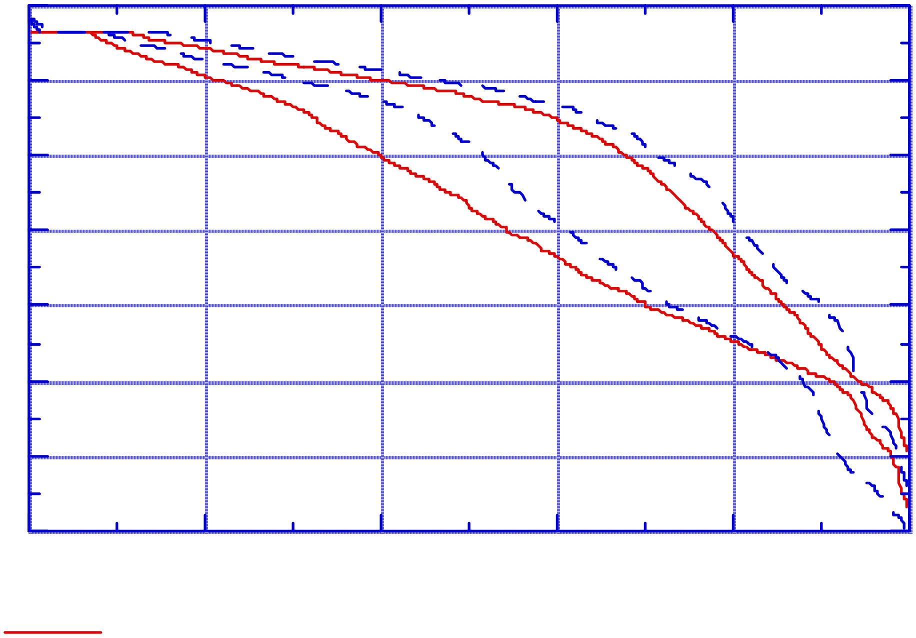


Figure 5.13 - Lake Tahoe Storage Exceedence Probabilities (y32o v. n62o)

These curves reinforce the dominance of alternative n62o over y32o, as storage levels in Lake Tahoe are maintained higher with n62o.

It was noted in Chapter 4 that relaxing maximum water surface constraints on Lake Tahoe had little effect on lake operation or on the ability of the system to satisfy downstream demands. With the environmental demands receiving higher priority, the extra storage capacity afforded by permitting lake levels to rise above 6229.1 ft was not used more frequently, as may have been expected. With annual foresight, the model was not able to take advantage of the extra storage capacity because it could not anticipate well future droughts, particularly over-year droughts (Figure 5.14). The greatest impact on Lake Tahoe storage of increased priority on environmental demands is the increased frequency with which Lake Tahoe water surface falls below the natural rim. With low priority on these demands, Lake Tahoe water surface is above the natural rim in about 90 percent of the months. With high priority on environmental uses, this percentage drops to roughly 70 percent. The loss of usable reservoir storage is reflected by the higher probabilities of demand shortage that result with y32o.

5.4 CONCLUSIONS

Conclusions are presented in three areas: technical conclusions, implications for policy making and management of the Truckee-Carson system, and limitations and potential extensions to the current analysis.

5.4.1 Technical Conclusions

The analysis in this chapter provided additional opportunities to implement the algorithm for determining rank-preserving unit penalty coefficients. Results of the analysis reflect the rigid priority-based allocation mechanism specified by the penalty functions. In water short situations, water uses of low priority were shorted fully so that demands of the more senior right holders could be satisfied to the greatest extent possible. However, strict adherence to prioritization in water allocation (as specified by the prior appropriation

