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Stochastic Optimization of the Highland Lakes System in Texas

by

David Raymond Kracman, A.B.

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Stochastic Optimization of the Highland Lakes System in Texas

**Approved by
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Dedication

For my parents, Larry and Phyllis Kracman,
who taught hard work, integrity and honesty by example.

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Abstract

Stochastic Optimization of the Highland Lakes System in Texas

David Raymond Kracman, M.S.E.

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Supervisor: Daene C. McKinney

A multistage stochastic optimization model using linear programming was developed to assist the Lower Colorado River Authority (LCRA) in the operation of the Highland Lakes system. Three primary objectives were maximized: (1) revenues from rice production, (2) recreation benefits from lake use, and (3) hydropower revenues. Secondary objectives included minimization of unmet municipal and irrigation water demands, rewarding final storage to reduce end-of-horizon effects, and other minor linearization and equity goals. The model provides a realistic representation of the Colorado River system, and should be useful in managing water deliveries to downstream irrigation districts, predicting future reservoir levels, and enhancing other planning capabilities.

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Chapter 1: Introduction

BACKGROUND

The Colorado River in Texas plays a vital role in the economy and quality of life of much of central Texas. From its origins in eastern New Mexico to its termination into Matagorda Bay, the Colorado River winds its way through dry expanses, densely populated regions, and marshy wetlands. It supports a wide variety of aquatic life and water fowl, and provides vital freshwater inflows for endangered fin fish and shellfish in the bay. The Colorado River also serves a variety of human purposes, including providing drinking water supplies, creating recreation opportunities, generating electricity, and irrigating crops. While smaller than the better known Colorado River in the western U.S., Texas' Colorado River has its own unique attributes and importance, and has been the subject of many political battles in the past. With increasing pressure to export water outside the basin, the influence of the Colorado River already extends beyond its watershed boundaries, and may soon serve as a major source of drinking water for the city of San Antonio.

Figure 1.1: The Colorado River Basin

Management of the Colorado River requires the joint efforts of a variety of state and federal agencies, river authorities, irrigation districts, municipalities and other interests. Because the different groups that use the river sometimes have competing water demands, a complex framework of water law and regulatory procedures has been established to attempt to equitably allocate the water resources. Optimization techniques to maximize benefits for water management systems have been used for several decades, and have been used in this study for the Colorado River and the Highland Lakes system.

STUDY AREA – LOWER COLORADO RIVER

The portion of the river of special relevance to this study is known as the Lower Colorado River, and is generally defined as the segment from San Saba County in central Texas to Matagorda Bay. This stretch of the river is overseen by the Lower Colorado River Authority (LCRA), a water conservation and

reclamation district created by the Texas Legislature in 1934 to manage river operations.

Figure 1.2: LCRA District and Service Area (LCRA)

In the region near the City of Austin, a series of six dams and reservoirs, known as the Highland Lakes, were created to regulate river flows. All six dams are now controlled by the LCRA, with the assistance of the Army Corps of Engineers for flooding situations in Lake Travis. Beginning at the upstream end and moving downstream, the reservoirs include Lakes Buchanan, Inks, LBJ, Marble Falls, Travis and Austin, respectively. The dams that create these reservoirs include Buchanan, Inks, Wirtz, Starcke, Mansfield and Tom Miller Dams, respectively. A smaller reservoir, known as Town Lake, is located between Tom Miller Dam and Longhorn Dam. Due to the small size of Town Lake and the fact that the City of Austin controls Longhorn Dam, it is generally not considered a part of the Highland Lakes.

Figure 1.3: The Highland Lakes (LCRA)

The two largest reservoirs in the Highland Lakes are Lakes Buchanan and Travis, which together contain about two million acre-feet of conservation pool storage. Both reservoirs experience variability in storage levels on an annual basis in order to meet water demands located downstream of the Highland Lakes. The other four reservoirs are too small to be operated as variable storage reservoirs, and are maintained at nearly constant pool elevations. All of the dams include turbines to generate hydroelectricity, and together possess an electrical capacity of approximately 270 megawatts.

Table 1.1: Highland Lakes Reservoir and Dam Specifications			
Reservoir	Dam	Conservation Pool Capacity (kAF)	Hydro Capacity (MW)
Buchanan	Buchanan	868.122	49
Inks	Inks	14.992	15
LBJ	Wirtz	113.691	54
Marble Falls	Starcke	5.718	34
Travis	Mansfield	1,115.775	100
Austin	Tom Miller	21.278	18

RESEARCH OBJECTIVES

The main demands for the Highland Lakes system include irrigation, municipal water supply, recreation, and hydroelectricity needs. A stochastic optimization model using linear programming was developed to assist LCRA in operation of the two largest reservoirs, Lakes Buchanan and Travis, in the Highland Lakes system through maximization of benefits accrued through water sales and recreation benefits (Watkins et al. 2000). The objective of more recent research was to use the Watkins model as a template, expanding it to include all six reservoirs, weather-dependant irrigation demands, LCRA's interruptible contract function, a new reservoir space rule for equalizing storage levels, a linear hydropower approximation, and other additional capabilities. Through the inclusion of irrigation water demand regressions, planted acreages can be used as decision variables, and allowed to vary annually and between scenarios. Another goal for this research was to create predictive storage cumulative distribution curves for the reservoirs, to provide statistical inferences as to future reservoir

operating levels. These curves could be used by LCRA to better predict available water supplies for irrigators and the City of Austin, and to perhaps allow LCRA greater latitude in reservoir release scheduling to improve hydropower efficiencies. The latter benefit could be especially useful if LCRA chooses to place a greater emphasis on hydropower given the increasingly deregulated electricity market in Texas.

LITERATURE REVIEW

Two general aspects of the research require review of existing literature: scenario generation techniques and stochastic optimization methods. Since the scenario generation component of this work is being handled primarily by investigators at Michigan Tech, only a brief review of that area is included here.

Scenario Generation

Probably the most important parameter for the model is the streamflow hydrographs for the three inputs into the Highland Lakes. The Colorado River is a perennial river, as are the Llano and Pedernales tributaries, which means that flow rates in the rivers can have a high variability around the more persistent baseflow rate maintained by groundwater discharge. In order to take into account the uncertainty in flow rates, stochastic modeling of the hydrological time series was employed for the optimization problem.

One of the most widely used stochastic methods in hydrology is the synthetic generation of streamflow hydrographs. The process basically consists of choosing a probability density function that approximates the statistical properties of the historical data, and then developing an inverse transform of the

probability distribution, explicitly or numerically, to generate synthetic streamflows (Haan 1977). Since three separate streamflows are involved for the Highland Lakes model, multivariate data generation must be employed, while preserving auto- and cross-correlations.

Various computer programs have been developed to facilitate streamflow generation, including LAST (Lane and Frevert 1990), SPIGOT (Grygier and Stedinger 1990), CSUPAC1 (Salas and Markus 1992) and SAMS (Salas et al. 1996), among many others. Descriptions for all of these techniques can be found elsewhere in the literature, but only the program used for this research, SPIGOT, is described here.

SPIGOT is a complex computer package that uses historical hydrological data, in the form of streamflow hydrographs, and from them creates new synthetic sequences that retain the historical joint distributions and other statistical features. The generation process takes place through several steps, beginning with the creation of a multivariate probabilistic model to characterize the spatial and temporal joint distributions of the system. Parameters are derived from this process to describe the serial- and cross-correlations, among other statistical features. Next, synthetic annual streamflows, with parameters similar to the historical data, are generated with autoregressive models of order one, denoted as AR(1). Depending on the type of generation scheme used, these annual streamflows are either for the entire basin or, using a multivariate technique, for several different sites. Finally, one of three disaggregation processes is used to divide the aggregate streamflows temporally and, in all cases except for the

multivariate generation scheme, spatially. The result is a set of streamflows, usually on a monthly time scale, for each of the desired locations, with preserved cross- and auto-correlations.

One of the primary advantages of SPIGOT over other synthetic streamflow software concerns its consideration of uncertainty in the parameters of the multivariate probabilistic model that approximates the historical data. Particularly when only short records of historical hydrological data are available, there may be very high sampling errors, meaning that the historical sample statistics may be very different from the long-term values (Grygier and Stedinger 1990). Normally, this uncertainty has been neglected, but SPIGOT includes the parameter uncertainty during synthetic streamflow generation. Doing so has been shown to improve estimates of system reliability and better account for future severe drought conditions.

Stochastic Optimization

Because deterministic planning models are often unable to handle the uncertainties common in water resource problems (Loucks et al. 1981), stochastic optimization has become a common tool for guiding management decisions. Instead of explicitly setting stochastic variables as known values, and ignoring variability, different methods in stochastic optimization incorporate approximations of the variable distribution functions. There is a wide variety of methods for optimizing stochastic water resources processes, including stochastic dynamic programming (SDP), sampling stochastic dynamic programming (SSDP), stochastic linear programming (LP), stochastic mixed integer

programming (MIP), and stochastic nonlinear programming (NLP). While several other methods exist or are being developed for stochastic optimization, only a brief description of the more widely used techniques is included in this section.

Dynamic programming has been used for many years in a wide variety of different applications, including water resources optimization. Buras was one of the early pioneers in the area (Buras 1966), but many others are also credited with developing the technique to help solve water resources problems. A subset of dynamic programming, with its origins stretching back into the 1940's (Masse 1946), is called stochastic dynamic programming (SDP). SDP has been used to construct recursive equations and estimated Markovian conditional probabilities of inflows in order to maximize the present value of returns (Yeh 1985). The algorithms with SDP must be solved backwards in order to obtain an optimal release schedule, regardless of the set of characteristics being optimized. Arunkumar and Yeh used SDP with multiple reservoir operations and power outputs (Arunkumar and Yeh 1973). More recently, SDP was modified to use predictions of inflow as a hydrologic state variable instead of using the previous inflow through Markov chains (Stedinger et al. 1984). Principles from this approach were used to develop sampling stochastic dynamic programming (SSDP), in which both reservoir storage levels and forecasts of the remainder of seasonal runoff are used as state variables (Kelman et al. 1990). SSDP performance has been shown to be capable of outperforming more traditional

SDP methods, particularly in watersheds where snowpack is the dominant source of streamflows.

An important disadvantage of dynamic programming is a principle known as the curse of dimensionality. When the number of state variables is larger than three or four, dynamic programming becomes logistically unmanageable (Yeh 1985). Several other methods have become widespread that are able to avoid this effect, and one of these is linear programming (LP). Applications of linear programming are extensive, and water resources problems have been solved with linear programming tools for many years (Yeh 1985). One specific area of linear programming, capable of handling nondeterministic parameters such as variable inflows, is called stochastic linear programming. In stochastic linear programming, the random nature of inflows is characterized through Markov chains, chance constraints, or multiple scenario systems. In Markov processes, inflows for each time increment can be modeled as a first order Markov chain, with transitional probabilities for inflows based on the statistics of historical flow values (Yeh 1985). For chance constraints, the probabilities of meeting or violating a constraint are defined by setting random variables at determinant values according to their cumulative distribution functions (Loucks et al. 1981). For multi-scenario optimization, separate streamflow hydrographs, each with a probability determined by historical streamflow statistical analysis, can be represented by scenario trees (Loucks et al. 1981), (Birge and Louveaux 1997). The scenario trees extend through time, represented in the tree diagrams as stages,

and fixed recourse and nonanticipativity constraints may be required (Birge and Louveaux 1997).

Mixed integer programming (MIP) is another technique used for solving optimization problems, including stochastic ones. MIP allows variables to be restricted to integer values, which permits the solution of non-convex problems that would be unsolvable by standard linear programming methods. For deterministic models, mixed integer linear programming has been used to examine reservoir operation analysis, with a focus on flood control, for a three reservoir system on the Iowa and Des Moines rivers (Needham et al. 2000). Related work used stochastic, instead of deterministic, methods with a mixed integer problem, which also involved flood control optimization (Watkins et al. 1999). MIP, like nonlinear programming discussed below, is computationally complex, which has made it less popular than more traditional techniques for applied research.

When linear approximations are unable to represent processes that are important to an optimization problem, nonlinear techniques can be used. Nonlinear programming (NLP) normally uses more complex mathematical algorithms than DP or LP (Yeh 1985), and can lead to a much larger overall computational burden. Applications of NLP with water resources problems are fairly limited, although work has been done concerning the maximization of nonlinear water benefits (Lee and Waziruddin 1970), hydroelectric generation (Hicks et al. 1974), and reservoir reliability (Simonovic and Marino 1980).

Chapter 2: Water Management Principles for the Highland Lakes

The Colorado River is a complex system of water inputs and outputs, multipurpose water benefits, and legal guidelines. Understanding how water is transported and used within the basin requires using principles from engineering, economics, public policy, law, agriculture, and other disciplines. Some of the most important components of the Highland Lakes and Lower Colorado River systems are described below.

MUNICIPAL WATER SUPPLIES

The largest municipal demand for water from the Lower Colorado River is from the City of Austin. Over 150,000 acre-feet was diverted by the city for municipal uses in 2000 (Musgrove 2002). The City of Austin pumps water from Lake Austin to the Davis and Ulrich Water Treatment Plants, and from Town Lake to the Green Water Treatment Plant. The majority of diverted municipal water comes from Lake Austin.

The City of Austin owns its own municipal water rights for more than 290,000 acre-feet of Colorado River flow each year. These rights are senior to LCRA's rights to store water within the Highland Lakes, so water must be passed through the reservoir system to the diversion points without being stored when the City calls for water. This supply of water is sometimes referred to as run-of-river, not to be confused with the run-of-river rights for irrigation districts downstream.

In addition to the senior run-of-river water rights, the City of Austin has secured an additional supply of “firm” water through contracts with LCRA. Firm water represents water that is stored within the Highland Lakes, and then diverted at a later date when the supply is needed for municipal use. The supply of firm water is guaranteed to be available even through a repetition of the critical drought of record, the most severe drought to ever occur in the area, which took place from 1947-1956 (Martin 1991). The contracts with LCRA guarantee that the City of Austin will have a total dependable water supply of 325,000 acre-feet each year, including both run-of-river and stored water supplies. The contracts were signed, and later amended, to ensure the City of Austin with a reliable drinking water source for several decades. Firm water is, however, also susceptible to extreme hydrologic conditions, and water conservation measures are enforced by the City when reservoir levels drop below a certain storage volume (LCRA 1999).

Firm water is only diverted when needed, and run-of-river withdrawals are preferred. For the Highland Lakes model, described in detail in chapter three, a small penalty was assigned to firm water withdrawals to ensure that run-of-river diversions were exhausted before any firm water was extracted.

IRRIGATION WATER SUPPLIES

There are four major irrigation districts that rely on water from the Colorado River for their operations: Lakeside, Garwood, Pierce Ranch and Gulf Coast Irrigation Districts.

Figure 2.1: Approximate Boundaries of Major Irrigation Districts

Over the 1988 to 1997 period, the four districts used a combined 417 kAF of water for agricultural use (Riley 2000). The Gulf Coast District diverts the most water of the four, followed by Lakeside, Garwood and Pierce Ranch, respectively. Over the years, LCRA has gradually acquired most of the water rights from the districts, and LCRA now manages all of the districts except for Pierce Ranch. Some of the relevant specifications on the districts are listed in Table 2.1 below (Riley 2000, Martin 1990).

Table 2.1: Irrigation District Specifications				
	Lakeside	Garwood	Pierce Ranch	Gulf Coast
Acres in Service Area	112,000	155,000	30,000	206,000
1988-97 Ave. 1 st Crop Acres	26,216	19,344	5,704	26,362
1988-97 Ave. 2 nd Crop Acres	19,814	16,582	575	11,955
1988-97 Ave. Annual Water Use (acre-feet)	129,327	97,555	35,910	154,237

Downstream irrigators on the Lower Colorado River divert two different types of water from the river: interruptible and run-of-river flows. Interruptible water is water that is stored by LCRA in the Highland Lakes system, and then released when needed, and when available, for the rice farms near the coast. Since the rights to the interruptible supplies are directly owned by LCRA, these supplies may be curtailed or cutoff if reservoir levels drop below predetermined minimum levels. Run-of-river flows consist of water that was passed through the Highland Lakes system without being stored, and is available for use regardless of reservoir storage levels. Run-of-river and interruptible water supplies are handled by separate accounting systems, with run-of-river diversions determined by separate water rights and seniority policies. The specific legal aspects related to run-of-river water rights are even more complex, since LCRA has purchased most of the district water rights, and since LCRA manages all of the districts except for Pierce Ranch. In the future, run-of-river water may be treated more on an interruptible basis, as municipal demands on the system continue to grow.

Interestingly, the current water management plan for the Lower Colorado River includes specification of a “Conservation Base” number of acres, which is the ten-year average acreage level irrigated by LCRA-owned irrigation districts (LCRA 1999). This Conservation Base was designed to be used with a 5.25 acre-ft/acre limit on surface water applications for the affected irrigation districts. Should this limit be strictly enforced in the future, it could have a significant impact on the irrigation practices of the districts, and may severely diminish the possibility of raising second-crop rice.

INTERRUPTIBLE CONTRACT DECISION FUNCTION

For interruptible water supplies, LCRA has developed a technique to determine the amount of stored water to be released for irrigators over the growing season. The technique basically consists of a piecewise linear decision function based on the projected combined storage values in Lakes Buchanan and Travis for January 1 of each year.

Figure 2.2: Interruptible Storage Contract Decision Function

As shown in Figure 2.2, when combined storage volumes in the two lakes are below 325,000 acre-feet, cutoff of the interruptible water supply is enforced. No interruptible water is allocated to the irrigation districts in this situation. For combined storage levels between 325,000 and 1.1 million acre-feet, curtailment will occur at a magnitude dependent on the exact combined storage level. If storage is above 1.1 million acre-feet, or about half the combined conservation storage capacity of Lakes Buchanan and Travis, no curtailment occurs, and the irrigation districts are allocated the full contract level of 272,000 acre-feet.

One element of the interruptible contract was ignored for modeling simplicity. In practice, during years when curtailment is implemented, if at any time before July 31 the combined storage is forecast to be greater than or equal to 1.1 million acre-feet for any period in July, the curtailment will be cancelled. This event is highly unlikely, especially given that curtailment has never been enforced, and has been neglected in the model.

IRRIGATION DISTRICT PRACTICES

The four irrigation districts in the Colorado, Wharton and Matagorda counties are primarily involved with the production of rice. Rice is a water-intensive crop, and water applications are made not only to meet plant evapotranspiration needs, but also to act as a herbicide by drowning out competitive plants (Martin 1990). One acre of rice in one of the Texas operations can require five feet or more of water each growing season, depending on weather conditions and management practices. Although much effort has been spent in recent years in developing production methods that reduce water application rates,

water shortages will likely occur in the future, and LCRA has developed a system to handle such situations.

Two Crop Rice Production

Rice is typically planted in March or early April, and harvested in July. Through modern advances in management practices, farmers within the districts now often allow the plants to regrow after the first-crop harvest, and harvest a second-crop in October or December. This two-crop practice began in the 1960's, and soon became popular because of the low production costs associated with the second-crop. Since the plants are already established, less water is required for plant development, and the second-crop harvest is usually profitable (Martin 1990).

A second crop is not always grown for every rice field. Late planting, shortages of water late in the season, and other economic and management factors lead some irrigators to only grow one crop over a growing season. Rice fields are also rotated with dryland crops or fallowed on a regular basis, usually following a one-year in rice and two-year fallowed or dryland schedule (Schultz 1996).

Distribution of Water Shortages

When available water supplies are not sufficient to meet the demands of the irrigation districts, LCRA has devised a special procedure to spread water deficits equitably between the irrigation districts (LCRA 1999). The basic procedure is fairly straightforward, and begins with the determination of the interruptible contract, as described above. Once the amount of interruptible supply for the coming year has been predicted, projections are made as to both

irrigation demands for the four districts, and run-of-river water reaching the diversion sites. The difference between the expected irrigation demand and run-of-river supply is called the interruptible stored water diversion demand.

The interruptible stored water diversion demand is then divided by the interruptible water contract to find the percentage of stored water demand available. This fraction is then multiplied by each irrigation district's individual interruptible stored water diversion demand to obtain the projected stored water supply for each of the districts. In this way, all districts share deficits which are approximately equal with respect to their demand for stored water.

For the linear program described in chapter three, this nonlinear subroutine was simplified by using historical water demands rather than interruptible stored water diversion demands. It is also important to note that the process described above is a guideline only, and actual management decisions during times of water scarcity would be dependant on the particular situation and the specific rules and policies applicable to the individual irrigation districts (LCRA 1999).

RECREATION DEMANDS

In 1990, over 800,000 people are estimated to have visited the Highland Lakes, with repeat visitations resulting in over 4 million visitor occasions (USACE 1992). Boaters, swimmers and other visitors at the Highland Lakes generated a total economic effect of about \$90 million, and spent about \$20 million in the same year in the region near the lakes. As the population in the Highland Lakes region has grown in subsequent years, so has the demand for

recreation on the lakes. With new challenges facing the lakes, such as the rapid spread of hydrilla in Lake Austin, and rising municipal water demands, meeting growing recreation demands will become increasingly more difficult.

While LCRA attempts to accommodate the recreation industry on all the Highland Lakes, the two variable storage reservoirs operate such that municipal and irrigation water needs are given a higher priority than those of recreation (LCRA 1999). Interruptible water sales for purposes outside of the irrigation districts can be restricted or terminated if water levels fall to levels adverse to recreation interests, but agricultural and municipal diversions will continue to be made even if adverse effects to recreation are experienced. This policy follows a long-standing set of guidelines that originated when the Highland Lakes and their respective dams were formed for the purposes of flood control and reliable irrigation and municipal water supplies (LCRA 1999).

In response to the growing impact of recreation on the region's economy, studies have been done on both the general monetary importance of recreation on the Highland Lakes (USACE 1992) and the particular effect of boating visitation under various reservoir storage levels (USACE 1994). By using estimates derived from these studies for annual recreation spending by Highland Lakes boating visitors under low-water and baseline reservoir level conditions, linear approximations for monthly recreation benefits as functions of reservoir storage were developed (Watkins et al. 2000). The linearization procedure is described more thoroughly in chapter three, but in essence, recreation interests benefit from higher reservoir levels and suffer when low water levels reduce shorelines and

create boating hazards. Since boating is only one, albeit important, form of recreation on the lakes, the linear benefit regressions should only be considered a rough estimate of the effects of changing water levels on the recreation industry.

HYDROELECTRICITY GENERATION

Another variable which must be considered in operation of the Highland Lakes concerns the generation of hydroelectricity. A total of thirteen turbines are used to produce electricity through hydropower releases, with at least one turbine installed in each of the six dams. Together, the units have a capacity of about 270 MW, and make up the cheapest energy source for LCRA. In a way similar to recreation demands, hydropower generation has been designated as subordinate to other needs in the reservoir system, and can only be optimized under constraints that protect competing water interests (LCRA 1999). This policy can be overruled during emergency situations, when power generation is determined to be of vital importance.