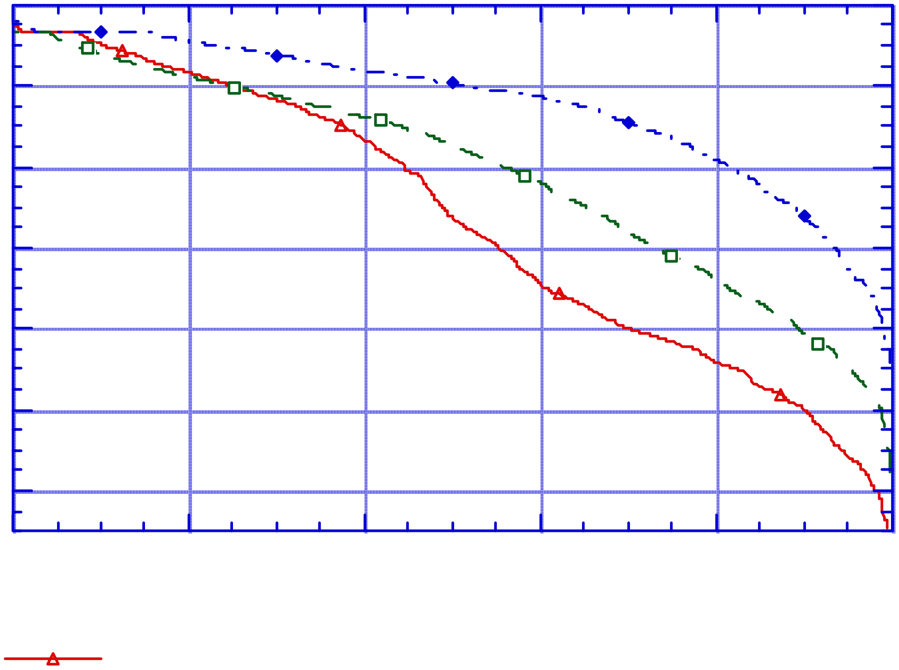


Figure 5.14 - Lake Tahoe Storage Exceedence Probabilities

doctrine, for example) is rarely enforced, particularly when water for human consumption is involved. Although a 100 percent shortage for M&I is not very realistic, the runs provide an upper bound for satisfying environmental demands. As discussed in Chapter 3, the priority-based penalty functions can be modified to reflect the importance of satisfying a minimum level of M&I and irrigation demands prior to satisfying more highly prioritized environmental or other system demands. Also, the priority-based penalty functions can be formulated to reflect water conservation and other potential water demand reductions.

In reality, relatively small demands, such as Pyramid Lake irrigation, may be conceded without discussion or need for much negotiation because the impact they have on system operation may be small, even if these demands have low priority. Priority-based penalties for these water uses can be structured to reflect these conditions.

Although the priority algorithm guarantees that user priorities are preserved to the greatest extent possible, it cannot account fully for the effects of system configuration and the unique relationship that may exist between some demand points and specific supply sources. This situation is represented by Carson Division demands and Lahontan Reservoir supply. Lahontan Reservoir buffers the Carson Division from extreme hydrologic or demand conditions in the Truckee River basin. While supply shortages or diversion to highly prioritized uses on the Truckee River will reduce availability for other Truckee River demands, the Carson Division, and Stillwater NWR when it has high priority, continue to be supplied from Lahontan Reservoir. In fact, Carson Division may be shorted less frequently than a higher prioritized water use dependent solely on Truckee River supplies.

As noted previously, optimization models are only as good as their penalty functions. Typically, the most difficult and most expensive aspect of an optimization study is development of penalty functions. This is especially true for environmental uses, for which clearly identifiable, economically-based penalty functions typically do not exist. The priority-based approach used in this study overcomes some of these difficulties and provides a mechanism for easily incorporating these uses in a comparative framework for water systems analysis. However, the manner in which priorities were selected in this study does not consider the intrinsic attributes of each environmental use. Multi-attribute analysis could be used to develop a more detailed priority ranking (Tecle, 1992). Nonetheless, the analysis has demonstrated that network flow models such as HEC-PRM are adequate for screening level analysis of different management alternatives.

5.4.2 Policy Implications

“For years, the water needs of Pyramid Lake and the Stillwater wetlands were seen to be in conflict. The source of both problems, however, is the same: heavy irrigation demands and the absence of environmental water rights (EDF, 1990)." However, a common problem source does not imply that the two water uses are no longer in conflict, and though some mechanisms exist for improving the situation of both demands simultaneously (water rights transfers, for example) and have the support of the 1990 Settlement Act (PL 101-618), inherently, the two demands compete for water. The conflict between the environmental uses intensifies as the priority of these demands falls relative to other system demands.

Shortages to and competition among environmental demands can be reduced in two ways, as demonstrated above. The first is to increase the priority assigned to these uses relative to other uses in the system. The second is to relax institutional constraints (e.g., Floriston Rates) on operation of the Truckee-Carson system. However, in moving to secure higher inflows for environmental uses, the underlying trade-offs with the water righted demands must be considered, especially given the relatively large increases in the probability of shortage for water righted uses.

The analysis in this chapter supports claims that Floriston Rates may be excessive. The No Floriston Rates alternatives consistently produced better results than the With Floriston Rates alternatives. Additional studies should be conducted to more thoroughly evaluate the technical and institutional merits and impediments of removing or reducing Floriston Rates. On the other hand, this study has not provided justification for seeking additional storage capacity in Lake Tahoe. When available, the extra capacity was used infrequently. The greatest impact on Lake Tahoe storage of increasing priority for environmental demands is the increased frequency with which Lake Tahoe water surface falls below the natural rim. This suggests that more detailed operation studies using a simulation model should be carried out to reduce the periods in which Lake Tahoe is ineffective, i.e., is below the rim.

While results of the analysis in Chapter 4 indicate that there may be a fair amount of flexibility in operating the Truckee-Carson system, results including prioritized environmental demands present a different picture. Increasing priorities on environmental demands places additional stresses on the system as indicated by reduced overall reservoir storage levels and increased probability of shortage for water righted uses. Analyses that do not fully consider these demands may provide a false indication of system performance.

5.4.3 Limitations and Extensions

Many of the modeling limitations discussed in Chapter 4 apply to the results of this chapter as well. The HEC-PRM analysis deals only with the quantity of water available to Pyramid Lake and Stillwater NWR. It does not account for the quality of those inflows, which is an important consideration. The results presented here must be evaluated further to determine their implications on water quality.

More appropriate performance measures could be developed for the various water uses that would be more representative of the nature or concerns of the use. For example, some environmental demands may be concerned more with consecutive months of inflow below some threshold level instead of the probability of shortage in a given month. Likewise, the performance criteria for reservoirs may be how quickly storage recovers following a drought.

Although the priority-based evaluation presented here implicitly assumes that a water use with high priority has high value, the economic value of water to the different uses should be considered in the trade-off analysis. For instance, is a 20 percent (or 10 or 5 percent) shortage for M&I at Reno equivalent to a 20 percent shortage for agriculture and are these shortages justified to avoid a 20 percent shortage in environmental flows? This type of question cannot be answered directly from the results presented here because economic information was not used in the formulation of the penalty functions, but it is precisely the type of question that decision-makers will have to deal with in devising an equitable and politically feasible water allocation or reallocation strategy for the Truckee-Carson system.

Chapter 6

Conclusions

ÒThe Truckee-Carson area provides a graphic example of the complexities of water allocation in the West. This hydrologic system clearly illustrates the conflicts that can occur among urban, agricultural, environmental, and tribal interests, and it raises issues about federal water project management, endangered species, wetland protection, and water quality degradation. The many pressures for reallocation of water highlight the need for institutions and decision-making processes capable of responding efficiently and equitably to accommodate new and traditional water values in the regionÓ (NRC, 1992).

As with many western water resource systems, operation of the Truckee-Carson system is overly constrained by existing legislation, agreements, court decrees, and other legal documents. Often it is unclear how these constraints may hinder or impede potential improvements in system performance. Because of the complicated legal issues, historical resistance to change, and strong emotions involved in reversing or renewing some of the existing agreements, little serious consideration has been given to such analysis. Currently, proposed solutions to water conflicts in the basin are constrained by and must be sought within the existing legal and legislative framework.

The objectives this research were twofold. The first was to evaluate potential improvements in performance of the Truckee-Carson system by relaxing some of the exisitng institutional constraints, namely, by eliminating Floriston Rates, relaxing restrictions on maximum water surface elevation in Lake Tahoe, and discontinuing diversions through the Truckee Canal. The existing water rights priority structure was retained in the evaluation and used as the basis for allocating supplies. By removing these constraints and not placing ownership rights on reservoir storage, as currently exists, allocations were made in an optimal manner according only to water rights and physical and hydrologic constraints.

The second objective of the research was to develop an algorithm for incorporating priority-based penalty functions in network flow modeling to properly reflect institutionally specified allocation priorities, e.g., by water rights. The U.S. Army Corps of Engineers Hydrologic Engineering Center's network flow model, HEC-PRM, was used for developing and implementing the algorithm. However, the algorithm is valid for any network flow or linear programming model.

Several conclusions emerge from this research.

The network flow model presented here can be a valuable tool for continued efforts to ameliorate water use conflicts in the Truckee-Carson basin.

Though limited in several respects because of the simplifications necessitated by the optimization model, the study demonstrated the usefulness and adequacy of this type of screening level analysis for addressing conflict situations and supports further pursuing similar modeling efforts. The institutional alternatives evaluated are illustrative of the many that could be explored in a broader systems study. These can be represented by changing physical constraints in the model, restructuring penalty functions to reflect different operating priorities and constraints, and varying water demands.