Because of the implementation of electricity deregulation in the state of Texas, greater importance may be given to hydropower generation in the future. In the meantime, methods have been developed to maximize hydropower production within daily or hourly time periods (Martin 1995). Hydropower generation is often ignored for the purpose of long-term water supply planning, particularly because of the sensitivity of plant efficiencies and other parameters to short-term variability in operating conditions, but an attempt was made in this research to include hydropower in order to obtain a rough estimate of its importance in the optimization process.

PASS-THROUGH RESERVOIR OPERATIONS

Four out of the six reservoirs in the Highland Lakes system, specifically Lakes Inks, LBJ, Marble Falls and Austin, have fairly minor storage capacities. Because their capacities are too small to handle seasonal or annual carryover, and because of the proximity of businesses and residences to their shorelines, LCRA operates these lakes as “pass-through” reservoirs. Basically, this means that the elevation levels are held nearly constant, and inflows balance reservoir releases and evaporation losses.

In reality, LCRA does allow the levels to rise and fall slightly, and at times will even lower the reservoirs significantly to allow for construction and maintenance work along the shoreline, and to retard the growth of invasive species such as hydrilla. Businesses along the shore often vehemently oppose any major elevation change because of the loss of revenue, and, in the case of high water levels, the danger of property damage.

Hydropower is still generated through the dams that form the pass-through reservoirs, and the generated power is much easier to predict because of the near constant upstream head. The pass-through reservoirs also attract a significant amount of recreation users, but because storage is considered a constant, recreation benefits for these lakes have not been included in the optimization process described in the next chapter.

SPACE RULE FOR STORAGE RESERVOIRS

When multiple reservoirs are aligned in series, special management decisions must be made as to how to operate the reservoirs in a complimentary

fashion. Lakes Buchanan and Travis, the two largest reservoirs in the Highland Lakes system with a combined conservation pool capacity of about two million acre-feet, have variable storage volumes capable of rising and falling over the course of the year. A variety of management policies may be used for systems such as this, and the choice of a proper set of guidelines should be based on the individual characteristics of the particular system (Lund and Guzman 1999). In order to equitably distribute storage and releases between the two largest reservoirs, LCRA has developed general guidelines for deciding releases from the reservoirs over the course of the year (Martin 2002).

Reservoir distribution principles are largely governed by downstream water demands from the irrigation districts. At the end of the growing season for rice, Lakes Buchanan and Travis may be at significantly different fractions of capacity. From approximately October to March of the following year, an effort is made to adjust storage levels so that the fraction of used capacity in each reservoir is roughly equal. Initially, this may seem counterintuitive, since Lake Travis has smaller evaporation losses and greater hydroelectricity generation capacity than Lake Buchanan. Both lakes, however, are used for recreation, and bad feelings can develop among boaters, area businesses and other recreation users when one reservoir is at a significantly higher percentage of storage than the other.

Next, estimates are made for inflows into the Highland Lakes and irrigation demands over the coming growing season. Once the rice plants in the irrigation districts have become established, which usually occurs in April,

diversions for irrigation begin from the Colorado River, and calls may be made for increased releases from the Highland Lakes. LCRA will normally begin making releases primarily from Lake Travis, in large part to create additional flood storage capacity in the more downstream reservoir, where more of the basin's incremental flows can be captured. About 50% of the projected irrigation demand may be withdrawn from Lake Travis during this period, which usually lasts until sometime in July, although the exact amounts and durations depend on the particular hydrologic conditions for the year.

From about mid-July to August, LCRA then attempts to make additional releases from the upstream Lake Buchanan, which are passed directly through the remaining downstream reservoirs, including Lake Travis, for diversion by the irrigation districts. Ideally, Lake Buchanan releases from this period will make up the remaining 50% of irrigation demand for the growing season, although the actual decisions are again subject to the particular year. Once irrigation diversions stop, focus again turns to equalizing the fractional storage volumes within the two larger reservoirs.

Attempting to model a policy such as this in a linear environment would not be a trivial task, and may also unnecessarily complicate the model (Martin 2002). For water planning models with monthly time steps, simplifying the management procedure for storage distribution can be done by solely attempting to equalize fractional storage levels between the reservoirs for all time steps. A description of this linearization technique is included in the following chapter.

Chapter 3: Operational Model Formulation and Design

The model developed for this study was built on an earlier version developed for optimization of the Highland Lakes system (Watkins et al. 2000), which will be referred to as the Watkins model from this point on for simplicity. This chapter describes how the old model was modified and expanded, the data and equations used to define the new model, and the procedures used by GAMS to obtain optimal solutions.

TIME HORIZON AND TIME INCREMENTS

The time horizon chosen for the model was five years, which is a period of sufficient duration to simulate a persistent drought. Due to end-of-horizon effects during the last months in the model, a phenomena discussed in greater depth later in this work, it may be necessary to ignore the final year for postprocessing analysis purposes.

A monthly time step, with the first step representing the January month, was chosen for the optimization model, as done in the Watkins model. Monthly time steps are commonly used for reservoir optimization problems, and are used as the basis for the U.S. Army Corps of Engineers HEC-PRM solver. Monthly time steps have also been used in previous studies of the Highland Lakes system (Martin 1991). Given current computer capabilities, monthly time steps provide a compromise between overly simple annual increments and burdensomely complex daily or hourly time intervals. Monthly steps work well for long-term water planning applications, but perform less well for hydropower generation

studies, which usually require daily increments. For the new model, hydropower was a factor in the objective function, but it was decided that the monthly time step would provide at least some approximation of the magnitude of hydropower generation for each month. A more refined modeling technique, using hourly and daily time increments, has been developed to maximize hydropower generation for the Highland Lakes (Martin 1995).

One additional change from the Watkins model, indirectly related to time increments, involved the choice between beginning- and end-of-the-month storage levels. In the Watkins model, storage represented the beginning-of-the-month level, while the updated version uses end-of-the-month storage values. Advantages and disadvantages exist for both methods, but the differences are mainly aesthetic in nature.

NETWORK CONCEPTUALIZATION

The Highland Lakes model is a simplified representation of the six dams and reservoirs that make up the system, along with one main inflow from the Colorado River upstream of Lake Buchanan, two tributary inflows from the Llano and Pedernales Rivers into Lakes LBJ and Travis, respectively, one municipal diversion from Lake Austin, one return flow input from City of Austin wastewater discharges, four irrigation diversions that are spatially lumped into one diversion site, and a final return flow input from irrigation runoff. Flows not diverted, or those that are reintroduced as return flows, continue in the Colorado River to Matagorda Bay. The network represented below in Figure 3.1 is more complex

than the original Watkins model, which only included Lakes Travis and Buchanan, and ignored return flows and flows into Matagorda Bay.

Figure 3.1: The Highland Lakes System

The main objective of the model includes several different weighted factors, with the main items being revenue from crop production, recreation benefits, hydropower generation, irrigation water deficits and municipal water deficits. Several other minor factors, described later in this chapter, are also included in the objective function, but are of a lesser importance in the overall objective. Flood control is not directly addressed with the model, although it may indirectly be a factor since Lake Travis storage levels are never allowed to enter the flood pool. Lake Travis is the only reservoir in the Highland Lakes system

with dedicated flood storage, and has approximately 748,502 acre-ft of flood storage capacity above the conservation storage. In flooding situations, the Army Corps of Engineers takes over some of the management responsibilities for Mansfield Dam (Lake Travis).

Stages are defined by those first-crop acreage level decision variables that are constrained by nonanticipativity. These decisions are made at the beginning of years one, two and three. Stage three is considered the period from year three to year five due to the structure of the scenario tree, described later in this section.

STOCHASTIC OPTIMIZATION

As discussed in chapter one, stochastic optimization was the method chosen for the Highland Lakes model. The uncertainty associated with inflows into the Highland Lakes system is the primary stochastic feature, although future models may incorporate scenario-indexed climate data for the irrigation districts, correlated with the hydrographs from the Colorado River and its tributaries.

Tree Structure

As shown in Figure 3.2, the stochastic model follows the same basic tree structure as that used in the original Watkins model. In the first year, five different possible hydrographs of equal probability are represented by the five branches emanating from the first node on the uppermost portion of the diagram. These branches could, for example, represent very dry, dry, average, wet, and very wet conditions, with corresponding inflow hydrographs. For year two, three hydrographs originate from the ends of each of the first-year branches. These are also equally probable hydrological scenarios, and together define 15 different

streamflow hydrographs up to the end of year two. At the end of year two, the scenario tree branches again, dividing the second-year branches into two new branches, each of which defines an equally probable three-year hydrograph for years three through five.

Figure 3.2: Scenario Tree for the Highland Lakes Model

Nonanticipativity Constraints

One of the main benefits of using a scenario tree is that nonanticipativity constraints can easily be used to prevent decision variables from being set with knowledge of future conditions. In the scenario tree represented in Figure 3.2, scenarios one through six all share identical hydrographs for the first year. Since all six scenarios started with the same initial storage conditions, and in each scenario identical inflows into the Highland Lakes occurred, decision variables for these six scenarios should be identical. For example, again looking at scenarios one through six, the interruptible contract at the beginning of the first year should be the same for all six scenarios, since they all experienced the same initial conditions. In fact, for the interruptible contract in the first year, all 30

scenarios should share the same contract amount, since all have common initial conditions.

For scenarios one through six, releases for each month in the first year should also be identical across scenarios, since allowing independent releases would imply that the reservoir operators had knowledge of future conditions, and could adjust their decisions accordingly. If, for example, scenario one had dry conditions in year two, while scenario six had wet conditions over the second year, operators could make higher releases in the first year for scenario six and smaller releases for scenario one. To avoid this clairvoyance, nonanticipativity constraints were added to require releases to be equal for scenario “groups” that share common hydrological conditions up to the point of the decision. Scenarios one through six must have common releases for each month of the first year, while scenarios one and two must also share identical releases for each month of the second year. In years three through five, all scenarios are allowed to have independent release decisions, since each scenario experiences unique inflow hydrographs for that period.

Stages for the scenario tree represent the periods during which decisions must be made that are constrained by nonanticipativity relationships. The primary decision variable for the model was the planted acreage of first-crop rice in the irrigation districts, so nonanticipativity is applied through requiring common first-crop acreage levels within scenario “groups”. This was done in a method basically identical to that used to constrain the interruptible contracts. For the first year, represented by the first stage, all 30 scenarios used identical first-crop

planted acreage levels, since all have the same initial conditions. For the second year, or second stage, each of the five groups of six scenarios shared the same first-crop acreages. The third stage acreage decisions were constrained by requiring the 15 groups of two scenarios to use consistent acreage levels for year three. For years four and five, acreage levels were unconstrained by nonanticipativity equations, since each scenario experienced different inflows prior to the beginning of year four.

In the original Watkins model, the optimization problem was referred to as a four stage model, rather than a three stage model. This is because the Watkins model used the interruptible contract and release variables as the main decision variables, rather than planted acreage. The four stages for the Watkins model were the “here and now”, year one, year two, and years three through five. The interruptible contract was constrained with nonanticipativity requirements for the “here and now” and the beginning of years two and three, while releases were constrained over years one, two and three. Nonanticipativity constraints applied for at least part of all four stages, with the exception of years four and five, when nonanticipativity was not enforced. For the updated three stage model, the stages include years one, two and three, when first-crop acreage decisions are made.

Scenario Generation

Because SPIGOT-generated scenarios were still under development, inflow sequences from the original Watkins model (Watkins et al. 2000) were used. Scenario generation for these sequences was done through a quantile sampling technique using historical hydrographs from 1941 to 1965. This time

period includes the drought of record (1947 to 1956), which was the most severe drought recorded in the area. Annual hydrographs for the three inflows (Colorado River, Pedernales River, Llano River) were first temporally linked by creating three-component vectors to preserve spatial correlation. In other words, 1945 inflows from the Colorado River were linked to the associated 1945 Pedernales and Llano River flows, respectively. Next, the annual hydrographs were ranked in terms of total combined cumulative flow, and then divided into quantile groups.

Using the scenario tree in Figure 3.2, annual hydrographs for the three linked inflows were picked at random from particular percentile groups. For the first year, which separates into five scenario branches, five percentile groups were formed for the five 20% quantiles. Hydrographs were then selected randomly from each of the quantile groups and assigned to the branches. A similar sampling procedure applied to the second year, where three quantile groups were delineated. For years three through five, two quantile groups were formed using three consecutive year hydrographs to partially preserve autocorrelation. For all 15 of these three-year scenario “pairs”, hydrographs were picked at random from the two quantile groups.

While this scenario generation technique does preserve spatial correlation between the three inflow sources, it also has several disadvantages, including a lack of year-to-year autocorrelation. While serial correlation of annual inflows for the Highland Lakes has been shown to be statistically small, it has also been shown to have a significant impact on expected storage levels (Vaugh and Maidment 1987). Inflow scenarios were also processed by the RESPONSE

model, which adjusts flows by considering the water rights seniority system for the Colorado River, and then subtracting senior rights from the inflow values (LCRA 1999). This method was sufficient for the earlier Highland Lakes model, but leads to underestimation of inflows under some scenarios for the new version. Future versions of this model will incorporate scenarios generated by the SPIGOT program, and should ensure that senior water rights are correctly accounted for if the RESPONSE model is again used.

RECREATION BENEFIT LINEARIZATION

The United States Army Corps of Engineers (USACE) conducted studies on the Highland Lakes to determine the effect of boating and other forms of recreation on the local economy (USACE 1994). The studies focused on the economic impacts from boating on Lakes Buchanan and Travis under “baseline” and “low water” conditions. By taking annual benefits under these two scenarios, using linear interpolation to estimate recreation benefits for intermediate storage levels, and then separating the benefits into monthly values for both winter and summer months, linear approximations of recreation benefit based on reservoir storage levels were developed (Watkins et al 2000). Graphs showing monthly recreation benefits as a function of reservoir storage are shown in Figure 3.3.

Figure 3.3: Recreation Benefit Linear Approximations

As shown in Figure 3.3, recreation benefits generally increase as reservoir levels rise. This is due to increased shoreline and surface area, along with a reduction in mud bars and other submerged hazards, during periods of high reservoir elevations. The use of piecewise linear approximations for the curves was avoided by simply setting an upper limit on monthly recreation benefits.

The smaller pass-through reservoirs also generate significant recreation benefits for the local economy, but since their storage levels and elevations stay relatively constant, benefits from the intermediate reservoirs were ignored for optimization purposes.

HYDROPOWER LINEARIZATION

Hydropower generation is a nonlinear function of the flow discharged through the penstock and the elevation difference between pool and tailwater levels. Additional parameters for hydroelectric generation include plant efficiencies, plant capacities, and plant factors. A general equation for nonlinear hydropower can be written as follows (Loucks et al. 1981):

$$KWH_t = 1.024q_t H_t \varepsilon \quad (3.1)$$

In this equation, KWH_t is the kilowatt-hours generated in period t , q_t is the total pulse flow in acre-feet over period t , H_t is the head difference in feet between the conservation pool and downstream tailwater (net head), and ε is the plant efficiency.

To maintain a linear environment for the model, average reservoir elevations from historical data spanning October, 1942, to December, 2001, were obtained from LCRA, along with tables for each of the 13 turbines showing power generated for various flows and elevation heads, and average tailwater elevations. Using this data, linear relations were formed to estimate hydropower generation based on monthly releases. This was done through linear regression, with power as the ordinate and pulse flow as the abscissa, where the intercept was forced to pass through the origin. Forcing the intercept to cross the origin prevented the calculation of negative power generation for low flow months. However, since turbines are unable to generate electricity below certain flowrates, this artificial forcing would seem to overestimate power generation for low-flow scenarios. This effect is counterbalanced by the fact that LCRA, in actual practice, uses a procedure to optimize hydropower generation by releasing short-period releases at high flow rates, which allows the turbines to operate at greater efficiencies. Similar linearization techniques have been used in studies of hydropower generation in the Highland Lakes in the past, and have yielded

satisfactory results (Martin 1995). As mentioned earlier, monthly time steps are too long to precisely forecast hydropower generation, but can still provide a rough estimate for planning purposes. The parameters used for hydropower generation for all six of the Highland Lake dams are shown in Table 3.1. An example of the linear approximation for Lake Travis is shown in Figure 3.4.

Table 3.1: Hydropower Parameters		
Reservoir	Net Head (ft)	Regression Slope (MW·d/kAF)
Buchanan	125	4.58
Inks	60	1.95
LBJ	83	2.97
Marble Falls	54	1.77
Travis	175	6.50
Austin	61	2.19

Figure 3.4: Lake Travis Linear Hydropower Regression

SPACE RULE FOR STORAGE RESERVOIRS

In water resource planning for reservoir operations, systems of multiple reservoirs are usually differentiated by whether the reservoirs are connected in a series or parallel arrangement. In parallel systems, forecasts of future inflows over the refill period are often used in “space rules”, where the ratio of unfilled capacity in each reservoir is set at a level equal to the ratio of the expected inflow into a particular reservoir over the refill period to the total expected inflow into all reservoirs. This can be expressed mathematically as follows (Maass et al. 1962):

$$\frac{S_{\max j} - S_{Ijk} - Q_{jk} + R_{jk}}{\sum_j^m (S_{\max j} - S_{Ijk} - Q_{jk}) + R_T} = \frac{Q_{j,n-k}}{\sum_j^m Q_{j,n-k}} \quad (3.2)$$

$S_{\max j}$ is the storage capacity of the j^{th} reservoir in a parallel system of m reservoirs, S_{Ijk} is the initial storage of the j^{th} reservoir in month k of n months, Q_{jk} is the known flow into the j^{th} reservoir over month k , R_{jk} is the release from reservoir j during month k , R_T is the sum of all reservoir releases during month k , and $Q_{j,n-k}$ is the expected inflow into reservoir j for the remainder of the refill period (months n through k).

For reservoirs in series, such as the Highland Lakes system, the general rule is to shift water storage towards the upstream reservoirs (Lund 1999). Doing so has several benefits, including minimizing the amount of spilled water, and providing the highest level of flood protection. By keeping available storage space in downstream reservoirs, spills from any reservoir other than the lowest in

the system can be captured for future use. Also, any incremental flow that enters the system during a flooding event will have a greater chance of being captured in a downstream reservoir than in one further upstream.

The simple rule of shifting storage upstream is not always optimal for a series of reservoirs, however. For the Highland Lakes system, the second-most downstream reservoir (Lake Travis) is able to generate more hydroelectricity per unit increase in flow than the most upstream reservoir (Lake Buchanan) under high reservoir elevation conditions. In addition, Lake Buchanan has a much greater surface area to volume ratio, which means that significant evaporation losses may result from keeping Lake Buchanan storage levels high.

LCRA operates the Highland Lakes system to meet a variety of demands, including municipal, irrigation, recreation, and instream and estuary flow requirements. Releases for downstream irrigators, which make up the largest component of demand, are timed and measured to coincide with the water demand needs of rice farming operations. One of the objectives LCRA tries to achieve, even as reservoir levels rise and fall, is to distribute reservoir drawdowns between Lakes Buchanan and Travis. Since the recreation and aesthetic benefits of both lakes decrease with falling water levels, LCRA attempts to evenly divide the fraction of available storage capacity between the two main storage reservoirs for a large part of the year. Except for the period from April to July, when large releases are made exclusively from Lake Travis to meet first-crop irrigation demands and to create extra available downstream storage for possible spring

floods, much of the year is spent bringing relative storages in the two reservoirs to similar levels (Martin 2002).

Modeling this kind of behavior in a linear programming environment introduces a few challenges. Since the objective is to minimize the difference between the two ratios of reservoir storage to reservoir capacity, absolute values must be used. In linear programming, this problem can be solved by introducing two new nonnegative variables, D_A and D_B , and using the following objective and constraints (Loucks et al. 1981):

$$\text{Maximize } z = -k(D_A + D_B) \quad (3.3)$$

$$\text{Subject to: } \frac{SR_{B,t}}{K_B} - \frac{SR_{T,t}}{K_T} = D_A - D_B \quad (3.3a)$$

$$SR_{B,t}, SR_{T,t}, D_A, D_B \geq 0 \quad (3.3b)$$

$SR_{B,t}$ and $SR_{T,t}$ represent the storage volumes at time t in Lakes Buchanan and Travis, respectively, and K_B and K_T represent their associated maximum storage capacities. The scenario index has been removed here for simplicity. Note that the objective has been written as a maximization problem, since that is the method used in the Highland Lakes model.

In the actual model, the sensitivity coefficient, k , must be adjusted to generate the desired level of importance placed on maintaining similar relative storage capacities. This process is described in more detail later in this chapter.

In earlier versions of the Highland Lakes GAMS model, a different space rule was used, which required that the fractional stored capacity of Lake Buchanan be greater than half the fractional stored capacity of Lake Travis:

$$\frac{SR_{B,t}}{K_B} \geq 0.5 \frac{SR_{T,t}}{K_T} \quad (3.4)$$

This constraint helped prevent Lake Buchanan from being emptied under conditions when Lake Travis was nearly full – a result that may occur when no space rule is used. The effect of the constraint is more helpful when examined graphically, as shown in Figure 3.5.

Figure 3.5: Original Watkins Model Space Rule

S_B and S_T in Figure 3.5 are the storage levels for Lakes Buchanan and Travis respectively, and K_B and K_T are their respective capacities. The original space rule would only allow for fractional storage values within the region of the upper trapezoid, and prevented any combinations within the region of the lower triangle.

The new rule does not prevent any fractional storage combinations outright, but rewards combinations that are close to the line $S_B/K_B = S_T/K_T$. This is a closer representation of LCRA's actual operation policies.

INTERRUPTIBLE CONTRACT LINEARIZATION

As discussed earlier, LCRA determines the interruptible water contract based on projected January 1 combined storage levels for Lakes Buchanan and Travis. Using the management function shown in Figure 2.2, LCRA is able to set contract levels with the irrigation districts, thereby providing the rice farmers with some indication of available water supplies for the upcoming growing season.

The contract function is not only nonlinear, it is also not concave, which presents a modeling challenge for maximization problems. A simple linear approximation of the interruptible contract function was developed by setting minimum levels for the combined reservoir storage, minimum and maximum interruptible contract amounts, and an intermediate line segment to represent the simplified decision function. Figure 3.6 shows both the actual contract function and its linear approximation.

Figure 3.6: Linearized Contract Function

On initial inspection, the linear approximation for the contract function also appears nonlinear, or at least piecewise-linear, but simple linearity was preserved through the use of slack variables. The exact mathematical construction is very similar to that used for the space rule. In short, upper and lower boundary conditions for contract amounts and combined storages were used in conjunction with a constraint penalizing deviations from the linear segment. Two positive slack variables were included in the interruptible contract constraint, and penalized in the objective function.

Within the combined storage range of 200 to 325 kAF, the linear approximation allows positive contracts while the actual decision function does not. This would imply that the simplified linear approximation would place greater priority on providing interruptible supplies to the irrigators, and would also seem to place greater “stress” on the reservoir system by encouraging higher

releases at lower storage levels. Because of the small range over which this discrepancy occurs, and the overall low probability of having combined storage levels within this range, the effect of the linear simplification appears to be minimal. A sensitivity test in which the minimum combined storage was set at 325 kAF, rather than 200 kAF, resulted in a change of only about 1.6% for the overall objective value, and nearly identical predicted storage levels.

The reason that a lower bound of 200 kAF was used for combined storage rather than 325 kAF is because 200 kAF is the lower limit that LCRA designates as reserve storage. When combined storage drops below the reserve storage level, all interruptible supplies, including those to the irrigation districts, are cutoff. This cutoff point applies for all time periods, while the interruptible contract decision function is set once a year¹. For the linear programming problem, either the reserve storage value of 200 kAF or the lower limit for providing interruptible supplies of 325 kAF, but not both, can be used as a lower bound on combined storage. To ease the restrictiveness on the domain of reservoir storage values, the smaller of the two lower bounds was chosen.

IRRIGATION DEMAND REGRESSIONS

The four irrigation districts near the coast, known as Lakeside, Garwood, Pierce Ranch and Gulf Coast, experience high demands for river diversions during the rice-growing season. Water applications for first-crop rice typically occur during the months of March through July, and second-crop rice, also known as the ratoon crop, requires water from August to October. Understanding the

¹ There is one exception, in that LCRA may readjust the contract if sufficient inflows during the growing season allow for greater downstream releases (LCRA 1999).

scale and timing of irrigation water demands is critical for water management of the Lower Colorado River, and for the Highland Lakes model. Efforts have been made to derive predictive methods for obtaining both monthly (Martin 1990) and seasonal (Nazneen 2001) water demands for the irrigation districts. Since the more recent regressions, capable of predicting water demands for first- and second-crop seasons, were formulated using more recent and complete data, and because the earlier monthly regression relied on gross lake evaporation data that were later updated by the Texas Water Development Board, the latter method was chosen for the Highland Lakes model. Monthly demand coefficients were calculated and used to decompose seasonal demands into monthly time steps.

Regression Construction

The seasonal regressions are dependant on three primary factors: rainfall amounts in the irrigation areas, gross lake evaporation for the districts, and the rice acreages for both the first- and second-crops. The forms of the regressions are shown below (Nazneen 2001):

$$WD_1 = (\alpha_1 GLE_1 + \beta_1 RAIN_1 + \tau) ACRE_1 + \delta_1 \quad (3.5)$$

$$WD_2 = (\alpha_2 GLE_2 + \beta_2 RAIN_2) ACRE_2 + \delta_2 \quad (3.6)$$

WD_1 and WD_2 are the total water diversions in thousands of acre-feet for first- and second- crops, GLE_1 and GLE_2 are the depths in feet of gross lake evaporation lost in the fields for the two respective growing periods, $RAIN_1$ and $RAIN_2$ are the depths in feet of rainfall occurring for each crop, T is a time factor

representing the number of years since 1968, and $ACRE_1$ and $ACRE_2$ are the areas of each crop planted to rice in thousands of acres. The coefficients α_1 , α_2 , β_1 , β_2 , δ_1 , δ_2 , and τ were determined through multiple linear regression, and are shown in Table 3.2.

Table 3.2: Multiple Linear Regression Coefficients (Nazneen 2001)							
Irrigation District	α_1	α_2	β_1	β_2	δ_1	δ_2	τ
Lakeside	1.1642	2.1016	-0.2592	-0.5230	15.665	7.5010	0.0334
Garwood	1.4888	1.3695	-0.1951	-0.2310	8.1434	21.3447	0
Pierce Ranch ²	1.4888	1.3695	-0.1951	-0.2310	8.1434	21.3447	0
Gulf Coast	1.0435	1.9096	0	-0.6497	83.9288	47.0513	0

As shown in the table, the coefficients for Pierce Ranch are identical to those of Garwood. No regression was conducted for Pierce Ranch because of the large percentage of crops other than rice grown in the district (Martin 1990). For the purposes of the model, Pierce Ranch water demands for each month were set as a linear function of acreage, multiplied by the ratio of historical average diversions for each month to the average historical acreage level. Historical averages for first- and second-crop acreages and monthly irrigation diversions were calculated using 1988 to 1997 data.

Because the regressions produce water demand data in terms of crop season, while the Highland Lakes model operates under monthly time steps, a

² No regression was developed for Pierce Ranch, so all coefficients were set equal to those of nearby Garwood Irrigation District.

simple temporal decomposition procedure was used to set monthly irrigation demands. First, average monthly water use data for each district over the period of 1988 to 1997 were collected from LCRA resources. For each district, the fraction of first- and second-crop water use occurring in each month was calculated from the historical data. These fractions were then applied to the seasonal water demand regressions to predict monthly irrigation demands for the districts.

For the current model, climatic data were included as deterministic parameters. Since the data are indexed by scenario, however, future versions of the model could include irrigation district climate as a stochastic factor, while providing spatial correlation with the stochastic upstream hydrology already accounted for in the model.

Planted first-crop acreage was included in the model as a decision variable, and nonanticipativity constraints were applied. The second-crop acreage was also restricted by nonanticipativity equations, and was not allowed to exceed first-crop acreage. This constraint is due to the fact that second-crop rice is raised from the same plants that were planted for the first-crop, simply by allowing the plants to regrow and providing sufficient care and water application after the first harvest.

The time factor included in the water demand equation for the Lakeside district is a result of a statistically significant increasing trend in water use (Nazneen 2001). This could be an indication of more widespread planting of

alternative crops, worsening seepage loss in the District's canal system, or other factors.

Sources of Data

The major data requirements for the irrigation regressions were historical water use, rainfall, evaporation, and planted acreage data. Historical water use and planted acreage information was provided by LCRA, rainfall data were acquired from the National Climatic Data Center, and evaporation rates were obtained from the Texas Water Development Board database of gross lake evaporation estimates. For the seasonal regressions developed by LCRA (Nazneen 2001), 1968 to 1986 data were used. The 1968 date is significant for characterizing historical rice water use, since it was around this date that the districts began to employ widespread second-crop production (Martin 1990).

New regressions were developed largely due to the fact that the older monthly regressions were created using outdated Texas Water Development Board gross lake evaporation data. The Development Board modified the evaporation data after the National Weather Service updated its pan coefficients in a technical report from 1982, which were later incorporated into a recently developed GIS application used by the Board for evaporation estimation (Solis 2001).

WATER DEFICITS AND PENALTIES

The two major consumptive uses of water on the lower Colorado River are for irrigation diversions by the rice-farming districts and municipal withdrawals for the City of Austin. When the demand for either of these sources is unmet,

penalties must be applied to the objective function to represent the loss in benefits.

In the case of municipal water diversions, deficits occur when the combination of run-of-river diversions and firm stored water supplies are unable to meet demands. Monthly demands are calculated using a set of monthly fractions derived from historical municipal water diversions (Watkins et al. 2000), and applied to an annual demand that is assumed to be deterministic. Both run-of-river and firm water sources have upper constraints. For municipal run-of-river supplies, total annual diversions are limited to the amount specified in a water right administered through the Texas Natural Resource Conservation Commission (TNRCC). In addition, run-of-river diversions cannot exceed the total inflow into the Highland Lakes, since any additional withdrawal must come from stored water supplies. For firm municipal water, the sum of annual stored and run-of-river withdrawals must be less than the contract amount established with LCRA.

Municipal water deficits receive a high penalty in the model objective function. This penalty, along with the cutoff effect from the interruptible contract function when stored supplies become scarce, ensure that all irrigation diversions are shut off before municipal water deficits are incurred. In reality, LCRA requests voluntary water conservation from all customers when the combined storage of Lakes Buchanan and Travis drops below approximately 1,600 kAF, and requests mandatory conservation when levels fall to 900 kAF (LCRA 1999).

Deficits in the irrigation districts are determined in a similar fashion. When the demands, calculated with the irrigation regressions, exceed the available water from run-of-river and stored interruptible supplies, the districts incur water deficits. For the purposes of the Highland Lakes model, these deficits represent a composite shortfall from the combined perspectives of both LCRA and the rice farmers. The reasons for using this composite approach, and for not looking only from the perspective of LCRA, are worth discussing in some detail.

In practice, LCRA is actually only obligated to fulfill its interruptible contract with the districts. If run-of-river supplies became scarce or obsolete, and the interruptible water deliveries are not enough to meet crop evapotranspiration needs, LCRA suffers no direct loss as long as the interruptible contract is fulfilled. Irrigators can conceivably experience severe economic loss to their crops, while LCRA is not directly affected.

There are two disadvantages to looking at irrigation deficits from the sole position of LCRA. First, the practice disregards the indirect benefit LCRA obtains from maintaining the economic well-being of the rice farmers. LCRA oversees the operations of three of the four irrigation districts, and works closely with the farmers in coordinating water deliveries to the individual fields. LCRA collects fees from the irrigators for making water deliveries, and would therefore be harmed, even if only indirectly, if the farmers were unable to make their payments on supplied water charges.

The second disadvantage of ignoring the perspective of the irrigators concerns the limitations of linear programming, and can be illustrated with the

following example. Consider a scenario in which the combined storage for Lakes Buchanan and Travis at the beginning of the year is very low, and the interruptible contract for the growing season has been curtailed. If rice farmers plant normal acreage amounts, the run-of-river and interruptible supplies may be insufficient to meet the crop demands. This scenario should, from LCRA's perspective, reflect no irrigation deficit, as long as the interruptible contract is fulfilled. A deficit of this type must, however, be expressed as a conditional of the variables representing the contract amount and total annual interruptible diversions, and not simply the difference between demand and supply. This type of conditional cannot easily be represented in a linear program, and is better suited for mixed-integer programming, or other solution techniques.

Because of these potential problems, the Highland Lakes model used a composite approach, in which deficits were simply defined as the difference between combined run-of-river and interruptible supplies and the crop water demands. Penalties can therefore be incurred even when LCRA's contract is met. The relative magnitudes of the penalties charged for first- and second-crop deficits are described later in this chapter, and basically reflect the fact that the first-crop rice harvest is of greater value than the second.

A final modeling consideration concerning deficits involves distribution of water shortages between individual irrigation districts. LCRA has designed a management procedure in which water shortages are divided as equal percentages of the district's interruptible stored water demand, defined as the difference

between irrigation water demand and available run-of-river supplies. A formal expression of this policy is shown below:

$$\frac{UI_{id,t}}{DI_{id,t} - ROR_{id,t}} = \frac{UI_{id',t}}{DI_{id',t} - ROR_{id',t}} \quad (3.7)$$

The indices id and t denote the irrigation district and time, respectively, while id' represents any district in the complementary set to district id . The scenario index has been omitted here for simplicity. In the Highland Lakes model, however, irrigation water deficits, irrigation water demands and irrigation run-of-river diversions are all variables, which results in the above equation being nonlinear.

To maintain linearity, a simplified deficit distribution equation was formulated, equating deficits as proportions of historical water diversions, and introducing slack and surplus variables. The form of the linear approximation is shown below, with the scenario index again omitted for simplicity:

$$\frac{UI_{id,t}}{DIV_{t,id}} = UIAV_t + GA_{id,t} - GB_{id,t} \quad (3.8)$$

For this equation, id and t again represent the irrigation district and time indices respectively, UI is the irrigation water deficit, GA and GB are positive elastic variables, DIV is the average 1988 to 1997 historical total water diversion for each district during the particular month, and $UIAV$ is a fraction defined as follows:

$$UIAV_t = \frac{1}{ID} \sum_{id} \left(\frac{UI_{id,t}}{DIV_{t,id}} \right) \quad (3.9)$$

In this equation, ID represents the total number of irrigation districts, in this case equal to four. Using this form of deficit distribution prevents one or more irrigation districts from experiencing deficits while other districts avoid any shortfalls, and roughly apportions deficits relative to the average water demand of each district. The elastic variables, which are penalized in the objective function, prevent infeasible solutions in situations where maintaining the distribution proportionality would violate a boundary constraint for an irrigation district.

A technique basically identical to that described for deficits above was also used to set first- and second-crop acreage levels equitably between the irrigation districts. These equations are described explicitly later in this chapter.

MODEL INDICES AND PARAMETERS

Before describing the individual features of the optimization model, a note should be made concerning the time index called t_c . In the model, t_c is a subset of the set t of all 60 months in the five-year time horizon. The subset t_c includes only the five January months in the period ($t_1, t_{13}, t_{25}, t_{37}, t_{49}$). In the descriptions below, an index called t_c' has been used to represent a set of 12 months, from January to December, in one of the five year periods. In the actual model, the set t_c' does not exist, and instead a conditional operation using dynamic sets was used to select the appropriate months within a given year. The set t_c' has been used in the following text to simplify the description of the constraint equations.

Table 3.3: Model Indices	
Index	Definition
<i>s</i>	Scenario
<i>sa</i>	1st year subset of <i>s</i>
<i>sb</i>	2nd year subset of <i>s</i>
<i>rs</i>	Reservoirs
<i>srs</i>	Storage reservoirs
<i>rrs</i>	Recreation reservoirs
<i>prs</i>	Pass-through (run-of-river) reservoirs
<i>id</i>	Irrigation districts
<i>t</i>	Time period (monthly)
<i>tc</i>	January month subset of <i>t</i>
<i>ti</i>	Time periods for irrigation
<i>ti₁</i>	Time periods for 1 st crop irrigation
<i>ti₂</i>	Time periods for 2 nd crop irrigation
<i>yr₁</i>	Time periods for first year
<i>yr₂</i>	Time periods for second year
<i>win</i>	Winter months
<i>sur</i>	Summer months
<i>i</i>	Index in first year

Table 3.4: Model Parameters	
Parameter	Definition
ω_1	Weight on recreation benefits
ω_2	Price of power (\$1000/kWh)
ω_3_{srs}	Benefit for retaining storage in the last time step (\$/AF)
α_1	Weight for equalizing Travis and Buchanan storage (\$1000/% Δ)
ca_1	Acreage 1 st crop benefit coefficient (\$/acre)
ca_2	Acreage 2 nd crop benefit coefficient (\$/acre)
cc	Penalty for municipal firm water diversions (\$/AF)
cd	Penalty for interruptible water diversions (\$/AF)
cu_1	Cost of irrigation water deficit for 1 st crop month (\$/AF)
cu_2	Cost of irrigation water deficit for 2 nd crop month (\$/AF)
cm	Cost of municipal water deficit (\$/AF)
RES	Reserve storage for Lakes Travis and Buchanan combined (kAF)
$DCOA$	Annual municipal water demand for City of Austin (kAF/yr)
$FRMC$	Annual firm water contract between COA and LCRA (kAF/yr)

MWR	Annual run-of-river water right for City of Austin (kAF/yr)
$frac_a$	Fraction of City of Austin diversions returning as return flows
$frac_r$	Fraction of irrigation diversions returning as return flows
YL	Minimum interruptible contract
YU	Maximum interruptible contract
YM	Interruptible contract line segment slope
YB	Interruptible contract line segment intercept
kev	Penalty on deviations from LCRA interruptible function
kg	Penalty on deviations from irrigation deficit sharing (\$/AF)
kh	Penalty on deviations from irrigation acreage differences
pr	Penalty on reservoir releases above normal range (\$/AF)
K	Reservoir conservation pool (active) capacities (kAF)
$frac_i_{rs}$	Initial storage fraction for reservoir rs
RHI_{rs}	Maximum recommended monthly release for reservoir rs (kAF)
ff_t	Fraction of municipal water demanded in period t
$RECW_{rrs}$	Max. monthly winter recreation benefit for reservoir rrs (k\$)
$RECS_{rrs}$	Max. monthly summer recreation benefit for reservoir rrs (k\$)
$RECINTW_{rrs}$	Recreation benefit intercept in winter for reservoir rrs (k\$)
$RECINTS_{rrs}$	Recreation benefit intercept in summer for reservoir rrs (k\$)
$RECSPLW_{rrs}$	Recreation benefit slope in winter for reservoir rrs (\$/AF)
$RECSPLS_{rrs}$	Recreation benefit slope in summer for reservoir rrs (\$/AF)
DAY_t	Number of days in month t (days/month)
$PMAX_{rs}$	Hydropower turbine maximum capacities for reservoir rs (MW)
mp_{rs}	Energy generated per flow volume for reservoir rs (MW*d/kAF)
$bG1_{id}$	1 st crop water demand regression evaporation factor in district id
$bG2_{id}$	2 nd crop water demand regression evaporation factor in district id
$bR1_{id}$	1 st crop water demand regression rainfall factor in district id
$bR2_{id}$	2 nd crop water demand regression rainfall factor in district id
$bA1_{id}$	1 st crop irrigation demand regression acreage factor in district id
$bC1_{id}$	1 st crop irrigation demand regression constant in district id
$bC2_{id}$	2 nd crop irrigation demand regression constant in district id
$ACRMX_{id}$	Max serviceable acreage in district id (1000 acres)
$ACRMN_{id}$	Min acreage in district id from 1968-1997 data (1000 acres)
$ACR1AV_{id}$	Ave (1988-97) 1 st crop acreage in district id (1000 acres)
$ACR2AV_{id}$	Ave (1988-97) 2 nd crop acreage in district id (1000 acres)
$fi1_{t,id}$	Fraction of 1 st crop water demanded in month t, district id
$fi2_{t,id}$	Fraction of 2 nd crop water demanded in month t, district id
$DIV_{t,id}$	Average (1988-97) monthly diversion for district id (kAF)
$Q_{rs,t,s}$	Inflows to reservoir rs in period t under scenario s (kAF)
$EA_{t,rs}$	Evaporation slopes for reservoir rs in time t
$EB_{t,rs}$	Evaporation intercepts for reservoir rs in time t
$GLE_{t,s,id}$	Gross lake evaporation for district id in time t, scenario s (ft)

$RAIN_{t,s,id}$	Rainfall for district id in time t, scenario s (ft)
$FROR_{t,s,id}$	Available run-of-river water, district id, time t, scenario s (kAF)
$BAYMIN$	Minimum monthly flow requirement for Matagorda Bay (kAF)

MODEL VARIABLES

The Highland Lakes model uses a significant number of variables to express the state of the system, and to assist in the optimization process. A complete list of the variables is included below:

Table 3.5: Model Variables	
Variable	Definition
$Y_{tc,s}$	Annual interruptible water contract (kAF/yr)
$SR_{rs,t,s}$	Storage in lake rs at end of period t, scenario s (kAF)
$R_{rs,t,s}$	Release from reservoir rs in period t, scenario s (kAF)
$RHYDRO_{rs,t,s}$	Hydro release from reservoir rs in period t, scenario s (kAF)
$RSPILL_{rs,t,s}$	Spill release from reservoir rs in period t, scenario s (kAF)
$RPLUS_{rs,t,s}$	Release above suggested limit, reservoir rs, period t, scenario s (kAF)
$RTRN_{t,s}$	Return flow from City of Austin in period t, scenario s (kAF)
$RBAS_{t,s}$	Colorado River flow at Bastrop in period t, scenario s (kAF)
$INTR_{id,t,s}$	Interruptible diversion for district id in period t, scenario s (kAF)
$INT1_{id,tc,s}$	Interruptible 1 st crop diversions, district id, tc year, scenario s (kAF)
$INT2_{id,tc,s}$	Interruptible 2 nd crop diversions, district id, tc year, scenario s (kAF)
$ROR_{id,t,s}$	Run-of-river diversions for district id in month t, scenario s (kAF)
$ROR1_{id,tc,s}$	Run-of-river 1 st crop diversions, district id, tc year, scenario s (kAF)
$ROR2_{id,tc,s}$	Run-of-river 2 nd crop diversions, district id, tc year, scenario s (kAF)
$BAY_{t,s}$	Matagorda Bay flow, month t, scenario s (kAF)
$P_{rs,t,s}$	Power generated through reservoir rs in month t, scenario s (MW)
$ACR1_{tc,s,id}$	First-crop acreage for tc year in scenario s, district id (1000 acres)
$ACR2_{tc,s,id}$	Second-crop acreage for tc year in scenario s, district id (1000 acres)
$AC1AV_{tc,s}$	Ave fraction of historical ave (1988-97) 1 st crop acreage planted
$AC2AV_{tc,s}$	Ave fraction of historical ave (1988-97) 2 nd crop acreage planted
$WD1_{id,tc,s}$	First-crop water demand for district id in tc year, scenario s (kAF)
$WD2_{id,tc,s}$	Second-crop water demand for district id in tc year, scenario s (kAF)
$DI_{id,t,s}$	Water demand for irrigation district id in month t, scenario s (kAF)

$GA_{id,t,s}$	Elastic variable penalizing unequal district deficits, month t, scenario s
$GB_{id,t,s}$	Elastic variable penalizing unequal district deficits, month t, scenario s
$HAI_{id,tc,s}$	Elastic variable penalizing unequal 1 st crop acreages
$HBI_{id,tc,s}$	Elastic variable penalizing unequal 1 st crop acreages
$HA2_{id,tc,s}$	Elastic variable penalizing unequal 2 nd crop acreages
$HB2_{id,tc,s}$	Elastic variable penalizing unequal 2 nd crop acreages
$DA_{t,s}$	Elastic variable equalizing Travis and Buchanan storage volumes
$DB_{t,s}$	Elastic variable equalizing Travis and Buchanan storage volumes
$ELVA_{tc,s}$	Elastic variable penalizing interruptible contract deviations
$ELVB_{tc,s}$	Elastic variable penalizing interruptible contract deviations
$MROR_{t,s}$	Municipal COA run-of-river diversions in month t, scenario s (kAF)
$MFRM_{t,s}$	Municipal COA firm water diversions, month t, scenario s (kAF)
$UM_{t,s}$	Unmet COA municipal water demand in period t, scenario s (kAF)
$UI_{id,t,s}$	Unmet irrigation demand for district id in period t, scenario s (kAF)
$UIAV_{t,s}$	Ave deficit fraction of historical average (1988-97) diversions
$REC_{rrs,t,s}$	Recreational benefit from reservoir rs in period t, scenario s (k\$)
$ELOS_{rs,t,s}$	Evaporation loss from reservoir rs in period t, scenario s (kAF)
$RECTOT$	Total expected annual recreational benefit (k\$)
$CRPTOT$	Total expected annual water delivery benefit (k\$)
$DEFTOT$	Total expected annual penalties from deficits (k\$)
$STOTOT$	Total expected final storage benefits (k\$)
$HYDTOT$	Total expected annual hydroelectric production (kWh)
$MISCTOT$	Total expected annual benefit from secondary and elastic variables (k\$)
Z	Objective function

MODEL OBJECTIVE FUNCTION

While the Watkins model optimized for a small number of objectives, the newer version includes hydropower benefits, benefits for crop production revenues, recreation benefits, and modified penalties for water deficits. In addition, several new elastic variables are included in the objective function, most of which are associated with equity constraints. The objective function can be represented by the following expression:

$$\text{Maximize } Z = \left(\begin{array}{l} CRPTOT + \omega 1 * RECTOT + \omega 2 * HYDTOT \\ + \omega 3_{srs} * STOTOT - DEFTOT - MISCTOT \end{array} \right) \quad (3.10)$$

The objective function has six main components, and is dimensionally constructed to maximize in terms of thousands of dollars. The first term in the objective, CRPTOT, represents the total revenue from crop production, and is a simple linear function of the total first- and second- crop planted acreages. The second term, RECTOT, includes the recreation benefits generated from the “recreation” reservoirs, defined as Lakes Buchanan and Travis. Recreation benefits are scaled by a coefficient $\omega 1$, a positive value less than one, to connote the fact that recreation is viewed as a subordinate use of water for management considerations. The third term, HYDTOT, includes revenues obtained from hydropower generation, and is related to the magnitude of reservoir releases. Hydropower benefits are scaled by a factor $\omega 2$, which can also be adjusted based on the level of importance desired.