Environmental demands need to be considered in detail in system operation studies.

Inflows to Pyramid Lake and Stillwater NWR are substantial demands on the water resources of the Truckee-Carson system. Assigning a high priority to the environmental demands significantly affects reservoir operation and supply reliability of the upstream water righted uses. Any sort of system evaluation that is carried out without adequately considering these environmental demands will overestimate performance of the Truckee-Carson system. Furthermore, the relative priorities among the environemtal uses should be considered carefully.

The study supports reducing or eliminating Floriston Rates as the primary operating policy in the Truckee-Carson system.

The policy options considered in this study represent extreme cases - Floriston Rates were removed and the Truckee Canal was closed. Realistically, such extremes may be institutionally and legally infeasible. However, reducing Floriston Rates or limiting diversions through the Truckee Canal beyond what is currently done may be feasible and should be pursued. These conditions can be evaluated with the model.

Of the eight alternatives evaluated in Chapter 4 and the three in Chapter 5, Alternative n62o (No Floriston Rates, Lake Tahoe permitted to encroach above el. 6229.1 ft for storage capacity of 762 KAF, and the Truckee Canal open), or possibly n32o (Lake Tahoe storage constrained to 732 KAF), is recommended for further evaluation with more detailed simulation modeling. Removing Floriston Rates appears to improve system performance in several ways. On average reservoir storage levels are maintained higher; the probability of fully satisfying all demands is greater; and, depending on the priority assigned to the environmental demands, this alternative reduces competition among environmental demands. It may be difficult to remove Floriston Rates entirely since it most likely would require protracted legal action. Nonetheless, this study supports relaxing these flow rates. Also, the potential benefits of reduced or eliminated Floriston Rates must be evaluated against the cost of lost hydropower generation on the Truckee River.

The algorithm developed for determining unit penalty coefficients that preserve priority rank in network flow modeling is a rigorous and efficient approach for priority-based operations modeling.

The unit penalty algorithm presented in Chapter 3 is sufficiently robust to handle various system configurations, including multiple diversions from a single node, combinations of flow and storage penalties, instream demands, and persuasion penalties. A special feature of the algorithm is the ability to account for the effects of return flow on flow allocation. Return flows introduce a complexity which inhibits the use of intuitive or trial and error methods for determining unit cost coefficients. Though there are limitations, the use of priority-based penalty functions can have several advantages over the more commonly used economically-based penalty functions. First, priority-based penalty functions can be used to represent some of the institutional constraints governing water allocation in a river system, such as water rights and other legislated or judicially mandated water use priorities, which economically-based penalty functions are not able to capture. Second, analyses with priority-based functions permits all uses to be considered in the analysis, including environmental uses whose use value cannot be expressed easily in monetary terms. Third, priority-based penalty functions usually can be developed in the linear, convex form required by network flow programs. However, convexity of the composite penalty function cannot not be guaranteed. The algorithm can be used as a pre-processor or can be incorporated directly in the network flow program.

To date negotiations over water use conflicts in the Truckee-Carson basin have not considered explicitly the economic value of water to the different uses, nor have the consequences of protracted negotiations been fully and quantifiably realized. Knowing the economic value of water to different uses is fundamental for determining from among the various alternatives. Are shortages of equal magnitude, in fact equal in value across users? How do the costs associated with an infrequent 0.25 foot increase in Lake Tahoe water surface compare to the likelihood of increased shortages to downstream demands, particularly inflows to Pyramid Lake. The price signals reflected by recent water marketing activity help to establish a value for some uses. However, additional studies are needed to evaluate the value of reservoir and instream recreational demands, wildlife habitat and instream environmental uses.

As conflicts over water use become more intense and the issues become more complicated, the cast of characters involved becomes more diverse, but, fortunately, so should the gamut of possible alternatives for resolving conflict, as each group introduces a unique perspective to the problem. A systems approach is necessary for analyzing complex water resource systems such as the Truckee-Carson system to overcome myopic and special interest focus; a focus which most likely would result in inferior solutions reflected by a patchwork of legal and operating agreements. Through a systems approach, this research has yielded an improved understanding of the Truckee-Carson system and the sources of conflict. The study has demonstrated that there is potential for improving system performance by addressing institutional policies governing operation of the system.

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