The final three components of the objective function deal with benefits and penalties that are more intangible than the first three, but are also important in the optimization process. The fourth term, STOTOT, defines benefits associated with final storage in the reservoirs during the last time step. This variable helps minimize end-of-horizon effects by preventing the reservoirs from draining during the last few months. STOTOT is scaled by the coefficient $\omega 3_{srs}$, and is indexed by “storage” reservoir. The importance of maintaining final storage in both Lakes Buchanan and Travis can be changed depending on the absolute and

relative magnitude of the two storage coefficients. The DEFTOT variable, included as the fifth term, represents the revenue lost from unmet municipal and irrigation water demands. The final term, MISCTOT, includes a number of slack, surplus, and secondary variables which are used in linearization processes, equity constraints, and for other purposes. All terms in the objective function are averaged over time and scenario, and, with the exception of STOTOT, represent expected annual values.

The values assigned to the three coefficients listed above can play a large role in determining the overall objective. In the original model (Watkins et al. 2000), the recreation coefficient, ω_1 , was varied to analyze its relative importance. Unless otherwise noted, for the purposes of this research it was assigned a value of 0.1, which resulted in a reasonable balance between maintaining storage and meeting downstream water demands. The coefficient ω_2 , used with the hydropower term, was initially set at a value of 5 cents per kWh, which is within an order of magnitude of current utility rates. In essence, the weight on hydropower is approximately unity, since it has been scaled to estimate actual hydroelectric revenues. The coefficient for end-of-horizon storage, $\omega_{3_{\text{srs}}}$, required greater manipulation, but values of \$20 and \$17 per acre-foot were chosen for Lakes Buchanan and Travis, respectively. Further discussion on the effect of this weight is included later in this document.

MODEL CONSTRAINTS

There are many constraints on the Highland Lakes system, from basic mass balance equations to nonanticipativity constraints for preventing perfect

knowledge of the future. The complete list of constraints, along with a brief discussion of each equation, is included below.

Continuity ($CONS_{rs,t,s}$)

$$(1 + EA_{t,rs}) * SR_{rs,t,s} = (1 - EA_{t,rs}) * SR_{rs,t-1,s} + Q_{rs,t,s} + R_{rs-1,t,s} - R_{rs,t,s} - EB_{rs,t} - (MFRM_{t,s} + MROR_{t,s})_{if\ rs=Austin} \quad (3.11)$$

Constraints (3.11) describe the mass balance relationship for each reservoir. Changes in storage are due to inputs from river inflows, and outputs from surface evaporation, dam releases, and in the case of Lake Austin only, municipal water diversions for the City of Austin. Reservoir evaporation has been approximated as a linear function of the average reservoir storage over a given month. Tables of surface area and storage levels based on elevation were obtained from LCRA, and used to derive linear relationships. The majority of municipal diversions for the City of Austin are pumped to three major drinking water treatment plants: Davis, Ulrich and Green. Both the Davis and Ulrich plants pump water from Lake Austin, while Green makes withdrawals downstream from Town Lake. Since the capacity of Green is only 14% of the total capacity of the three plants (City of Austin 2001), all municipal diversions for the City of Austin were assumed to come from Lake Austin for the purposes of the model.

Reserve storage ($RESERVE_{t,s}$)

$$SR_{Buchanan,t,s} + SR_{Travis,t,s} \geq RES \quad (3.12)$$

Constraints (3.12) define the reserve storage volume for the combined storage of Lakes Buchanan and Travis. In practice, LCRA cuts off all interruptible water deliveries when storage drops below the reserve level.

Space rule (SPACE_{t,s})

$$\frac{SR_{Buchanan,t,s}}{K_{Buchanan}} - \frac{SR_{Travis,t,s}}{K_{Travis}} = DA_{t,s} - DB_{t,s} \quad (3.13)$$

Constraints (3.13) pertain to the space rule used to equalize the fractional storages of Lakes Buchanan and Travis. The difference of two positive slack variables is set equal to the fractional difference, and the sum of the slack variables is minimized later in the objective function.

Interruptible contract function (INTP_{t,s})

$$Y_{tc,s} - ELVA_{tc,s} + ELVB_{tc,s} = YB + YM * (SR_{Buchanan,t=tc-1,s} + SR_{Travis,t=tc-1,s}) \quad (3.14)$$

Constraints (3.14) describe the calculation of a highly constrained interruptible contract variable. The contract, determined for each January month, varies linearly with the combined end-of-month storage of Lakes Buchanan and Travis for the previous December month.

Flow through hydroturbines and spills (RELEASE_{rs,t,s})

$$R_{rs,t,s} = RHYDRO_{rs,t,s} + RSPILL_{rs,t,s} \quad (3.15)$$

Constraints (3.15) separate releases from each reservoir into flows through the turbines and spill flows. Flows through the penstocks are implicitly limited later by constraints (3.59), which place an upper bound on the power generation for each reservoir equal to the plant capacity.

Normal and excess reservoir releases (RELREG_{rs,t,s})

$$R_{rs,t,s} = RHI_{rs} + RPLUS_{rs,t,s} \quad (3.16)$$

Constraints (3.16) divide reservoir releases into “normal” and “excess” flows, the latter of which are penalized in the objective function. These constraints only come into play during periods of very high flows, when downstream scour and flooding could occur. Since the hydrologic scenarios used for the Highland Lakes model contained relatively dry conditions, these constraints generally did not play a role in the optimization process. However, if future models incorporate wetter scenarios, the constraints can both penalize channel erosion losses, and provide a soft upper bound on reservoir releases. No explicit upper bound on reservoir releases was used since the discharge capacities for all dams far exceeded any of the calculated model releases.

Municipal run-of-river diversions limited to water right (MUNIC_{tc,s})

$$\sum_{t \in tc'} MROR_{t,s} \leq MWR \quad (3.17)$$

Total municipal water diversions limited to LCRA contract (MUNIF_{tc,s})

$$\sum_{t \in tc'} (MFRM_{t,s} + MROR_{t,s}) \leq FRMC \quad (3.18)$$

Constraints (3.17) define an upper limit for annual municipal run-of-river diversions. Municipal diversions cannot exceed the amount specified in the water right administered through the Texas Natural Resources Conservation Commission. In a similar fashion, constraints (3.18) prevent the City of Austin from withdrawing total stored and run-of-river water supplies in excess of the amount contracted with LCRA.

Municipal water deficit (DEFM_{t,s})

$$UM_{t,s} = ff_t * DCOA - MFRM_{t,s} - MROR_{t,s} \quad (3.19)$$

When available water supplies are unable to satisfy demands, water deficits occur. Constraints (3.19) define a deficit for the City of Austin, equal to the difference between monthly municipal demands and the sum of firm and run-of-river diversions.

Return flows from City of Austin (RETRN_{t,s})

$$RTRN_{t,s} = frac_a * (MROR_{t,s} + MFRM_{t,s}) \quad (3.20)$$

Constraints (3.20) set the municipal return flows equal to a fraction of the total municipal diversions for the same month. The diversions used for the calculation include both run-of-river and firm stored water withdrawals. The fraction was set at 55%, which is a historical average value used for LCRA management purposes (LCRA 1999).

Addition of City of Austin return flows (BASTROP_{t,s})

$$RBAS_{t,s} = R_{Austin,t,s} + RTRN_{t,s} \quad (3.21)$$

Constraints (3.21) specify a mass balance for a location downstream of the Highland Lakes, where return flows from City of Austin municipal diversions are released back into the river. Municipal return flows are discharged into the Colorado River below Lake Austin and Town Lake, and before the city of Bastrop, Texas.

Flow into Matagorda Bay (IRELEASE_{t,s})

$$BAY_{t,s} = RBAS_{t,s} - (1 - frac_r) \sum_{id} INTR_{id,t,s} + frac_r * \sum_{id} ROR_{id,t,s} \quad (3.22)$$

Constraints (3.22) express a mass balance for determining flows into Matagorda Bay, which is useful for evaluating the environmental impact of management decisions for the bay ecosystem. Flows into Matagorda Bay are defined as the flow at Bastrop, calculated through constraints (3.21), minus the consumptive fraction of interruptible irrigation diversions, plus return flows from run-of-river irrigation diversions. The fraction of irrigation diversions returning to the river from field runoff was set at 30%, which is between specific values, 25% predicted for year 2030 conditions and 35% for historical conditions, referenced in LCRA water management documents (LCRA 1999).

The mass balance equations for constraints (3.22) follow a very rough assumption that incremental flows below the Highland Lakes are approximately equal to run-of-river diversions by the irrigation districts. In other words, the model operates as if run-of-river diversions for the irrigation districts originated from an outside source, while also ignoring downstream incremental flows. This simplification was made due to the high variability and uncertainty in downstream incremental flows, and because of the accounting complexities associated with run-of-river flows.

1st and 2nd crop water demands ($IDEM1_{id,tc,s}$, $IDEM2_{id,tc,s}$)

$$WD1_{id,tc,s} = \left(bG1_{id} \sum_{t \in t1 \cap tc'} GLE_{t,s,id} + bR1_{id} \sum_{t \in t1 \cap tc'} RAIN_{t,s,id} + bA1_{id} \right) ACR1_{tc,s,id} + bC1_{id} \quad (3.23)$$

$\forall id \neq Pierce$

$$WD2_{id,tc,s} = \left(bG2_{id} \sum_{t \in t2 \cap tc'} GLE_{t,s,id} + bR2_{id} \sum_{t \in t2 \cap tc'} RAIN_{t,s,id} \right) ACR2_{tc,s,id} + bC2_{id} \quad (3.24)$$

$\forall id \neq Pierce$

Constraints (3.23) and (3.24) derive first- and second-crop water demands for each irrigation district, using the regressions described earlier in this chapter. As noted, these regressions apply to all districts except Pierce Ranch.

Decomposition of monthly irrigation demands ($IDEMM_{id,t,s}$, $IDEMP_{id,t,s}$)

$$DI_{id,t \in tc',s} = \hat{f}1_{t \in tc',id} * WD1_{id,tc,s} + \hat{f}2_{t \in tc',id} * WD2_{id,tc,s} \quad \forall id \neq Pierce \quad (3.25a)$$

$$DI_{id,t \in tc',s} = DIV_{t,id} \frac{ACR1_{tc,s,id}}{ACR1AV_{id}} \quad \text{if } id = Pierce \text{ AND } t \in ti_1 \quad (3.25b)$$

$$DI_{id,t \in tc',s} = DIV_{t,id} \frac{ACR2_{tc,s,id}}{ACR2AV_{id}} \quad \text{if } id = Pierce \text{ AND } t \in ti_2 \quad (3.25b)$$

The seasonal irrigation demands calculated in equations (3.23) and (3.24) are decomposed into monthly demands through constraints (3.25a), which apply to all districts except for Pierce Ranch. Constraints (3.25b) and (3.25c) set Pierce Ranch demands for first- and second-crops as linear functions of historical average diversions, scaling the result by the fraction of historical average (1988 to 1997) acreage under production.

Irrigation water deficit ($DEFI_{id,t,s}$)

$$UI_{id,t,s} = DI_{id,t,s} - ROR_{id,t,s} - INTR_{id,t,s} \quad (3.26)$$

Similar to the equations for municipal deficits, constraints (3.26) express an irrigation deficit as the difference between monthly crop demand and the sum of run-of-river and interruptible diversions.

Average fractional irrigation deficits ($DEF_{t,s}$)

$$UIAV_{t,s} = \frac{1}{ID} \sum_{id} \frac{UI_{id,t,s}}{DIV_{t,id}} \quad (3.27)$$

Constraints (3.27) calculate average fractional irrigation deficits, relative to historical average diversions from 1988 to 1997. Constraints (3.27) are the complete form, including the scenario index, of equations (3.9) described earlier in the chapter.

Equality in irrigation deficits (DEFEQ_{id,t,s})

$$\frac{UI_{id,t,s}}{DIV_{t,id}} = UIAV_{t,s} + GA_{id,t,s} - GB_{id,t,s} \quad (3.28)$$

Inequalities between irrigation district diversions are dealt with in equations (3.28). The deficit distribution equations use slack and surplus variables, as discussed earlier in this chapter, to encourage deficits between districts to be approximately equal on a fractional basis, with respect to average historical water diversions.

Interruptible diversions limited to contract (CONTR_{tc,s})

$$\sum_{t \in tc} \sum_{id} INTR_{id,t,s} \leq Y_{tc,s} \quad (3.29)$$

For the irrigation districts, constraints (3.29) specify that total interruptible water diversions for all districts must be less than the amount determined through the contract decision function. Since there is no differentiation made between the districts, inequality concerns are addressed through additional constraints, as described earlier.

2nd crop limit on irrigation acreage (ACRGE_{tc,s,id})

$$ACR2_{tc,s,id} \leq ACR1_{tc,s,id} \quad (3.30)$$

Constraints (3.30) prevent second-crop rice acreages from exceeding those for the first-crop. Second-crop (ratoon) rice comes from first-crop plants that are

allowed to regrow after harvest. No additional planting takes place for the second-crop rice.

Average fractional 1st and 2nd crop acreage ($ACRAV1_{tc,s}$, $ACRAV2_{tc,s}$)

$$AC1AV_{tc,s} = \frac{1}{ID} \sum_{id} \frac{ACR1_{tc,s,id}}{ACR1AV_{id}} \quad (3.31)$$

$$AC2AV_{tc,s} = \frac{1}{ID} \sum_{id} \frac{ACR2_{tc,s,id}}{ACR2AV_{id}} \quad (3.32)$$

Constraints (3.31) and (3.32) determine average fractional first- and second-crop acreage levels across the irrigation districts, relative to each district's respective historical average acreage under production from the 1988 to 1997 period. These acreage equity equations are similar to those for irrigation deficits in constraints (3.27).

Equality in 1st and 2nd crop acreage levels ($ACR1EQ_{id,t,s}$, $ACR2EQ_{id,t,s}$)

$$\frac{ACR1_{tc,s,id}}{ACR1AV_{id}} = AC1AV_{tc,s} + HA1_{id,tc,s} - HB1_{id,tc,s} \quad (3.33)$$

$$\frac{ACR2_{tc,s,id}}{ACR2AV_{id}} = AC2AV_{tc,s} + HA2_{id,tc,s} - HB2_{id,tc,s} \quad (3.34)$$

As with the irrigation deficits in constraints (3.28), inequalities between irrigation district acreage levels are minimized in equations (3.33) and (3.34) by using slack and surplus variables. The elastic variables represent deviations from historical (1988-1997) average fractional 1st and 2nd crop planted acreage levels.

Summation of 1st and 2nd crop run-of-river flows ($ROR1_{id,tc,s}$, $ROR2_{id,tc,s}$)

$$ROR1_{id,tc,s} = \sum_{t \in I1_1 \cap tc'} ROR_{id,t,s} \quad (3.35)$$

$$ROR2_{id,tc,s} = \sum_{t \in I2_2 \cap tc'} ROR_{id,t,s} \quad (3.36)$$

Constraints (3.35) and (3.36) are accounting equations used to determine total seasonal run-of-river withdrawals from monthly diversions for the irrigation districts in both the first- and second-crop periods.

Summation of 1st and 2nd crop interruptible flows ($INTER1_{id,tc,s}$ $INTER2_{id,tc,s}$)

$$INT1_{id,tc,s} = \sum_{t \in ti_1 \cap tc'} INTR_{id,t,s} \quad (3.37)$$

$$INT2_{id,tc,s} = \sum_{t \in ti_2 \cap tc'} INTR_{id,t,s} \quad (3.38)$$

Constraints (3.37) and (3.38) are additional accounting equations for interruptible irrigation water diversions for each first- and second-crop season.

Non-anticipativity ($ANT1R_{rs,t,s,i}$ $ANT2R_{rs,t,s}$ $ANT1I_{tc,s}$ $ANT2I_{tc,s,i}$ $ANT3I_{tc,s}$ $ANT1A_{tc,id,s}$ $ANT2A_{tc,id,s,i}$ $ANT3A_{tc,id,s}$ $ANT1B_{tc,id,s,i}$ $ANT2B_{tc,id,s}$)

$$R_{rs,t,s} = R_{rs,t,s+i} \quad \text{if } t \in YR_1 \quad \text{and } s \in sa \quad (3.39)$$

$$R_{rs,t,s} = R_{rs,t,s+1} \quad \text{if } t \in YR_2 \quad \text{and } s \in sb \quad (3.40)$$

$$Y_{tc,s} = Y_{tc,s'} \quad \text{if } tc = 1 \quad \forall s \quad (3.41)$$

$$Y_{tc,s} = Y_{tc,s+i} \quad \text{if } tc = 2 \quad \text{and } s \in sa \quad (3.42)$$

$$Y_{tc,s} = Y_{tc,s+1} \quad \text{if } tc = 3 \quad \text{and } s \in sb \quad (3.43)$$

$$ACR1_{tc,s,id} = ACR1_{tc,s',id} \quad \text{if } tc = 1 \quad \forall s \quad (3.44)$$

$$ACR1_{tc,s,id} = ACR1_{tc,s+i,id} \quad \text{if } tc = 2 \quad \text{and } s \in sa \quad (3.45)$$

$$ACR1_{tc,s,id} = ACR1_{tc,s+1,id} \quad \text{if } tc = 3 \quad \text{and } s \in sb \quad (3.46)$$

$$ACR2_{tc,s,id} = ACR2_{tc,s+i,id} \quad \text{if } tc = 1 \quad \text{and } s \in sa \quad (3.47)$$

$$ACR2_{tc,s,id} = ACR2_{tc,s+1,id} \quad \text{if } tc = 2 \quad \text{and } s \in sb \quad (3.48)$$

Constraints (3.39) through (3.48) are used to enforce nonanticipativity, which prevents decisions from being made with perfect knowledge of future conditions. The general objective of the nonanticipativity equations is to force all

decision variables to be equal when all stochastic elements up to the point of the decision in the scenario tree are identical. For the Highland Lakes model, this means that whenever hydrographs for inflows into the Highland Lakes, up to the month when a decision must be made, are identical, the same decision must also be implemented across those particular scenarios.

For nonanticipativity constraints (3.39) and (3.40), reservoir releases are forced to be equal within groups of scenarios that share common inflows. The scenario subsets s_a and s_b define the first ordered members of the scenario groups sharing common inflow histories. For example, the subset s_a includes scenarios 1, 7, 13, 19 and 25. The index i ranges from one to five, and is used to help group the scenarios into five groups of six members each for year one. In year two, the scenario tree splits into 15 groups of two scenarios each, as shown in Figure 3.2, and subset s_b is used to organize the groupings.

Constraints (3.41) through (3.43) apply nonanticipativity on interruptible storage contracts. The contracts, decided based on projected reservoir storage on January 1, are also forced to be equal when past inflows are the same across groups of scenarios. Contract nonanticipativity is enforced for the beginning of the first through third years. In almost exactly the same fashion, constraints (3.44) through (3.46) require nonanticipativity for first-crop planting decisions. Given the same past hydrological conditions, farmers must plant the same number of acres to rice within the irrigation districts. Nonanticipativity constraints for second-crop rice in equations (3.47) and (3.48) are similar to the release

nonanticipativity constraints, since second-crop production decisions have the advantage of additional information on inflows since the beginning of the year.

Recreation benefits ($RECREA_{rs,t,s}$)

$$REC_{rrs,t,s} \leq \begin{cases} RECINTW_{rrs} + RECSLPW_{rrs} * \frac{1}{2}(SR_{rs,t,s} + SR_{rs,t-1,s}) & \text{if } t \in win \\ RECINTS_{rrs} + RECSLPS_{rrs} * \frac{1}{2}(SR_{rs,t,s} + SR_{rs,t-1,s}) & \text{if } t \in sur \end{cases} \quad (3.49)$$

Recreation benefits for each month are calculated in constraints (3.49), in which benefits are estimated as a linear function of average reservoir storage for each month. One of two separate benefit equations is used, depending on if the month falls in the “winter” or “summer” months, defined as September through May and June through August, respectively. Recreation benefits are greater for the summer months, due to increased public use.

Total expected annual recreation benefits ($RECBEN$)

$$RECTOT = \frac{12}{S * T} \sum_{rrs} \sum_t \sum_s REC_{rrs,t,s} \quad (3.50)$$

Monthly recreation benefits for both reservoirs and all scenarios are summed in constraint (3.50), and then adjusted to yield an expected annual value. The number 12 in the denominator is needed since the time increments are months, while the left-hand side benefit term is in thousands of dollars per year.

Total expected annual crop revenue ($CRPBEN$)

$$CRPTOT = \frac{12}{S * T} \sum_{tc} \sum_s \sum_{id} (ca_1 ACR1_{tc,s,id} + ca_2 ACR2_{tc,s,id}) \quad (3.51)$$

Total expected annual crop revenues are calculated in equation (3.51) by summing crop benefits for first- and second-crop production. The coefficients ca_1

and ca_2 represent profit expectations from rice production for the first- and second-crops in dollars per acre. Values for the coefficients were taken from studies done by the Texas A&M Agricultural Extension Service (Rister et al. 1989) and the Lyndon B. Johnson School of Public Affairs at the University of Texas at Austin (Schultz 1996).

Total expected annual deficit penalties (DEFPEN)

$$DEFTOT = \frac{12}{S * T} \left[\left(\sum_t \sum_s cm UM_{t,s} \right) + \left(\sum_{id} \sum_t \sum_s (cu_1 UI_{id,t \in i_1,s} + cu_2 UI_{id,t \in i_2,s}) \right) \right] \quad (3.52)$$

Deficit penalties for not meeting municipal and irrigation water demands are summed in equation (3.52). The coefficient cm represents the cost in dollars per acre-foot of municipal water deficit, and was set at \$600/acre-ft. This value was suggested by LCRA as representative of the marginal economic loss associated with unmet municipal demand. For irrigation deficit coefficients cu_1 and cu_2 , LCRA also supplied an estimated marginal loss of \$120/acre-ft, which was used for the first-crop coefficient, cu_1 . Following LCRA's suggestion, the second-crop coefficient, cu_2 , was set at a lower value of \$100/acre-ft to account for the smaller marginal revenue associated with second-crop rice production.

Power generation (POWER_{rs,t,s})

$$P_{rs,t,s} = \frac{mp_{rs} RHYDRO_{rs,t,s}}{DAY_t} \quad (3.53)$$

Power generation is calculated through constraints (3.53), which assume that hydropower is a linear function of the release through the turbines. The unit conversions used in the equation result in power generation values in megawatts (MW), and are average power levels for each month.

Total expected annual hydropower (HYDROBEN)

$$HYDTOT = \frac{12}{S * T} \sum_{rs} \sum_t \sum_s 24,000 * P_{rs,t,s} DAY_t \quad (3.54)$$

Unit conversions and summations in equation (3.54) transform monthly average power generation values into expected annual hydroelectric generation in kWh. The 24,000 coefficient is needed to change megawatt-days into kilowatt-hours.

Final storage benefits (STOBEN)

$$STOTOT = \frac{1}{S} \sum_{srs} \sum_s \omega 3_{srs} SR_{srs,t=60,s} \quad (3.55)$$

Equation (3.55) calculates a total expected storage benefit during the final time period in the model. This equation was included to prevent end-of-horizon effects, which tend to empty reservoirs near the end of model time horizons to achieve non-storage benefits. Note that the coefficient $\omega 3$ is included both in this equation, as well as within the objective function, represented by equation (3.10). In the actual model, the coefficients are only included in the STOBEN equation (within the STOTOT variable), since they are indexed by reservoir, and therefore must remain within the summation.

Expected annual secondary penalties (MISC)

$$MISCTOT = \frac{12}{S * T} \left\{ \begin{aligned} &kev \sum_{tc,s} (ELVA_{tc,s} + ELVB_{tc,s}) + kg \sum_{id,t,s} (GA_{id,t,s} + GB_{id,t,s}) \\ &+ kh \sum_{id,tc,s} (HA_{id,tc,s} + HB1_{id,tc,s} + HA2_{id,tc,s} + HB2_{id,tc,s}) \\ &+ pr \sum_{rs,t,s} RPLUS_{rs,t,s} + \alpha_1 \sum_{t,s} (DA_{t,s} + DB_{t,s}) + cc \sum_{t,s} MFRM_{t,s} \\ &+ cd \sum_{id,t,s} INTR_{id,t,s} \end{aligned} \right\} \quad (3.56)$$

Constraint (3.56) includes a number of slack and surplus variables, along with secondary variables of minor importance to the overall objective. The minor components aid with linearization processes, assure that variables “fill” in the correct order, and serve other secondary purposes.

The first bracketed term, with coefficient k_{ev} , includes the slack and surplus variables for the interruptible water contract defined in equations (3.14). The magnitude of the coefficient was set equal to twice the penalty on municipal water deficits (cm), in order to ensure that the contract function was followed. By setting the k_{ev} coefficient at a high value, interruptible contracts are forced to follow the operation curve, even if municipal deficits occur as a result. It is important to note, however, that even with this high penalty, all interruptible flows will still be cutoff before municipal supplies are curtailed, since the marginal penalty for municipal deficits remains higher than that for irrigation deficits. While the interruptible decision function may indicate a contractual promise for interruptible water supplies, actual hydrological conditions may still force deficits after the contract has been set.

The second penalty term concerns the slack variables with equity constraints (3.28) for sharing irrigation deficits between districts. Similar to the method used to choose the weight on interruptible contract deviations, the coefficient on the elastic variables for irrigation deficit equality (k_g) was initially set equal to twice the penalty on first-crop irrigation water deficits (cu_1).

Equity constraints for planted acreages are addressed with the third term, which penalizes fractional acreage levels that deviate from average fractions

across the districts. The coefficient used for the term was determined experimentally by varying the magnitude and evaluating the resulting fractional differences. The weight was initially set to \$1.15 million per fractional acreage deviation, which resulted in maximum deviations less than 25%.

The fourth component of equation (3.56) concerns reservoir releases above recommended levels. An initial value of \$1,000 per acre-feet was chosen for the coefficient pr . This was a fairly arbitrary choice used to represent the losses associated with downstream scour and channel erosion during periods of high releases. Because high releases are generally discouraged by the model itself in order to hedge against future low-flow scenarios, and since the maximum recommended flow values, RHI_{rs} , are rarely exceeded except in flood situations, this weight is considered of lesser importance, and shouldn't play a major role in the solution process.

Within the fifth term, deviations from equitable fractional storage between Lakes Buchanan and Travis are penalized, again using slack and surplus variables. The penalty coefficient on deviations from the space rule (α_1) was determined experimentally. A value of \$700 per fractional difference in storages seemed to yield storage levels that agreed well with historical patterns.

The sixth term in constraint (3.56) addresses municipal firm water diversions for the City of Austin. The weight used to penalize municipal firm water withdrawals, cc , was set at a very small value (1 cent per kAF), since its only purpose is to ensure run-of-river withdrawals are made before firm water extraction. The City of Austin will use all available water from its senior water

right before exercising its firm water contract with LCRA (LCRA 1999). In an identical fashion, the seventh term assigns a small penalty to interruptible irrigation diversions to ensure that run-of-river supplies are used up before interruptible supplies are used. The coefficient cd was also set at 1 cent per kAF.

All terms in the MISC equation have been averaged over scenario and time, resulting in an average annual value. Since all elastic and secondary variables, and their associated coefficients, are positive, the MISCTOT variable must be subtracted from the other terms in the objective function.

Capacity upper bounds

$$SR_{rs,t,s} \leq K_{rs} \quad (3.57)$$

Reservoir storages are limited to capacity values through boundary constraints (3.57). Capacities were obtained through LCRA, which used storage curves developed both internally, and through surveys carried out by the Texas Water Development Board.

Pass-through reservoir storage fixed bounds

$$SR_{prs,t,s} = frac_i_{prs} * K_{prs} \quad (3.58)$$

Pass-through reservoirs were further constrained through equations (3.58), by requiring storage values to be constant within the smaller reservoirs for all time steps. This reflects the lack of significant carryover storage capacity for the pass-through reservoirs, and other economic reasons for maintaining constant reservoir elevations at these sites.

Hydroturbine capacity upper bounds

$$P_{rs,t,s} \leq PMAX_{rs} \quad (3.59)$$

Constraints (3.59) define maximum capacities for the hydroturbines, and, in concert with constraints (3.15) and (3.53), limit the flow through the turbines. Capacities for all turbines were obtained from tables provided by LCRA.

Recreation benefit upper bounds

$$REC_{rrs,t,s} \leq \begin{cases} REC W_{rrs} & \text{if } t \in \text{win} \\ RECS_{rrs} & \text{if } t \in \text{sur} \end{cases} \quad (3.60)$$

As explained earlier, constraints (3.49) define recreation benefits as linear functions of reservoir storage levels, with linear parameters that are dependant on the time of year. Constraints (3.60) place upper limits on these benefits, implying that there is an elevation level above which no marginal recreation benefits are accrued.

Interruptible contract lower and upper bounds

$$Y_{tc,s} \geq YL \quad (3.61)$$

$$Y_{tc,s} \leq YU \quad (3.62)$$

Constraints (3.61) and (3.62) place lower and upper bounds on the interruptible water contract with the irrigators. These bounds are part of the linearization process for contract decisions described earlier in the chapter.

Irrigation run-of-river diversion upper bounds

$$ROR_{id,t,s} \leq FROR_{t,s,id} \quad (3.63)$$

Constraints (3.63) require run-of-river diversions made by the irrigators to not exceed what is available. Available run-of-river supplies were obtained from an LCRA RESPONSE model run, which used estimated demands for 2010 and hydrological conditions from 1941-1965. The FROR parameter is indexed by

time, scenario and district, although the current model uses identical values for all scenarios, and repeats identical annual supplies for all five years. For simplicity, run-of-river supplies are assumed to originate from an external source.

City of Austin run-of-river diversion upper bounds

$$MROR_{t,s} \leq \sum_{rs} Q_{rs,t,s} \quad (3.64)$$

Limits on municipal run-of-river diversions are specified in constraints (3.64), and force diversions to be below the level of inflows entering the Highland Lakes. This follows water law concerning run-of-river rights owned by the City of Austin.

Critical bay and estuary flow lower bounds

$$BAY_{t,s} \geq BAYMIN \quad (3.65)$$

Bay and estuary flow requirements are enforced in constraints (3.65), which set a lower bound on flows into Matagorda Bay. These minimum flows are based on existing LCRA guidelines (LCRA 1999), and are designed primarily to prevent salinity levels from reaching levels adverse to aquatic life in the bay.

1st crop irrigation acreage lower bounds

$$ACR1_{tc,s,id} \geq ACRMN_{id} \quad (3.66)$$

1st crop irrigation acreage upper bounds

$$ACR1_{tc,s,id} \leq ACRMX_{id} \quad (3.67)$$

Constraints (3.66) and (3.67) set lower and upper bounds on first-crop rice acreage for the irrigation districts, respectively. Upper bounds for all districts except Pierce Ranch were taken from data on serviceable acreage, representing

the total acreage that could currently be irrigated without major delivery system modifications (LCRA 2002). The value of serviceable acreage for Pierce Ranch was obtained directly from the district (Armour 2002). Lower bounds were set as five percent of the minimum acreage planted in the 1968 to 1997 period. The lower bounds were used mainly to prevent the model from assigning zero planted acres to some districts. The lower bounds are only applied to first-crop acreages, and second-crop levels are allowed to drop to zero.

Non-negativity restrictions

$$\begin{aligned}
&Y_{tc,s}, R_{rs,t,s}, RHYDRO_{rs,t,s}, RSPILL_{rs,t,s}, RPLUS_{rs,t,s}, RTRN_{t,s}, \\
&RBAS_{t,s}, INTR_{id,t,s}, INT1_{id,tc,s}, INT2_{id,tc,s}, ROR_{id,t,s}, ROR1_{id,tc,s}, \\
&ROR2_{id,tc,s}, BAY_{t,s}, P_{rs,t,s}, ACR1_{tc,s,id}, ACR2_{tc,s,id}, AC1AV_{tc,s}, \\
&AC2AV_{tc,s}, WD1_{id,tc,s}, WD2_{id,tc,s}, DI_{id,t,s}, GA_{id,t,s}, GB_{id,t,s}, HA1_{id,tc,s}, \\
&HB1_{id,tc,s}, HA2_{id,tc,s}, HB2_{id,tc,s}, DA_{t,s}, DB_{t,s}, ELVA_{tc,s}, ELVB_{tc,s}, \\
&MROR_{t,s}, MFRM_{t,s}, UM_{t,s}, UI_{id,t,s}, UIAV_{t,s}, SR_{rs,t,s} \geq 0
\end{aligned} \tag{3.68}$$

Finally, constraints (3.68) assign non-negativity restrictions for a variety of variables. Non-negativity is required for physical reasons that prevent quantities from falling below zero, or for other considerations regarding model design.

SOLUTION PROCEDURE

The Highland Lakes model is a multistage, and multiobjective, linear stochastic water management problem, consisting of over 130,000 columns, 82,000 rows, and 334,000 non-zeroes. Solution of problems of this scale require complex algorithmic procedures, for which there are several computer packages available. The General Algebraic Modeling System (GAMS) was chosen as the

platform, since it was used for the original Watkins model, and because of its speed, flexibility, and ease of use.

GAMS Overview

GAMS is a high level language which draws from mathematical programming and relational database theory (Brooke et al. 1998). Data and equations are entered in the form of sets, scalars, parameters, variables and equations. GAMS enables easy formulation of indexing, and also allows the concise application of conditionals within equations.

GAMS output can be modified in a variety of ways, and can be generated through customized output files created by the user. A customized file was written to show reservoir levels, interruptible contracts, reservoir releases, planted acreages, and water deficits, along with other variables, all indexed by time and scenario, as calculated by the GAMS solver.

Solver Selection

GAMS is capable of using a wide variety of solvers for the optimization process, including OSL, CONOPT, Cplex and MINOS. While OSL was used for the original Watkins model, the use of Cplex resulted in a significant reduction in computational time. Solution times for a Pentium III PC were about one CPU minute, and required a little over 37,000 simplex iterations, when using Cplex as the solver. Cplex uses the primal simplex algorithm as a default for linear programs, and has considerable presolve and infeasibility analysis capabilities.

The presolve features in Cplex considerably reduced the computational complexity of the Highland Lakes problem. Columns and rows were reduced by

over 6,400 and 35,600, respectively, by the presolve routine. After the additional use of the Cplex aggregator, the reduced linear program included about 44,600 rows, 62,800 columns, and 153,500 nonzeros.

Computational Considerations

Because of the final reservoir storage benefits used in the model through equation (3.55), unusual behavior in terms of reservoir storage changes and release values occur over the final time steps. The magnitude of this end-of-horizon effect is dependant on the magnitude of the benefit coefficients, prior month reservoir storage levels, and other factors.

Because of this effect, it is recommended that the results from year five be ignored for management purposes. Releases over the last few time steps may noticeably differ from those made in earlier years. This effect appears to be limited to the last few months in the model, and should not have a significant impact on the results for earlier time periods.

Chapter 4: Results

Solutions for the Highland Lakes problem can be used for a variety of different purposes, including the analysis of crop production and water use in the irrigation districts, and the prediction of future reservoir storage. In addition, sensitivity tests can help assess the relative importance of individual components of the optimization problem.

As mentioned earlier, the inflow scenarios used for this model were taken from the original Watkins model (Watkins et al. 2000), and are based on historical streamflow sequences that have been filtered through LCRA's RESPONSE reservoir simulation program. Because the RESPONSE program subtracts water rights that are now explicitly included in mass balance relationships, and because the historical sequence chosen includes the most critical drought ever experienced in the area, the scenarios should produce results with low supply characteristics. Until more accurate SPIGOT-generated scenarios are available, the current data can still provide useful information on how the Highland Lakes system reacts to different management priorities. Future scenarios can also easily be incorporated into the model by simply including an updated, external data file.

A complete listing of the parameters used in the base version of the GAMS model is included in the appendices. Unless otherwise specified, results discussed in this chapter will be for the base case. Explanations for the choice of coefficient values and other parameters for the base version can be found in chapter three.

RESERVOIR STORAGE LEVELS

One of the most useful representations of the model output is reservoir storage volumes as a function of time. Figures 4.1 and 4.2 below show predicted 10th, 50th (median), and 90th percentiles for Lakes Buchanan and Travis storage, respectively. In addition, the 1942 to 2001 historical average storage levels for each reservoir and month have been plotted for comparison.

Figure 4.1: Lake Buchanan Predicted Storage Percentiles

Figure 4.2: Lake Travis Predicted Storage Percentiles

Perhaps the most obvious feature concerning the plots is the fact that median storage levels for both lakes are significantly below historical averages. This is likely due to the choice of scenario generation scheme, as explained earlier. For all but the 90th percentile plot, there is also a noticeable decreasing trend in storage for both reservoirs. To understand the storage trend, it is first important to take a closer look at the inflow scenarios. Figure 4.3 shows monthly pulse inflows from the Colorado River and its two main tributaries, averaged over scenario. As indicated by the slope of the linear trendline, model inflows into the Highland Lakes system are decreasing over time, on average. Because of the decreasing supply of inflows, it is reasonable to expect storage levels in the lakes to decrease as well.

Figure 4.3: Average Total Monthly Pulse Inflows and Linear Trendline

Another interesting characteristic of the storage plots pertains to the periodic wavelike nature of storage levels. Historically, both Lakes Buchanan and Travis store water during the non-irrigation period, and then make releases as water demands increase in the rice-growing districts. This pattern is shown clearly in the historical plots, and is also evident in most of the model percentile plots. A noticeable exception is the Lake Buchanan median (50th percentile) storage plot, which shows a larger degree of noise throughout, and a missing peak in year four. The absent peak could be due to the fact that several of the median-level inflow scenarios for the fourth year have low flows for the middle of the year, and very high flows at the end of the year. Peaks do occur in the fourth year for both the 10th and 90th percentile storage plots for Lake Buchanan.

DISCRETE CUMULATIVE DISTRIBUTIONS FOR STORAGE

Another way to examine variations in storage levels is with discrete cumulative distribution plots at given times in the future. Figure 4.4 shows the scenario-based cumulative distribution for Lake Buchanan at time t_6 , or about July 1 of the first year. The five vertical lines in the discrete distribution reveal the effects of the tree structure and nonanticipativity constraints on the model, which group scenarios into five groups of six scenarios each for the first year. All six scenarios in each group maintain identical storage values throughout year one, since the releases within scenario groups are forced to be equal by the constraints of nonanticipativity.

Figure 4.4: Lake Buchanan Cumulative Distribution at July 1, Year 1

The spread of the distribution is fairly significant, ranging from a little over 400 kAF to about 830 kAF, just below capacity. Larger ranges in storage

indicate a higher degree of uncertainty as to the predicted future value. The median storage level is approximately 550 kAF, although the mean is somewhat higher, at about 620 kAF. There is a sharp differentiation between the drier three scenario groups and the wetter two, where storage values jump from 550 kAF to about 800 kAF.

Figure 4.5: Lake Travis Cumulative Distribution at July 1, Year 1

As shown in Figure 4.5, the distribution plot for Lake Travis is similar to that for Lake Buchanan in terms of its overall shape, but is shifted out to higher storage volumes. The shapes of the distributions are similar due to the influence of the space rule, which assigns penalties when the fractional storage volumes of the two reservoirs differ. Higher storage values in general are evident for Lake Travis because of its larger capacity.

Figure 4.6: Lake Buchanan Cumulative Distribution at January 1, Year 2

Moving six months into the future, Figure 4.5 shows the cumulative distribution for Lake Buchanan at time t12, or about January 1 of the second year. The range of possible storage levels has dropped dramatically, covering a span from about 350 kAF to 480 kAF, or a range of approximately 130 kAF. Given the management priorities outlined in the model, water resource planners should have a fairly high degree of certainty that reservoir levels in Lake Buchanan should be near 400 kAF at the beginning of the second year.

As was the case for the earlier time period, the distribution for Lake Travis on January 1 of the second year is similar to that for Buchanan, except shifted to higher storage values. While the model output does show deviations from the space rule from time to time, for the most part relative storage levels stay fairly constant between Lakes Buchanan and Travis within scenario groups.

PLANTED ACREAGE LEVELS

Planted acreage levels for both first- and second-crop rice are critical variables in the Highland Lakes model, and the actual river system. A graph of the 10th, 50th and 90th percentiles for combined irrigated acreage in all districts is shown for the first-crop in Figure 4.7.

Figure 4.7: Predicted 1st Crop Acreage Percentiles for All Districts

The most noticeable feature of the graph is the small magnitude of median levels compared to historical averages for the last three years. First-crop rice for the first year is predicted to be planted on about 79 thousand acres, compared to an average of 77.6 thousand acres planted over 1988 to 1997. Median first-crop acreage levels drop to 44 thousand acres in the third year, and about 25 thousand acres for years four and five. The small acreage levels for the last years are

probably also a byproduct of the low flows and decreasing trend for the inflow scenarios.

The first year decisions show the effect of nonanticipativity constraints, which force all first-crop acres to be the same for the first year. Variability then increases between the percentile groups in years two through four, with the 90th percentile acreage level reaching a peak of about 79 thousand total acres. In year five, however, all three percentiles predict equal acreage levels of about 25 thousand total acres.

The reason for the convergence of percentiles in year five is uncertain, especially given the very nature of the scenario tree, in which the groups of identical scenarios break up over time until all scenarios are unique. The convergence may be related to the final storage benefit equations used to reduce end-of-horizon effects. Since the marginal benefits assigned to final period storage are uniform across all scenarios, this may have an impact on the marginal value of first-crop rice acreage in year five as well.

Second-crop results are shown in Figure 4.8. As with the first-crop results, median acreage levels are significantly below average historical values for the last three years. For second-crop rice, the deviation is even more pronounced, with all percentiles predicting near zero planted acres for year five, and the 10th percentile predicting near zero acreage for the last four years. The 90th percentile acreage remains fairly constant at about 61 thousand acres. Fifth year second-crop acreage levels, like those for the first-crop results, may be influenced by the

end storage benefits, which would reduce the incentive to provide water supplies for irrigation use.

Figure 4.8: Predicted 2nd Crop Acreage Percentiles for All Districts

DIVERSIONS VERSUS INTERRUPTIBLE STORAGE CONTRACTS

In the original Watkins model (Watkins et al. 2000), the interruptible storage contract was the primary decision variable used for optimization. In the newer version, interruptible contracts are highly constrained to follow LCRA's contract decision function. While contract levels are largely dependant on storage volumes, the actual diversions made for irrigation use are less constrained. Figure 4.9 shows predicted contracts, interruptible diversions, run-of-river diversions, and total diversions for all five years. These values were obtained by calculating mean values for each year considering all 30 scenarios.

Figure 4.9: Predicted Interruptible Contracts and Irrigation Diversions

The first data set (column) for each year in Figure 4.9 represents the interruptible contracts set by LCRA based on projected January 1 combined storage levels in Lakes Buchanan and Travis. As shown in the graph, contract amounts remain fairly constant for all five years, falling only slightly from 272 kAF in year one to 255 kAF in year five. Actual interruptible diversions, represented by the second column for each year, are below the contract amount, and become a smaller fraction of the associated contract amount over time. Even though storage levels are high enough to allow for full interruptible contracts, districts sometimes choose not to withdraw their full contract according to the results.

The reasons for irrigators not withdrawing their full contract probably are again related to very low flow conditions for some scenarios. Even if storage in year one is sufficient to meet the full interruptible contract, irrigators may be

hedging against the future, when inflows may drop dramatically. Since Figure 4.9 shows average (mean) results across all scenarios, very dry scenarios may have a significant impact on the expected values shown in the graph.

Likewise, run-of-river diversions also show a decreasing trend over time, starting at about 224 kAF in year one, just short of the maximum annual supply of about 230 kAF, to 180 kAF in year five. Since available run-of-river supplies for the model were set equal across scenarios, and repeat identical supplies for each year, it initially seems counterintuitive for the districts to not withdraw all run-of-river supplies every year. As mentioned earlier, run-of-river water is assumed, for the purposes of this model, to come from a source external to the river. Consumptive use of the run-of-river supply would have no negative impact on other water demands, and return flows from run-of-river use would in fact help meet the bay and estuary flow requirements.

Acreage levels and water deficits are, however, linked between the irrigation districts through the equity constraints in equations (3.28), (3.33) and (3.34). These constraints may result in acreage levels being limited in certain districts, such that the crops in those districts may not require the full run-of-river supply for all months. Available run-of-river supplies, as shown in equations (3.63), are indexed by irrigation district, so it is possible for one district to use up all its run-of-river supplies while being unable to access unused supplies from another district. If the acreage equity constraints prevented an underutilizing district from boosting its crop base to make use of the available run-of-river water, unused supplies would result.

Understanding of the complex relationship between the interruptible contracts, acreage planting decisions, equity constraints, and water diversions would be greatly enhanced by the use of more realistic inflow scenarios, and diversions and planted acreage should increase as a result of higher flow values.

RECREATION BENEFITS

While recreation is considered a less important water demand by LCRA than municipal and irrigation supplies, it is still an important component of the Highland Lakes system. For the base case, the model used a weight of 0.1 for recreation benefits to represent its subordinate status. Results showing annual recreation benefit percentiles for Lakes Buchanan and Travis combined are shown in Figure 4.10.

Figure 4.10: Annual Recreation Benefit Percentiles for Buchanan and Travis

Since recreation benefits for the lakes are linear functions of the reservoir storage levels, it is not surprising that benefit levels closely follow the storage percentile plots in Figures 4.1 and 4.2. Median recreation revenues show a steady decline in years one through four, followed by an increase in the fifth year.

As described in chapter three, previous studies have been done to estimate the economic effect of recreation for the Highland Lakes (U.S. Army Corps of Engineers 1994). Baseline recreation expenditures by boaters were estimated in the Army Corps study to be about \$13 million and \$47 million annually for Lakes Buchanan and Travis, respectively. Since historical average reservoir storage levels are slightly greater on average than the 90th percentile storage values for the base case Highland Lakes model, and since 90th percentile annual combined reservoir recreation benefits for the base case predict around \$50 million in revenue for both lakes combined per year, estimates of annual benefit levels seem to agree nicely between the two sources. This is to be expected, since recreation benefits in the Highland Lakes model are calculated using the procedures from the Army Corps report.

Recreation use of the lakes is highest during the summer months, and drops off during the winter. To see the seasonal nature of recreation use, combined with the variability in lake storage levels, Figure 4.11 shows mean monthly recreation benefits over the five-year time horizon. The mean values were calculated by averaging over all scenarios for each time step.

Figure 4.11: Mean Monthly Recreation Benefits for Lakes Buchanan and Travis

Recreation revenues increase during the summer months, partially due to peaks in storage levels early in the season, and also because of increased recreational use. The effect of increased recreational use during the summer months is represented in the model by separate sets of coefficients for the linear storage-benefit relationships based on the time of year, as expressed in equations (3.49).

HYDROPOWER GENERATION

While precise analysis of hydroelectric generation is not possible using monthly time steps, some information can be gained by examining predicted power generation. Generation can be measured either in terms of instantaneous power, measured in megawatts (MW), or in energy production over a certain

length of time, measured in kilowatt- or megawatt-hours (kWh or MWh). Figure 4.12 shows hydropower percentiles for combined generation from all reservoirs.

Figure 4.12: Combined Hydropower Percentiles for All Reservoirs

Hydropower generation has been approximated in the model as a linear function of reservoir releases. Figure 4.12 therefore should closely resemble the graph of total reservoir releases plotted over time. Generation levels are in general far below the total capacity of 270 MW, and are probably also heavily influenced by the low-flow nature of the inflow scenarios.

For the median plot of hydropower, five smaller peaks are centered around the June and July months, which tend to be the months of highest irrigation water demand for the downstream rice farms. Two additional peaks of much higher magnitude are also evident in the December months at the end of the first and second years. Examination of mean inflows in Figure 4.3 and median storage

levels in Figures 4.1 and 4.2 shows that these hydropower peaks seem to precede large inflows, and occur during sharp but short-term drops in storage volumes.

For energy production, Figure 4.13 shows mean monthly hydroelectric generation in terms of GWh. The peaks, to a large degree, follow those in Figure 4.12. Total generation for all 60 months was about 1,080 GWh.

Figure 4.13: Mean Combined Electrical Generation for All Reservoirs

SENSITIVITY ANALYSES

Several tests were conducted on the sensitivity of the model to various parameters, including the weights on recreation benefits, power generation, final storage, storage equity, acreage in production, and acreage equity. Beginning storage levels were also increased to capacity levels to study the effect of changing initial conditions. A brief summary of some of the most important results is included in this section.

The model uses three main performance variables, named CRPTOT, RECTOT, and HYDTOT, to measure rice crop revenues, recreation benefits, and hydroelectric benefits, respectively. These variables are useful in assessing changes during sensitivity analysis, and are used, along with other indicators, in the procedures that follow.

Weight on Recreation Benefits

A weight is applied to recreation benefits in the objective function to reduce its influence relative to other demands such as municipal and irrigation needs. To study the effect of the coefficient, the weight, ω_1 , was changed from 0.1 to 1.

As expected, increasing the weight resulted in significantly higher recreation benefits. Table 4.1 shows that average annual recreation benefits increased by about 45% over the base case. Hydropower benefits also increase slightly, while agricultural revenues decrease by about 36%.

Perhaps the most striking effect of the recreation weight adjustment involves predicted storage levels for two reservoirs. Figure 4.14 shows median storage levels for the base case and the adjusted model, along with the historical average (mean) storage levels, for Lake Travis.

Figure 4.14: Lake Travis Storage Changes for Recreation Sensitivity Test

As shown in Figure 4.14, storage levels increase significantly for Lake Travis as a result of increasing the recreation coefficient. Median storage levels slightly surpass historical average levels, and the shape of the storage peaks more closely resembles the historical average plot. Storage for Lake Buchanan, although not shown, drops in response, since the marginal benefit of recreation in Lake Travis is higher than that for Lake Buchanan. This downstream shift in storage is made possible since the effect of the space rule, which attempts to balance fractional storage levels between the two lakes, is no longer sufficient to prevent large storage differences. Increasing the weight on recreation benefits promotes storage in Lake Travis at the expense of irrigation demands, and equitable sharing of storage between Lakes Buchanan and Travis becomes

impossible. It is also important to note that while no municipal water deficits result from the modified coefficient, irrigation deficits do occur. No deficits are experienced in any of the irrigation districts under base conditions.

Weight on Hydropower Generation

Under the base case, the weight on hydropower, ω_2 , was set according to approximate current electricity prices, or about 5 cents per kilowatt-hour (kWh). A sensitivity test was conducted by reducing the value of the coefficient to 1 cent per kWh, and a summary of the results can be seen in Table 4.1.

For the most part, there are few noticeable changes from the base case results. Although hydropower benefits in monetary terms decrease, actual hydro production is basically identical to the base case. The base case predicts 216 GWh of electrical generation per year, while the sensitivity test estimates about 211 GWh annually. Effects on other optimization components are minimal, with second-crop acreage levels increasing slightly, but first-crop levels declining.

The weight on hydropower does not appear to play a significant role in the overall objective function. Setting the weight at a value approximately equal to current energy prices would seem to be a reasonable modeling choice.

Weight on Final Storage

The original Watkins model dealt with end-of-horizon effects by using a final storage constraint that set a minimum level for scenario-averaged final storage volumes (Watkins et al. 2000). While this technique was a softer constraint that allowed for variation across scenarios, a number of these variations were extreme. In response, the new model was changed to employ final storage

benefits, which provided uniform benefits across scenarios to prevent reservoirs from draining toward the end of the planning horizon.

Coefficients on the final storage benefits were set for the base case by trial and error, and through examining resulting storage levels. Initially the coefficients were set equal for both Lakes Buchanan and Travis, but doing so resulted in several of the drier scenarios producing zero storage levels in Buchanan. For low-flow scenarios with available storage in downstream Lake Travis, the model apparently took advantage of hydropower generation through Lake Buchanan, and subsequent storage in Lake Travis. To alleviate this effect, the benefit coefficient for Lake Buchanan was set slightly larger than that for Lake Travis. The results, shown in Figures 4.1 and 4.2, show comparable relative storage levels for time periods near the end-of-horizon.

As an example of the effect caused by increasing the benefit coefficients, Table 4.1 shows some of the key performance data for the modified model, which uses coefficients with twice the magnitude of the base case. Crop revenues fell relative to the base case, as did hydropower benefits. Recreation benefits grew slightly over the base case.

The resulting storage levels clearly show the effect of increasing final storage benefits, as shown in Figure 4.15. The graph shows median storage values for the base case and for the “adjusted” case with increased end-storage coefficients. Storage levels remain basically identical through most of the planning period, but begin to diverge after about the third year. The divergence

remains fairly minor until about the last year, when the modified version predicts significantly higher storage volumes.

Figure 4.15: Lake Buchanan Storage Changes for End Storage Sensitivity Test

Magnitude of Initial Storage

In the base case, initial storage conditions for Lakes Buchanan and Travis were set at 57.6% and 62.7% of capacity, respectively, or 500 and 700 kAF. A sensitivity test on initial storage conditions was conducted by increasing initial storages for both reservoirs to capacity levels.

Increasing initial storage levels differs from the other sensitivity tests in that new water has been introduced into the system. As a result, and as shown in Table 4.1, all three major performance indices increase in magnitude. Acreage

levels increase for the first few years in response to the added water supply, and hydropower generation also accrues greater revenues.

The effect of increasing initial storage appears to be relatively localized to earlier time periods, as shown in the plot of median storage levels for Lake Travis in Figure 4.16.

Figure 4.16: Lake Travis Storage Changes for Initial Storage Sensitivity Test

As was the case when final storage constraints were altered, changes to beginning storage values appear to have an effect for a duration of about one year. For planning purposes, initial storage levels could be set to actual present volumes to eliminate this effect entirely.

Weight on Space Rule

The space rule for the Highland Lakes model penalizes fractional storage differences between Lakes Buchanan and Travis, and assigns a weight to this penalty defined by the coefficient α_1 . For the base case, the magnitude of the weight was determined experimentally, and set at a value of \$700 per fractional difference in storages. To test the sensitivity of this coefficient, the weight was reduced to \$100 per fractional deviation.

Figure 4.17: Lake Buchanan Storage Changes for Space Rule Sensitivity Test

From Table 4.1, gains are apparent for recreation and hydropower generation benefits over the base case, and crop revenues are almost unchanged. The primary difference, however, is the extreme change in storage levels, especially for Lake Buchanan. Figure 4.17 shows the changes in median storage

levels from the base case for Lake Buchanan. Because of the reduced evaporation rates and higher marginal recreation benefits for Lake Travis, along with the ability to release additional water through the Lake Buchanan (Buchanan Dam) hydro plant, reducing the weight on the space rule significantly drains Lake Buchanan and fills Lake Travis.

It is important to note that flood control benefits have not been accounted for in the model, except perhaps explicitly through reservoir capacity limits. Keeping available storage in Lake Travis for potential flood events is important, and practical, and the low-flow nature of the inflow scenarios should tend to underestimate flood control benefits. Maintaining an adequate magnitude for the space rule penalty coefficient is obviously important to account for externalities, including flood control, and to more closely represent actual reservoir operations.

Weight on Acreage Benefits

Acreage levels for first- and second-crop rice are maximized in the objective function through the CRPTOT variable, and are assigned coefficients to estimate their marginal benefits. For the base case, coefficients were based on data from the Texas A&M Agricultural Extension Service (Rister et al 1989). More recent information from the Lyndon B. Johnson (LBJ) School of Public Affairs at the University of Texas at Austin is available for profits from rice production based on crop acreage (Schultz 1996), although this data may overestimate profits because they do not include expenses related to water delivery. Despite these limitations, the LBJ data were used to assess the importance of the rice acreage benefit coefficients. Coefficients for first- and

second-crop acreage were increased from \$31.84 and \$18.53 per acre to \$116 and \$37 per acre, respectively.

The summary results in Table 4.1 show that crop revenues increased significantly while recreation benefits suffered minor losses, and hydropower generation rose slightly due to an increase in reservoir releases. A growth in acreage under production was observed for all years for the first-crop, as shown in Figure 4.18.

Figure 4.18: 1st Crop Acreage Percentiles for Crop Benefit Sensitivity Test

First-crop acreage levels increased from the base case for each year, but particularly for years three through five, where median levels jumped by over 40 thousand acres.

Second-crop acreage, however, declined as a result of the coefficient change. Comparing Figure 4.19 with Figure 4.8 shows that median second-crop

acreage levels for years one and two dropped by about 30 thousand acres, and 90th percentile acreage was reduced by approximately 30 thousand acres in year four.

Figure 4.19: 2nd Crop Acreage Percentiles for Crop Benefit Sensitivity Test

The shift from second- to first-crop production should be expected, since the magnitude of the first-crop coefficient increased relative to the second-crop coefficient for the sensitivity test. The fact that second-crop acreage levels decreased even though the second-crop coefficient increased in absolute terms indicates that total crop acreage levels are highly constrained by the available irrigation water supply.

Weight on Acreage Equity

The current version of the Highland Lakes model assigns penalties through elastic variables when fractional acreage levels in any district deviate

from the inter-district average. The weight applied to the elastic variables is called kh , which was given a value of 1,150 for the base case. This magnitude was determined by varying the coefficient until the maximum fractional deviation for all districts and scenarios was below 25%.

A sensitivity test was performed on the acreage equity coefficient by reducing the penalty to 500. The summary results in Table 4.1 show very little change in any of the three major categories, including crop revenues. Crop revenues increased only slightly, while recreation and benefits were unaffected.

Acreage levels for both first- and second-crop production remained basically unchanged, except for minor fluctuations. Figure 4.20 shows the sensitivity results for first-crop production levels, which are nearly indistinguishable from the base case results in Figure 4.7.

Figure 4.20: 1st Crop Acreage Percentiles for Acreage Equity Sensitivity Test

These results suggest that the weight associated with the acreage equity constraints is not very important for the overall objective. As an alternative approach for future models, it may be preferable to use hard constraints, rather than penalizing slack variables, for the acreage equity equations. Specifying maximum ranges of deviations from average fractional acreage levels might allow for greater model flexibility, and could help take advantage of the higher water efficiency levels in some districts. Because of infeasibility concerns, these adjustments weren't made for the current version of the Highland Lakes model, but future versions may use this altered approach. Using hard constraints may help to avoid some of the initial calibration work necessary with the soft constraint method.

Table 4.1: Sensitivity Test Changes as a Percentage of Base Case			
Sensitivity Adjustment	CRPTOT	RECTOT	HYDTOT
Recreation Coefficient Increased to 1.0	-36.02	+44.99	+3.14
Power Coefficient Reduced to 1 ¢/kWh	-3.41	+0.11	-80.42
Final Storage Coefficients Increased $\times 2$	-21.80	+8.21	-6.73
Initial Storage Levels at Capacity	+5.45	+15.67	+22.78
Space Rule Penalty Reduced to 100	+0.35	+32.80	+9.07
Acreage Benefit Coefficients Increased	+359.02	-8.09	+4.05
Acreage Equity Penalties Reduced to 500	+1.02	+0.04	-0.03

Chapter 5: Conclusions

A multistage stochastic optimization model using linear programming was developed, building on earlier research (Watkins et al. 2000), to provide planning tools for LCRA in the operation of the Highland Lakes system. A framework was also created for examining the operation of four irrigation districts, including three currently owned by LCRA, which makeup the largest water demand on the Lower Colorado River. Three primary objectives were maximized in the optimization process: (1) revenues from rice production, (2) recreation benefits associated with lake use, and (3) revenues from hydropower generation. Secondary objectives included minimization of municipal and irrigation water deficits, assigning benefits to final storage in order to reduce end-of-horizon effects, and other minor linearization and equity purposes.

Capabilities added to the new model include the use of weather-dependant irrigation demands, a linear approximation of LCRA's interruptible contract decision function, a modified space rule for Lakes Buchanan and Travis, a linear approximation for calculating hydropower production, inclusion of municipal and irrigation return flows, minimum bay and estuary flow requirements, and other features. The new capabilities allow for a more accurate representation of the Colorado River system, and should help produce more realistic results.

While the inflow scenarios, because of the way in which they were produced, tended to underestimate available water supplies, preliminary results were still useful in predicting reservoir storage levels, acreage production levels,

recreation benefits, hydropower generation, and interruptible water contracts. Model weights and coefficients were calibrated to reflect actual market prices and economic constraints, or to represent water management priorities. Results also showed that the end-of-horizon effect, minimized in the model by rewarding end storage, is limited to about the last year of the time horizon. Water management officials may wish to disregard the results from the last year, and focus on the first four years for planning purposes.

MODEL APPLICATIONS

Much of the work done by LCRA in the past for water planning has focused on using deterministic methods (Watkins et al. 2000), which assume that future meteorological conditions are known. Ignoring the stochastic nature of streamflows, evaporation rates, rainfall, and other processes can have detrimental impacts on the accuracy of planning models (Loucks et al. 1981). This is especially important for a system such as the Colorado River basin, where perennial flows can experience high variability due to frequent storm events, and regular droughts.

Stochastic optimization is able to account for meteorological uncertainty by considering the probabilistic structure of events, and using scenarios that preserve the moments of the original probability distributions. For the Highland Lakes model, this means that river inflow and other meteorological scenarios can be produced that accurately represent the realm of possibilities faced by water planners at LCRA. By using the operating policy followed through the interruptible contract function, and assigning benefits to other water uses, the

model predicts optimum acreage levels, reservoir storage levels, reservoir releases, and other decisions, in order to maximize total benefits in the system. This information can be used to evaluate possible future conditions, while also suggesting appropriate immediate actions.

CDF Curves

One planning tool provided by the model in particular that could be useful for LCRA is the discrete cumulative distributions for reservoir storage volumes, which provide statistical inferences as to future operating levels. Understanding the probability of retaining a certain amount of storage at a given time in the future is extremely beneficial for ensuring the availability of municipal and irrigation water supplies. It could also allow LCRA to make modifications in short-term reservoir releases to increase hydropower efficiencies and total energy production. Given that Texas has now begun to deregulate its electrical markets, this could be of increasing importance in order for LCRA to remain a competitive power provider.

Planted Acreage Levels

While the relations for acreage under production, water demands, and crop revenues in this model are fairly simple representations of complex processes, the Highland Lakes model does provide basic information as to optimal acreage levels. Water efficiencies are accounted for in the water demand regressions, and simple profit margins were used for determining profits from rice production. Predicted acreage levels provide a useful source of information as to how to best distribute limited irrigation supplies and minimize crop water deficits. With

municipal demands for Colorado River water expected to continue to rise, and with LCRA owning all water rights for the four irrigation districts and managing all but the smallest district, the acreage levels from the model results could provide an objective suggestion if tough choices must be made in the future as to allowable rice acreage levels.

FUTURE MODEL REFINEMENTS

Over the course of model development, several suggestions were made as to possible future refinements to improve the Highland Lakes model. Some of the most important modifications that could be made are included in this section.

As noted earlier, the inflow scenarios used for this research were constructed for the original Watkins model, and do not include water supplies that should be available for the current model version. Using the SPIGOT scenario generation program, while following an accurate representation of water rights and allocation seniority, should provide better results, and more closely approximate the stochastic nature of the streamflows. Autocorrelation between years should also improve by using the SPIGOT techniques.

Also related to scenario generation, meteorological conditions for the irrigation districts, along with evaporation rates for the reservoirs, could be included in the generation procedure in order to preserve cross-correlation with the Highland Lake inflows. Much of the data for meteorological conditions have already been indexed by scenario to allow for this future improvement.

Incremental flows below the Highland Lakes should also be included in later models. Currently, the model assumes that incremental flows are equal to

the run-of-river diversions made by irrigation districts. This assumption was made because of the highly variable nature of downstream incremental flows, along with the complex legal and accounting principles associated with run-of-river supplies. Future efforts could be made to tackle these complicated challenges, and incremental flows could also be indexed by scenario, and included in the SPIGOT generation process.

Some time was spent considering representing scenarios with string structures rather than a scenario tree. Recent investigations have found that using a string form to represent scenarios can have advantages over tree structures (Rush et al. 2000), although ensuring nonanticipativity may present special challenges with the Highland Lakes model. Since current versions of SPIGOT do not automatically generate scenarios in tree form, there are additional logistical and practical reasons for considering the use of scenario strings. Further research should be done to determine if using a string form would improve the results and ease-of-use of the Highland Lakes model.

Earlier versions of the model maximized run-of-river and interruptible diversions rather than acreage levels, assigning weights to interruptible benefits equal to the price LCRA charges the districts for stored supplies. There may be some advantages in keeping interruptible diversions within the objective function, especially from an accounting perspective for LCRA. This can easily be done with a simple modification of the current model if it is later deemed necessary. Similarly, acreage levels may be deterministically fixed to average historical levels, rather than using acreage as a decision variable.

While the current model uses LCRA's interruptible contract function as a constraint, and assigns large penalties through elastic variables to prevent the function from being violated, future work could examine alternative contract policies, as done with the original Watkins model (Watkins et al. 2000) and other studies (Martin 1992). Some work was done to evaluate various decision rules, as outlined in Appendix C, but infeasibility problems prevented a thorough investigation. Newer inflow scenarios, along with updates made to the model since the decision rule tests were conducted, could enable more detailed studies of alternative storage policies for Lakes Buchanan and Travis.

Another improvement that could be made to the model involves the economic and production aspects related to irrigation district acreage decisions. The Highland Lakes model currently uses simple crop profit coefficients, along with water demand regressions based on acreage and climate conditions, to determine acreage levels. Future versions could include more detailed analyses of crop production using advance deficiency payments, market prices for rice, and other economic factors. Studies of this kind have already been done specifically for LCRA rice districts (Schultz 1996). Since the current model version assumes that all districts take water from the same diversion point, these new economic capabilities for individual districts could be enhanced by spatially differentiating the districts, and accounting for diversions in the appropriate order.

The objective function now includes several elastic variables related to equity constraints, such as those used with the space rule, acreage equity constraints, and irrigation deficit sharing equations. Rather than using soft

constraints and penalizing deviations, hard constraints could be set to prevent deviations greater than a certain magnitude. Irrigation district acreages could, for example, be constrained by only allowing for deviations from inter-district fractional averages below a certain level, such as 25%. This technique would be similar to the original reservoir space rule, as described in chapter three. Hard constraints would eliminate the present need for careful evaluation of the weights assigned to elastic variables, but could also introduce new infeasibility problems.

In examining the predicted water demands for irrigation districts, the regressions designed by LCRA seemed at times to overestimate demands, given recent water use data. This could be due to the fact that significant water conservation efforts have recently been made in the districts, while the regressions are derived from water demand data dating back to 1968. It may be desirable to design new water demand relationships that consider contemporary water use practices. This could be especially important if there is ever an effort to strictly enforce the 5.25 ft/acre-foot surface water irrigation limit described in LCRA's Water Management Plan (LCRA 1999). Water use regressions for Pierce Ranch would also be helpful, although the widespread production of crops other than rice in the district may make it difficult to evaluate rice water demands separately.

Alternative system performance criteria could also be included in evaluating results from the Highland Lakes model. Presently, statistics on crop revenues, recreation benefits, and hydropower revenues serve as a base for examining model output, but other criteria have been developed in the literature. Performance measures such as reliability, resiliency, and vulnerability, are

effective tools in evaluating a system's ability to meet, or return to, a target level (Lund and Guzman 1996). Determining the type of targets used for the Highland Lakes model may be difficult, however, especially since standard model results predict no municipal or irrigation water deficits.

As described in chapter three, the current space rule for dividing storage between Lakes Buchanan and Travis uses a single coefficient to penalize deviations from equal fractional storage levels. Since actual LCRA policies allow greater levels of deviation in some months, coefficients could be indexed by time, and weighted to mimic actual operation policies. Likewise, minimum bay and estuary flow requirements could be indexed by time to better meet the seasonal needs of aquatic habitat.

While some sensitivity testing was performed on the coefficients used to translate reservoir releases into hydropower generation, a nonlinear form of the Highland Lakes model could be constructed to evaluate the effect of variable pool elevations on hydro production. The sensitivity tests that were performed showed little change when coefficients based on different reservoir elevations were used, indicating that releases, rather than storage levels, tend to dominate hydropower generation under normal operating ranges.

Since the model was developed, it was learned that Pierce Ranch no longer has access to run-of-river water supplies since LCRA purchased the district water rights in 2000 (Kabir 2002). The district can now only obtain interruptible water supplies from LCRA, at a rate of \$4.50/acre-foot. Future models could

represent this fact, although the small size of the district likely means that model results will not be significantly changed.

Finally, output files for the Highland Lakes model have currently been designed mainly for problem-solving and calibration purposes related to the model formulation. Future output files could be created to provide more user-friendly information, and could be formatted to be compatible to the specific needs and designs of LCRA water management officials.

Appendix A: GAMS Code

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*
*      A 3-STAGE LP MODEL FOR THE HIGHLAND LAKES, LCRA
*      Scenario tree built empirically from historical data
*      5 branches in first stage, 3 in second, 2 in third
*
*      Original Model developed by David Watkins, March 7,1996
*
*      Revised and updated by Dr.'s Daene McKinney, Leon Lasdon, Dave Morton,
*      David Watkins, and Mr. David Kracman
*      The University of Texas at Austin
*      Last updated Apr. 24, 2002.
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$OFFSYMXREF OFFSYMLIST

SETS
  S      hydrologic scenario      /S1*S30/
  SA(S)  1st year subset of S     /S1,S7,S13,S19,S25/
  SB(S)  2nd year subset of S     /S1,S3,S5,S7,S9,S11,S13,S15,
                                   S17,S19,S21,S23,S25,S27,S29/
  RS      reservoirs              /Buchanan, Inks, LBJ, MarbleFalls, Travis, Austin/
  SRS(RS) storage reservoirs      /Buchanan, Travis/
  RRS(RS) recreation reservoirs   /Buchanan, Travis/
  PRS(RS) pass-through reservoirs /Inks, LBJ, MarbleFalls, Austin/
  ID      irrigation districts     /Lakeside, Garwood, Pierce, GulfCoast/
  T        time period            /T1*T60/
  TC(T)   interrupt. contract periods /T1,T13,T25,T37,T49/
  TI(T)   time periods for irrigation /T3*T10,T15*T22,T27*T34,T39*T46,T51*T58/
  TI1(T)  time periods for 1st crop /T3*T7,T15*T19,T27*T31,T39*T43,T51*T55/
  TI2(T)  time periods for 2nd crop /T8*T10,T20*T22,T32*T34,T44*T46,T56*T58/
  YR1(T)  time periods for first year /T1*T12/
  YR2(T)  time periods for second year /T13*T24/
  WIN(T)  winter months           /T1*T5,T9*T17,T21*T29,T33*T41,T45*T53,T57*T60/
  SUR(T)  summer months          /T6*T8,T18*T20,T30*T32,T42*T44,T54*T56/
  I        index in first year     /1*5/;

SCALARS
  W1      weight on recreational benefit      /0.1/
  W2      price of power ($1000 per kWh)      /0.00005/
  alpha_1 weight on space rule ($1000 per fractional difference) /700/
  CA1     acreage 1st crop benefit coefficient ($ per acre)      /31.84/
  CA2     acreage 2nd crop benefit coefficient ($ per acre)      /18.53/
  CC      penalty for withdrawing muncpal firm water ($ per acre) /0.00001/
  CD      penalty for withdrawing interruptible water ($ per acre) /0.00001/
  CU1     penalty for not meeting 1st crop irrigation demands {$ per AF) /120/
  CU2     penalty for not meeting 2nd crop irrigation demands ($ per AF) /100/
  CM      penalty for not meeting municipal demands {$ per AF)   /600/
  RES     reserve storage (kAF)                /200/
  DCOA    City of Austin annual municipal water demand (kAF)     /160/
  FRMC    City of Austin annual firm water LCRA contract (kAF)    /325/
  MWR     City of Austin annual run-of-river water right (kAF)     /294/
  frac_A  fraction of COA diversions returning as return flows     /0.55/
  frac_R  fraction of irrigation diversions returning as return flows /0.30/
  YL      minimum interruptible contract (kAF) /188.387/
  YU      maximum interruptible contract (kAF) /272/
  YM      interruptible contract line segment slope                /0.092903/
  YB      interruptible contract line segment intercept            /169.807/
  KEV     penalty on deviations from LCRA interruptible function
  KG      penalty on deviations from irrigation deficit sharing
  KH      penalty on deviations from irrigation acreage differences /1150/

```

PR	penalty on releases above normal range (\$ per AF)	/1000/
BAYMIN	minimum bay and estuary flow for Matagorda Bay (kAF)	/14.26/ ;

PARAMETERS

K(RS)	reservoir conservation pool capacities (kAF)	
	/	
	Buchanan	868.122
	Inks	14.992
	LBJ	113.691
	MarbleFalls	5.718
	Travis	1115.775
	Austin	21.278
	/	
FRAC_I(RS)	initial storage fraction of conservation pool	
	/	
	Buchanan	0.576
	Inks	0.934
	LBJ	0.983
	MarbleFalls	0.899
	Travis	0.627
	Austin	0.965
	/	
RHI(RS)	maximum recommended reservoir release (kAF per month)	
	/	
	Buchanan	500
	Inks	500
	LBJ	500
	MarbleFalls	500
	Travis	500
	Austin	500
	/	
FF(T)	fraction of municipal water demanded in period t	
	/	
	(T1,T13,T25,T37,T49)	.062
	(T2,T14,T26,T38,T50)	.062
	(T3,T15,T27,T39,T51)	.065
	(T4,T16,T28,T40,T52)	.077
	(T5,T17,T29,T41,T53)	.080
	(T6,T18,T30,T42,T54)	.095
	(T7,T19,T31,T43,T55)	.116
	(T8,T20,T32,T44,T56)	.122
	(T9,T21,T33,T45,T57)	.098
	(T10,T22,T34,T46,T58)	.083
	(T11,T23,T35,T47,T59)	.072
	(T12,T24,T36,T48,T60)	.068
	/	
RECW(RRS)	maximum monthly winter recreation benefits (\$1000)	
	/	
	Buchanan	619
	Travis	2240
	/	
RECS(RRS)	maximum monthly summer recreation benefits (\$1000)	
	/	
	Buchanan	2480
	Travis	8950
	/	
RECINTW(RRS)	recreation benefit intercept for reservoirs in winter (\$1000)	
	/	
	Buchanan	-914
	Travis	-1221
	/	

RECINTS (RRS)	recreation benefit intercept for reservoirs in summer (\$1000)
	/
	Buchanan -365.4
	Travis -4890
	/
RECSLPW (RRS)	recreation benefit slope for reservoirs in winter (\$ per AF)
	/
	Buchanan 1.744
	Travis 3.5
	/
RECSLPS (RRS)	recreation benefit slope for reservoirs in summer (\$ per AF)
	/
	Buchanan 6.98
	Travis 13.98
	/
W3 (SRS)	benefit for retaining storage in last time step (\$ per AF)
	/
	Buchanan 20.00
	Travis 17.00
	/
DAY (T)	number of days in period t for hydropower calculations
	/
	(T1,T13,T25,T37,T49) 31
	(T2,T14,T26,T38,T50) 28.25
	(T3,T15,T27,T39,T51) 31
	(T4,T16,T28,T40,T52) 30
	(T5,T17,T29,T41,T53) 31
	(T6,T18,T30,T42,T54) 30
	(T7,T19,T31,T43,T55) 31
	(T8,T20,T32,T44,T56) 31
	(T9,T21,T33,T45,T57) 30
	(T10,T22,T34,T46,T58) 31
	(T11,T23,T35,T47,T59) 30
	(T12,T24,T36,T48,T60) 31
	/
PMAX (RS)	hydro turbine maximum capacities (MW)
	/
	Buchanan 49
	Inks 15
	LBJ 54
	MarbleFalls 34
	Travis 100
	Austin 18
	/
MP (RS)	energy generated per flow volume for each reservoir (MW*d per kAF)
	/
	Buchanan 4.58
	Inks 1.95
	LBJ 2.97
	MarbleFalls 1.77
	Travis 6.50
	Austin 2.19
	/
bG1 (ID)	irrigation demand regression factors for first crop gross lake evap
	/
	Lakeside 1.1642
	Garwood 1.4888
	Pierce 1.4888
	GulfCoast 1.0435
	/

bG2(ID)	irrigation demand regression factors for second crop gross lake evap
	/
	Lakeside 2.1016
	Garwood 1.3695
	Pierce 1.3695
	GulfCoast 1.9096
	/
bR1(ID)	irrigation demand regression factors for first crop rainfall
	/
	Lakeside -0.2592
	Garwood -0.1951
	Pierce -0.1951
	GulfCoast 0.0000
	/
bR2(ID)	irrigation demand regression factors for second crop rainfall
	/
	Lakeside -0.5230
	Garwood -0.2310
	Pierce -0.2310
	GulfCoast -0.6497
	/
bA1(ID)	irrigation demand regression factors for first crop acreage
	/
	Lakeside 1.1356
	Garwood 0.0000
	Pierce 0.0000
	GulfCoast 0.0000
	/
bC1(ID)	irrigation demand regression constants for first crop
	/
	Lakeside 15.6650
	Garwood 8.1434
	Pierce 8.1434
	GulfCoast 83.9288
	/
bC2(ID)	irrigation demand regression constants for second crop
	/
	Lakeside 7.5010
	Garwood 21.3447
	Pierce 21.3447
	GulfCoast 47.0513
	/
ACRMX(ID)	acreage capable of being serviced today in districts (1000 acres)
	/
	Lakeside 28.000
	Garwood 77.600
	Pierce 18.000
	GulfCoast 41.000
	/
*Pierce max acreage has been set according to Pierce Ranch management 2002 data	
*The other three are set according to LCRA max serviceable acreage levels	
ACRMN(ID)	minimum irrigation district acreage (5 percent 1968-1997 min) (1000 acres)
	/
	Lakeside 0.9314
	Garwood 0.7387
	Pierce 0.1421
	GulfCoast 0.9674
	/

```

ACR1AV(ID)      average irrigation district 1st crop acreage (1988-97 ave) (1000 acres)
/
Lakeside        26.212
Garwood         19.344
Pierce          5.704
GulfCoast       26.362
/

ACR2AV(ID)      average irrigation district 2nd crop acreage (1988-97 ave) (1000 acres)
/
Lakeside        19.814
Garwood         16.582
Pierce          3.051
GulfCoast       11.955
/

EQ(ID)          average irrigation district fraction of total water demand (1988-97 ave)
/
Lakeside        0.310
Garwood         0.234
Pierce          0.086
GulfCoast       0.370
/

```

;

TABLE FI1(T,ID) fraction of first crop irrigation water demanded in time t
*These fractions are derived from 1988 to 1997 water use averages

	Lakeside	Garwood	Pierce	GulfCoast
(T3,T15,T27,T39,T51)	0.001	0.005	0.051	0.031
(T4,T16,T28,T40,T52)	0.061	0.112	0.142	0.096
(T5,T17,T29,T41,T53)	0.266	0.274	0.234	0.216
(T6,T18,T30,T42,T54)	0.329	0.309	0.298	0.324
(T7,T19,T31,T43,T55)	0.343	0.300	0.274	0.332

;

TABLE FI2(T,ID) fraction of second crop irrigation water demanded in time t
*These fractions are derived from 1988 to 1997 water use averages

	Lakeside	Garwood	Pierce	GulfCoast
(T8,T20,T32,T44,T56)	0.413	0.420	0.486	0.485
(T9,T21,T33,T45,T57)	0.410	0.459	0.314	0.346
(T10,T22,T34,T46,T58)	0.177	0.121	0.200	0.170

TABLE DIV(T,ID) average irrigation district total water diversion (kAF)
*These values are derived from 1988 to 1997 water use averages

	Lakeside	Garwood	Pierce	GulfCoast
(T3,T15,T27,T39,T51)	0.103	0.307	1.156	3.315
(T4,T16,T28,T40,T52)	4.782	6.560	3.233	10.230
(T5,T17,T29,T41,T53)	20.723	16.020	5.320	22.997
(T6,T18,T30,T42,T54)	25.638	18.044	6.768	34.525
(T7,T19,T31,T43,T55)	26.748	17.538	6.217	35.335
(T8,T20,T32,T44,T56)	21.196	16.410	5.917	23.193
(T9,T21,T33,T45,T57)	21.042	17.935	3.820	16.531
(T10,T22,T34,T46,T58)	9.095	4.741	2.439	8.111

;

* Read inflow data

\$INCLUDE "inflow.txt"

* Read evaporation data

\$INCLUDE "eva.txt"

\$INCLUDE "evb.txt"

```

* Read irrigation climate data

$INCLUDE "GLE.txt"
$INCLUDE "RAIN.txt"

* Read available run-of-river irrigation water
$INCLUDE "FROR.txt"

VARIABLES
Y(TC,S)                interruptible water contracts (kAF)
R(RS,T,S)              total release from reservoirs in period t scenario s (kAF)
RHYDRO(RS,T,S)         hydro release from reservoirs in period t scenario s (kAF)
RSPILL(RS,T,S)         spill release from reservoirs in period t scenario s (kAF)
RPLUS(RS,T,S)          reservoir release above recommended limit (kAF)
RTRN(T,S)              City of Austin return flows below Lake Austin (kAF)
RBAS(T,S)              Colorado River flow at Bastrop (below COA return flows) (kAF)
INTR(ID,T,S)           interruptible irrigation diversions made each month (kAF)
INT1(ID,TC,S)          interruptible diversions made for first crop (kAF)
INT2(ID,TC,S)          interruptible diversions made for second crop (kAF)
ROR(ID,T,S)            run-of-river irrigation diversions made each month (kAF)
ROR1(ID,TC,S)          run-of-river diversions made for first crop (kAF)
ROR2(ID,TC,S)          run-of-river diversions made for second crop (kAF)
BAY(T,S)              remainder of downstream flow after irrigation diversions (kAF)
P(RS,T,S)             power generated for a reservoir during a month (MW)
ACR1(TC,S,ID)          first crop planted acreage for irrigation districts (1000 acres)
ACR2(TC,S,ID)          second crop acreage for irrigation districts (1000 acres)
AC1AV(TC,S)            ave. of fraction of 1st crop historical ave. planted
AC2AV(TC,S)            ave. of fraction of 2nd crop historical ave. planted
WD1(ID,TC,S)           first crop water demand from irrigation districts (kAF)
WD2(ID,TC,S)           second crop water demand from irrigation districts (kAF)
DI(ID,T,S)            monthly water demands from irrigation districts (kAF)
GA(ID,T,S)            elastic variable penalizing unequal district deficits
GB(ID,T,S)            elastic variable penalizing unequal district deficits
HA1(ID,TC,S)          elastic variable penalizing unequal 1st crop acreages
HB1(ID,TC,S)          elastic variable penalizing unequal 1st crop acreages
HA2(ID,TC,S)          elastic variable penalizing unequal 2nd crop acreages
HB2(ID,TC,S)          elastic variable penalizing unequal 2nd crop acreages
DA(T,S)              helps keep Travis and Buchanan at similar storage volumes
DB(T,S)              helps keep Travis and Buchanan at similar storage volumes
ELVA(TC,S)            penalizes for interruptible deviations from LCRA function
ELVB(TC,S)            penalizes for interruptible deviations from LCRA function
MROR(T,S)            City of Austin municipal run-of-river diversions made(kAF)
MFRM(T,S)            City of Austin municipal firm water diversions made (kAF)
UM(T,S)              unmet municipal water demand (deficit) for City of Austin (kAF)
UI(ID,T,S)           unmet irrigation demand (deficit) (kAF)
UIAV(T,S)            ave. of fraction of historical irrigation diversion ave's
SR(RS,T,S)           storage in reservoir at end of period t (kAF)
REC(RRS,T,S)         recreational benefit of reservoir in period t
RECTOT              expected annual recreational benefit ($1000)
CRPTOT              expected annual revenue from crops ($1000)
DEFTOT              expected annual penalty from deficits ($1000)
STOTOT              expected final storage benefits ($1000)
HYDTOT              expected annual hydroelectric energy production (kWh)
MISCTOT             expected annual benefit from elastic variables ($1000)
Z                   objective function
;

POSITIVE VARIABLES Y, R, RHYDRO, RSPILL, RPLUS, RTRN, RBAS, INTR, INT1, INT2, ROR, ROR1,
ROR2, BAY, P, ACR1, ACR2, AC1AV, AC2AV, WD1, WD2, DI, GA, GB,
HA1, HB1, HA2, HB2, DA, DB, ELVA, ELVB, MROR, MFRM, UM, UI, UIAV, SR ;

* BEGIN SETTING UPPER OR LOWER BOUNDS ON VARIABLES

* Upper bound on reservoir storage equals reservoir capacity
SR.UP(SRS,T,S) = K(SRS);

* Fixed bounds on pass-through reservoir storages
SR.FX(PRS,T,S) = FRAC_I(PRS) * K(PRS);

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* Upper bound on hydroelectric power generation
P.UP(RS,T,S) = PMAX(RS);

* Upper bound on monthly recreation benefits for recreation reservoirs
REC.UP(RRS,T,S) = RECW(RRS)$WIN(T) + RECS(RRS)$SUR(T);

* Lower bound on interruptible contract
Y.LO(TC,S) = YL;

* Upper bound on interruptible contract
Y.UP(TC,S) = YU;

* Upper bound on irrigation run-of-river diversions, set by LCRA RESPONSE model output
ROR.UP(ID,T,S) = FROR(T,S,ID);

* City of Austin run-of-river diversions limited to inflows into Highland Lakes
MROR.UP(T,S) = SUM(RS,Q(RS,T,S));

* Critical bay and estuary flow requirements for Matagorda Bay
BAY.LO(T,S) = BAYMIN;

* Lower bound on irrigation district farmed acreage, from 1968-97 minimum values
ACR1.LO(TC,S,ID) = ACRMN(ID);

* Upper bound on irrigation district farmed acreage, from LCRA information
ACR1.UP(TC,S,ID) = ACRMN(ID);

* Defines penalties on deviations from LCRA interruptible contract function
KEV = 2*CM;

* Defines penalties on deviations from irrigation deficit sharing
KG = 2*CU1;

* END SETTING UPPER OR LOWER BOUNDS ON VARIABLES

EQUATIONS
  CONS(RS,T,S)      mass conservation at reservoirs
  RESERVE(T,S)      reserve storage requirement
  SPACE(T,S)        minimizes Buchanan and Travis fractional storage differences

  INTP(T,S)         interruptible contract-combined storage linear function

  RELEASE(RS,T,S)   separation of release into hydro and spill flows
  RELREG(RS,T,S)    designation of maximum recommended releases from reservoirs

  MUNIC(TC,S)       annual COA run-of-river diversions less than water right
  MUNIF(TC,S)       annual COA municipal firm diversions less than LCRA contract
  DEFM(T,S)         definition of a deficit for municipal City of Austin water
  RETRN(T,S)        City of Austin return flows equal fraction of diversions

  BASTROP(T,S)      Bastrop flow equals Tom Miller release plus return flows
  IRELEAS(T,S)      Flow into bay = Bastrop flow - diversions + return flow

  IDEM1(ID,TC,S)    irrigation district first crop demands from LCRA regressions
  IDEM2(ID,TC,S)    irrigation district second crop demands from LCRA regressions
  IDEMM(ID,T,S)     irrigation district monthly demands from LCRA regressions
  IDEMP(ID,T,S)     irrigation district monthly demands for Pierce Ranch
  DEFI(ID,T,S)      definition of a deficit for irrigation water
  DEFAV(T,S)        ave. of deficits divided by historical ave. diversions
  DEFEQ(ID,T,S)     water shortages shared equitably by irrigation districts
  CONTR(TC,S)       total irrigation diversions limited to contracted amounts

  ACRGE(TC,S,ID)    second crop acreage must be less than first crop acreage
  ACRAV1(TC,S)       ave. of fraction of historical ave. 1st crop acres planted
  ACRAV2(TC,S)       ave. of fraction of historical ave. 1st crop acres planted
  ACR1EQ(ID,TC,S)    fractions of 1st crop max acreage equalized across districts
  ACR2EQ(ID,TC,S)    fractions of 2nd crop max acreage equalized across districts

  RORI1(ID,TC,S)    summation of first crop run-of-river irrigation diversions
  RORI2(ID,TC,S)    summation of second crop run-of-river irrigation diversions

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INTER1(ID,TC,S) summation of first crop interruptible irrigation diversions

INTER2(ID,TC,S) summation of second crop interruptible irrigation diversions

ANT1R(RS,T,S,I) nonanticipativity for releases in first year
ANT2R(RS,T,S)   nonanticipativity for releases in second year
ANT1I(TC,S)     nonanticipativity for interruptible contract in first year
ANT2I(TC,S,I)   nonanticipativity for interruptible contract in second year
ANT3I(TC,S)     nonanticipativity for interruptible contract in third year
ANT1A(TC,ID,S)  nonanticipativity for first crop acreage planted in first year
ANT2A(TC,ID,S,I) nonanticipativity for first crop acreage planted in second year
ANT3A(TC,ID,S)  nonanticipativity for first crop acreage planted in third year
ANT1B(TC,ID,S,I) nonanticipativity for second crop acreage planted in first year
ANT2B(TC,ID,S)  nonanticipativity for second crop acreage planted in second year

RECREA(RRS,T,S) recreation benefit function for reservoirs
RECBEN          average annual recreational benefit
CRPBEN          average annual revenue from crop production
DEFPEN          average annual penalty from municipal and irrigation deficits
POWER(RS,T,S)   power production for hydroelectric turbines
HYDROBEN        average annual hydroelectric power generation
STOBEN          average final storage benefit
MISC            sums surplus variable penalties to reduce obj. function clutter

OBJ             objective function;

* Flow conservation constraints at each reservoir. The EA and EB terms model evaporation
* losses. Q is inflows from Colorado River and tributaries, and R(RS-1,T,S) is the
* release from the upstream reservoir. Outflows are the release from this reservoir, and
* the firm and run of river diversions used by Austin. This term assumes that drinking
* water is diverted from Lake Austin.
* The 0.001 factor on Q is due to the fact that Q is in acre-feet instead of kAF.

CONS(RS,T,S) .. (1 + EA(T,RS)) * SR(RS,T,S) =E=
    (1 - EA(T,RS)) * ((SR(RS,T-1,S))$(ord(T) gt 1)
    + (FRAC_I(RS) * K(RS))$(ord(T) eq 1))
    + 0.001*Q(RS,T,S)
    + R(RS-1,T,S)$(ord(RS) gt 1)
    - R(RS,T,S)

    - EB(T,RS)
    - (MFRM(T,S) + MROR(T,S))$(ord(RS) eq 6) ;

* total monthly storage in Buchanan and Travis must exceed reserve storage
* lower limit, RES, in each month and each scenario

RESERVE(T,S) .. SR('Buchanan',T,S) + SR('Travis',T,S) =G= RES;

* penalizes unequal fractional storage values between Buchanan and Travis

SPACE(T,S) .. SR('Buchanan',T,S)/K('Buchanan') - SR('Travis',T,S)/K('Travis') =E=
    DA(T,S) - DB(T,S);

* define set MonthInYr(T,TC) containing months in year beginning with month TC
* this is needed to aggregate monthly amounts into annual amounts, and to specify
* the start of year month associated with a given month

SET MonthInYr(T,TC) months in the year starting with month TC ;

MonthInYr(T,TC) = YES $ ( (12*ORD(TC) le ORD(T)+11) AND (12*ORD(TC) ge ORD(T)) ) ;

```

```

* define annual deviation variables ELVA and ELVB for piecewise linear function
* specifying interruptible contract amounts as function of combined storage at
* Buchanan and Travis

INTP(T,S)$TC(T) ..SUM(TC$ MonthInYr(T,TC),
    Y(TC,S) - ELVA(TC,S) + ELVB(TC,S)) =E=
    YB + YM * ((FRAC_I('Buchanan') * K('Buchanan')
    + FRAC_I('Travis') * K('Travis'))$(ORD(T) eq 1)
    + (SR('Buchanan',T-1,S) + SR('Travis',T-1,S))$(ORD(T) gt 1)) ;

* total reservoir release is the sum of hydro release and spill
* note that hydropower has an upper bound specified in the bound section above.
* hydropower, P, is computed in the objective function section. The upper bound
* on hydropower, P, defines an upper bound on hydro releases, R. Any remaining
* release is spill

RELEASE(RS,T,S) .. R(RS,T,S) =E= RHYDRO(RS,T,S) + RSPILL(RS,T,S);

* define elastic variable RPLUS as monthly releases above recommended limits, RPLUS

RELREG(RS,T,S) .. R(RS,T,S) =L= RHI(RS) + RPLUS(RS,T,S) ;

* total annual run-of-river diversion from Lake Austin for municipal use
* can't exceed limit MWR

MUNIC(TC,S) .. SUM(T$ MonthInYr(T,TC), MROR(T,S)) =L= MWR ;

* total annual diversion from Lake Austin for municipal use
* can't exceed limit FRMC

MUNIF(TC,S) .. SUM(T$ MonthInYr(T,TC), MROR(T,S) + MFRM(T,S)) =L= FRMC ;

* define deviation variables UM, which measures unmet demand for water at Austin

DEFM(T,S) .. UM(T,S) =E= FF(T)*DCOA - MFRM(T,S) - MROR(T,S);

* a fraction frac_A of Austin's monthly municipal water use is returned to the
* river below Lake Austin

RETRN(T,S) .. RTRN(T,S) =E= frac_A*(MROR(T,S) + MFRM(T,S)) ;

* the monthly flow into Bastrop is the release from Lake Austin plus the
* above return flow

BASTROP(T,S) .. RBAS(T,S) =E= R('Austin',T,S) + RTRN(T,S) ;

* the flow into Matagordo bay, BAY, is the flow out of Bastrop, less the sum of
* interruptible diversions to all irrigation districts, plus the return flows
* from interruptible and run-of-river diversions.

IRELEAS(T,S) .. RBAS(T,S) =E= (1 - frac_R)*SUM(ID, INTR(ID,T,S))
    - frac_R*SUM(ID, ROR(ID,T,S)) + BAY(T,S) ;

* BEGIN SECTION MODELING AGRICULTURAL DEMAND

* first define sets of months when the first and second crops are irrigated

SET CROP1(T,TC) months when crop one is irrigated in the year starting with month TC ;

CROP1(T,TC) = YES $ ( (ORD(T) ge 12*ORD(TC)-9) AND (ORD(T) le 12*ORD(TC)-5)) ;

SET CROP2(T,TC) months when crop two is irrigated in the year starting with month TC ;

CROP2(T,TC) = YES $ ( (ORD(T) ge 12*ORD(TC)-4) AND (ORD(T) le 12*ORD(TC)-2)) ;

*Display CROP1, CROP2 ;

```

```

* Define WD1 and WD2, which are annual water demands from each irrigation district
* for first (WD1) and second (WD2) crops.
* These equations apply to all districts except Pierce Ranch.

IDEM1(ID,TC,S)$ (ORD(ID) ne 3) .. WD1(ID,TC,S) =E= ((bG1(ID)*SUM(T$ CROP1(T,TC), GLE(T,S,ID))
+ bR1(ID)*SUM(T$ CROP1(T,TC), RAIN(T,S,ID)) + bA1(ID))*ACR1(TC,S,ID)
+ bC1(ID)) ;

IDEM2(ID,TC,S)$ (ORD(ID) ne 3) .. WD2(ID,TC,S) =E= ((bG2(ID)*SUM(T$ CROP2(T,TC), GLE(T,S,ID))
+ bR2(ID)*SUM(T$ CROP2(T,TC), RAIN(T,S,ID)))*ACR2(TC,S,ID)
+ bC2(ID)) ;

* Divide annual agricultural water demands WD1 and WD2 into monthly demands
* DI using allocation fractions FI1 and FI2 for first and second crops. Do
* this only for months in TI(T), when crops can be irrigated

IDEMM(ID,T,S)$ (TI(T) AND (ORD(ID) ne 3)) .. DI(ID,T,S) =E= SUM(TC $ MonthInYr(T,TC),
WD1(ID,TC,S)*FI1(T,ID)$TI1(T) + WD2(ID,TC,S)*FI2(T,ID)$TI2(T)) ;

* Calculates Pierce Ranch water demands based on historical average diversions,
* scaled according to fraction of historical ave. acreage in production.

IDEMP(ID,T,S)$ (TI(T) AND (ORD(ID) eq 3)) .. DI(ID,T,S) =E=
DIV(T,ID)*SUM(TC$ MonthInYr(T,TC), (ACR1(TC,S,ID)/ACR1AV(ID))$CROP1(T,TC)
+ (ACR2(TC,S,ID)/ACR2AV(ID))$CROP2(T,TC)) ;

* divide monthly agricultural water demands, DI, defined above,
* into run of river diversions, ROR, and interruptible diversions, INTR. They also define
* the deviation variables UI as the unsatisfied demand for irrigation water

DEFI(ID,T,S) $ TI(T) .. UI(ID,T,S) =E= DI(ID,T,S) - ROR(ID,T,S) - INTR(ID,T,S) ;

* divides irrigation deficits for each month by historical average diversions for that
* month, and determines an average across the districts

DEFAV(T,S)$TI(T) .. UIAV(T,S) =E= (1/CARD(ID))*SUM(ID, UI(ID,T,S)/DIV(T,ID));

* define elastic variables GA and GB measuring deviations from ave. fractional deficits

DEFEQ(ID,T,S)$TI(T) .. UI(ID,T,S)/DIV(T,ID) =E= UIAV(T,S) + GA(ID,T,S) - GB(ID,T,S);

* total annual interruptible releases to all irrigation districts can't exceed
* contracted volumes Y

CONTR(TC,S) .. SUM(T $ MonthInYr(T,TC), SUM(ID,INTR(ID,T,S))) =L= Y(TC,S);

* second crop acreage can't exceed first crop acreage.

ACRGE(TC,S,ID) .. ACR2(TC,S,ID) =L= ACR1(TC,S,ID) ;

* define average percent of historical ave. 1st crop acreages planted across districts

ACRAV1(TC,S) .. AC1AV(TC,S) =E= (1/CARD(ID))*SUM(ID, ACR1(TC,S,ID)/ACR1AV(ID));

* define average percent of historical ave. 2nd crop acreages planted across districts

ACRAV2(TC,S) .. AC2AV(TC,S) =E= (1/CARD(ID))*SUM(ID, ACR2(TC,S,ID)/ACR2AV(ID));

* define elastic variables HA1 and HB1 measuring inequitable 1st crop district acreages

ACR1EQ(ID,TC,S) .. ACR1(TC,S,ID)/ACR1AV(ID) =E= AC1AV(TC,S) + HA1(ID,TC,S) - HB1(ID,TC,S);

* define elastic variables HA2 and HB2 measuring inequitable 2nd crop district acreages

ACR2EQ(ID,TC,S) .. ACR2(TC,S,ID)/ACR2AV(ID) =E= AC2AV(TC,S) + HA2(ID,TC,S) - HB2(ID,TC,S);

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```

* compute annual run of river agricultural diversions from monthly diversions ROR
* introduced above. ROR1 is for first crop, ROR2 for second

ROR1I(ID,TC,S) .. ROR1(ID,TC,S) =E= SUM(T$ CROP1(T,TC), ROR(ID,T,S)) ;

ROR2I(ID,TC,S) .. ROR2(ID,TC,S) =E= SUM(T$ CROP2(T,TC), ROR(ID,T,S)) ;

* compute annual interruptible agricultural diversions for first crop (INT1)
* and second crop (INT2)

INTER1(ID,TC,S) .. INT1(ID,TC,S) =E= SUM(T$ CROP1(T,TC), INTR(ID,T,S)) ;

INTER2(ID,TC,S) .. INT2(ID,TC,S) =E= SUM(T$ CROP2(T,TC), INTR(ID,T,S)) ;

* END SECTION MODELING AGRICULTURAL DEMAND

* BEGIN NONANTICIPATIVITY CONSTRAINTS

* index I goes from 1 to 5, so this insures that first year releases are
* the same for scenarios 1 to 6, 7 to 12, etc, because all these have the same
* first year inflows

ANT1R(RS,T,S,I)$((YR1(T)) AND (SA(S)))..R(RS,T,S) =E= R(RS,T,S+ORD(I));

* this insures that second year releases are the same for scenarios 1 and 2,
* 3 and 4, etc, because these have the same second year inflows

ANT2R(RS,T,S)$((YR2(T)) AND (SB(S)))..R(RS,T,S) =E= R(RS,T,S+1);

* all first year interruptible contract amounts should be equal

ANT1I(TC,S)$((ORD(TC) eq 1) AND (ORD(S) lt CARD(S))) .. Y(TC,S) =E= Y(TC,S+1);

* second year interruptible contract amounts equal for scenarios 1 thru 6,
* 7 thru 12, etc

ANT2I(TC,S,I)$((ORD(TC) eq 2) AND (SA(S)))..Y(TC,S) =E= Y(TC,S+ORD(I));

* third year interruptible contract amounts equal for scenarios 1 and 2, 3 and 4, etc

ANT3I(TC,S)$((ORD(TC) eq 3) AND (SB(S)))..Y(TC,S) =E= Y(TC,S+1);

* these 3 sets of constraints enforce the same equalities on planted acreages in
* each rice farming region for first crop acreages as the above 3 do on
* interruptible contract amounts

ANT1A(TC,ID,S)$((ORD(TC) eq 1) AND (ORD(S) lt CARD(S))) .. ACR1(TC,S,ID) =E= ACR1(TC,S+1,ID);

ANT2A(TC,ID,S,I)$((ORD(TC) eq 2) AND (SA(S)))..ACR1(TC,S,ID) =E= ACR1(TC,S+ORD(I),ID);

ANT3A(TC,ID,S)$((ORD(TC) eq 3) AND (SB(S)))..ACR1(TC,S,ID) =E= ACR1(TC,S+1,ID);

* these 3 sets of constraints enforce equalities on planted acreages in
* each rice farming region for second crop acreages in a way similar to the
* release nonanticipativity constraints above

ANT1B(TC,ID,S,I)$((ORD(TC) eq 1) AND (SA(S))) .. ACR2(TC,S,ID) =E= ACR2(TC,S+ORD(I),ID);

ANT2B(TC,ID,S)$((ORD(TC) eq 2) AND (SB(S))) .. ACR2(TC,S,ID) =E= ACR2(TC,S+1,ID);

* END NONANTICIPATIVITY CONSTRAINTS

```

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* BEGIN OBJECTIVE COMPUTATION

* summer and winter monthly recreational benefits for lakes Buchanan and Travis

RECREA(RRS,T,S) .. REC(RRS,T,S) =L=
    RECINTW(RRS)$WIN(T) + RECINTS(RRS)$SUR(T)
    + (RECSLPW(RRS)$WIN(T) + RECSLPS(RRS)$SUR(T))*0.5*(SR(RRS,T,S)
    + SR(RRS,T-1,S)$ (ord(T) ge 2) + (FRAC_I(RRS)*K(RRS))$(ORD(T) le 1));

* total annual recreational benefits =12*average over time and scenarios of above

RECBEN .. RECTOT =E= (12/(CARD(S)*CARD(T)))*SUM((RRS,T,S), REC(RRS,T,S));

* total annual expected profits from first and second crops

CRPBEN .. CRPTOT =E= (1/(CARD(S)*CARD(TC)))*SUM((ID,TC,S),
    CA1*ACR1(TC,S,ID) + CA2*ACR2(TC,S,ID)) ;

* total annual municipal and irrigation deficit penalties

DEFPEN .. DEFTOT =E= (12/(CARD(S)*CARD(T)))*(SUM((T,S), CM*UM(T,S))
    + SUM((ID,T,S), (CU1$TI1(T) + CU2$TI2(T))*UI(ID,T,S)));

* average hydropower generated during each month (MW)

POWER(RS,T,S) .. P(RS,T,S) =E= MP(RS)*RHYDRO(RS,T,S)/DAY(T);

* average annual hydro energy over entire horizon (kWh)

HYDROBEN .. HYDTOT =E= (12/(CARD(S)*CARD(T)))*(SUM((RS,T,S), P(RS,T,S)*DAY(T)*24000));

* final storage benefits to counteract end-of-horizon effects

STOBEN .. STOTOT =E= (1/CARD(S))*SUM((SRS,S), W3(SRS)*SR(SRS,'T60',S));

* penalty on all slack, surplus and secondary variables

MISC .. MISCTOT =E=
    (1/(CARD(S)*CARD(TC)))*SUM((TC,S), KEV*(ELVA(TC,S) + ELVB(TC,S)))
    + (12/(CARD(S)*CARD(T)))*(SUM((ID,T,S), KG*(GA(ID,T,S)+ GB(ID,T,S)))
    + SUM((ID,TC,S), KH*(HA1(ID,TC,S) + HB1(ID,TC,S)+ HA2(ID,TC,S) + HB2(ID,TC,S)))
    + SUM((RS,T,S), PR*RPLUS(RS,T,S)) + alpha_1*SUM((T,S), DA(T,S) + DB(T,S))
    + SUM((T,S), CC*MFRM(T,S)) + SUM((ID,T,S), CD*INTR(ID,T,S))) ;

* final objective. W2 is price of hydro energy

OBJ .. Z =E= CRPTOT + W1*RECTOT + W2*HYDTOT + STOTOT - DEFTOT - MISCTOT;

* END OBJECTIVE COMPUTATION

* no echo of equations or variables to listing file

OPTION LIMROW = 0;
OPTION LIMCOL = 0;

* no solution listing on listing file (its too large)

OPTION SOLPRINT = OFF;

* set max solver iterations and time

OPTION ITERLIM = 50000;
OPTION RESLIM = 20000;

MODEL LCRA interruptible contract model /ALL/ ;

OPTION lp = cplex;

LCRA.WORKSPACE = 80;

```

```
* define output file as file "results.out" in project directory
FILE OUT1 /results.out/;

* solve model

SOLVE LCRA USING LP MAXIMIZING Z ;

* put results to output include file "outpathydroll.inc"

PUT OUT1;
$INCLUDE "outpathydroll.inc"
```

Appendix B: GAMS Model “Include” Data

Several sets of data were linked to the GAMS model through include statements. These data are summarized below, and include information on reservoir evaporation, gross lake evaporation and rainfall for the irrigation districts, and available run-of-river irrigation supplies. Although part of the data was indexed by scenario, the current version of the model only uses one annual set of data for all scenarios, repeated five times. Future versions of the Highland Lakes model may incorporate these hydrologic parameters into the scenario generation process, linking cross-correlations with the inflow hydrographs.

Inflow scenarios are not included here, but can be obtained from the author by request.

Table A.1: Evaporation Slope Parameters for Reservoirs ($EA_{t,rs}$)						
	Buchanan	Inks	LBJ	MarbleFalls	Travis	Austin
January	0.0010906	0.0023450	0.0017164	0.0029502	0.0005555	0.0016161
February	0.0006366	0.0013122	0.0008538	0.0015137	0.0002118	0.0004595
March	0.0024635	0.0053460	0.0038289	0.0067190	0.0014200	0.0061634
April	0.0013452	0.0028917	0.0020685	0.0035835	0.0008263	0.0028203
May	0.0019653	0.0043376	0.0031423	0.0054833	0.0014860	0.0073834
June	0.0052813	0.0115790	0.0084499	0.0146428	0.0030311	0.0126437
July	0.0091621	0.0201447	0.0147434	0.0255168	0.0052462	0.0232276
August	0.0098375	0.0215663	0.0156940	0.0272159	0.0055031	0.0246695
September	0.0059291	0.0129155	0.0091189	0.0161102	0.0030623	0.0141806
October	0.0042849	0.0092948	0.0066103	0.0116617	0.0022499	0.0103463
November	0.0030337	0.0067068	0.0049643	0.0084490	0.0015346	0.0045315
December	0.0014947	0.0032441	0.0023325	0.0040160	0.0006597	0.0012834

Table A.2: Evaporation Intercept Parameters for Reservoirs in kAF ($EB_{t,rs}$)						
	Buchanan	Inks	LBJ	MarbleFalls	Travis	Austin
January	0.134	0.004	0.120	0.005	0.073	0.003
February	0.078	0.002	0.060	0.002	0.028	0.001
March	0.302	0.008	0.268	0.010	0.186	0.011
April	0.165	0.005	0.145	0.005	0.108	0.005
May	0.241	0.007	0.220	0.008	0.194	0.014
June	0.647	0.018	0.592	0.022	0.397	0.023
July	1.122	0.032	1.032	0.039	0.687	0.043
August	1.205	0.034	1.099	0.042	0.720	0.046
September	0.726	0.020	0.639	0.025	0.401	0.026
October	0.525	0.015	0.463	0.018	0.294	0.019
November	0.372	0.011	0.348	0.013	0.201	0.008
December	0.183	0.005	0.163	0.006	0.086	0.002

Table A.3: Gross Lake Evaporation Parameters for Districts in Feet ($GLE_{t,s,id}$)				
	Lakeside	Garwood	Pierce Ranch	Gulf Coast
January	0.3082	0.3082	0.3082	0.3095
February	0.3613	0.3613	0.3613	0.3609
March	0.3984	0.3984	0.3984	0.4159
April	0.4854	0.4854	0.4854	0.5070
May	0.5545	0.5545	0.5545	0.5647
June	0.5108	0.5108	0.5108	0.5312
July	0.3961	0.3961	0.3961	0.4037
August	0.0000	0.0000	0.0000	0.3095
September	0.3082	0.3082	0.3082	0.3609
October	0.3613	0.3613	0.3613	0.4159
November	0.3984	0.3984	0.3984	0.5070
December	0.4854	0.4854	0.4854	0.5647

Table A.3: Rainfall Parameters for Districts in Feet ($RAIN_{t,s,id}$)				
	Lakeside	Garwood	Pierce Ranch	Gulf Coast
January	0.2446	0.2446	0.2446	0.2246
February	0.2833	0.2833	0.2833	0.2372
March	0.5104	0.5104	0.5104	0.4087
April	0.3626	0.3626	0.3626	0.3870
May	0.2318	0.2318	0.2318	0.3791
June	0.2454	0.2454	0.2454	0.2917
July	0.4467	0.4467	0.4467	0.5491
August	0.0000	0.2446	0.2446	0.2246
September	0.2446	0.2833	0.2833	0.2372
October	0.2833	0.5104	0.5104	0.4087
November	0.5104	0.3626	0.3626	0.3870
December	0.3626	0.2318	0.2318	0.3791

Table A.4: Available Run-of-river Flows in kAF ($FROR_{t,s,id}$)				
	Lakeside	Garwood	Pierce Ranch	Gulf Coast
January	2.3630	2.5979	0.9125	4.3768
February	5.3402	7.2801	2.0328	10.1622
March	11.9216	15.2497	3.9128	20.6228
April	10.9686	18.0598	3.6286	20.7318
May	4.6559	11.7567	2.1895	11.6730
June	2.6370	18.8933	1.3316	4.8310
July	3.4032	14.8429	2.4201	8.0614
August	0.6549	1.4691	0.4340	1.5221
September	2.3630	2.5979	0.9125	4.3768
October	5.3402	7.2801	2.0328	10.1622
November	11.9216	15.2497	3.9128	20.6228
December	10.9686	18.0598	3.6286	20.7318

Appendix C: Alternative Decision Rules

Various decision rules were added to the model and used in an attempt to derive new optimal operating rules for the storage reservoirs (Buchanan and Travis). These rules are variations of those outlined in several sources (Leclerc and Marks 1973), (Loucks et al. 1981), (Kindler and Tyszewski 1989), (Stendinger, Sule and Pei 1983), (Lund and Guzman 1999). An attempt was made to start with the more basic linear decision rules before trying increasingly more complex rules with the model.

The two linear decision rules (LDR's) and five nonlinear decision rules (NLDR's) chosen for testing are shown below:

LDR's:

$$R_{rs,t,s} = S_{rs,t,s} - b_{rs,t} \quad (A.1)$$

$$R_{rs,t,s} = S_{rs,t,s} + Q_{rs,t,s} - b_{rs,t} \quad (A.2)$$

NLDR's:

$$R_{rs,t,s} = a_{rs,t} * S_{rs,t,s} - b_{rs,t} \quad (A.3)$$

$$R_{rs,t,s} = a_{rs,t} * S_{rs,t,s} \quad (A.4)$$

$$R_{rs,t,s} = a_{rs,t} * (S_{rs,t,s} + Q_{rs,t,s}) \quad (A.5)$$

$$R_{rs,t,s} = a_{rs,t} * (S_{rs,t,s})^{b_{rs,t}} \quad (A.6)$$

$$R_{rs,t,s} = a_{rs,t} * (S_{rs,t,s} + Q_{rs,t,s})^{b_{rs,t}} \quad (A.7)$$

where:

- rs = reservoir index
- t = monthly time index
- s = scenario
- R = reservoir release
- S = reservoir storage
- Q = inflow into the reservoir rs
- a, b = unknown decision parameters

Unfortunately, early attempts using the decision rules consistently resulted in infeasibility errors with the GAMS solvers. Limited feasible results were obtained from the second LDR, listed as equation (A.2) above, but doing so

required the removal of many important constraints, resulting in impractical model output. Although nonanticipativity constraints for reservoir releases and interruptible contracts were removed, there was some concern that the high variability of flows between individual scenarios might be creating part, or all, of the infeasibility problems.

As a test, two single scenario inflows were created, one using the driest inflow scenario, and the other using a scenario-averaged five-year hydrograph. The scenario-averaged hydrograph did yield feasible results for most of the decision rules, and the dry scenario hydrograph also yielded feasible results for many of the rules.

Since single scenario stochastic problems are basically deterministic, the preliminary results may indicate special challenges in applying decision rules to stochastic multi-scenario models. Careful examination of the literature should be done before further attempts are made to use linear or nonlinear decision rules with the Highland Lakes model.

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Vita

David Raymond Kracman was born in North Platte, Nebraska on October 31, 2002, the son of Larry and Phyllis Kracman. After graduating North Platte Senior High School in 1992, he began studies at Harvard University in Cambridge, Massachusetts. He received the degree of Bachelor of Arts from Harvard University in June, 1996. After working as a legislative intern for the National Water Resources Association in Arlington, Virginia, he was employed as a legislative correspondent in Washington, D.C. for United States Senator Chuck Hagel from January, 1997, to October, 1998. He then worked on his parents' farm in North Platte, Nebraska, until entering graduate school in Environmental and Water Resources Engineering at the University of Texas at Austin.

Permanent address: 4505 Duval Street #250
Austin, TX 78751

This thesis was typed by the author.