## CHAPTER 3 -- METHODS OF ANALYSIS

### Task 1: Formulate Drought Scenarios

This task assessed the probability of severe drought and developed drought scenarios for the major water resource systems of the study area. Scenarios were developed for the 50 and 100-year return period droughts. The 1950s drought was also replicated, an event still significant in minds of many current senior water managers today.

These drought scenarios were characterized from gaged historical flow records of the Rio Grande and its tributaries. Fairly complete flow data along the river is available for the past 100 years. Drought scenarios for the analysis proposed here were developed under the supervision of Dr. Phil King with assistance by Mr. Brad Dixon who completed his masters degree in summer 2000 at New Mexico State University's Department of Civil, Agricultural, and Geological Engineering.

First, based on time series analysis of the existing flow data, synthetic drought scenarios of a given return period were formulated using methods similar to those developed for the Colorado Basin drought study (Tarboten 1995). The Colorado Basin study, modeled with independent annual flows, autoregression order one with fixed parameters, autoregressive order one with uncertain parameters, and fractional Gaussian noise modeling, used the estimated Hurst coefficient. While the existing data for the Rio Grande Basin only covers a 100-year period, it appears that severe and sustained drought with significant impact on the area's population has a return period in that order of magnitude. Extrapolation to longer return period droughts through dendrohydrology or other indirect methods appeared unnecessary.

Second, statistical analysis was used following established hydrologic principles (e.g., Benjamin and Cornell 1970; Hann 1977). The drought of the late 1950s was very severe. Farmers responded by installing wells and supplementing their surface water with groundwater. Since that time, competition for water has increased considerably. An evaluation of that drought scenario on current water users was conducted. In order to put the drought into perspective, its return period was calculated from the statistical analysis performed as described above.

## Task 2: Formulate a Hydrology-Institutions Model of the Rio Grande Basin

The aim of this task was to develop a hydrologic-institutions component to the overall model that accounts for major sources and uses of water in the Rio Grande Basin. Water use patterns throughout the basin will be altered as supplies are reduced due to drought.

This component accounts for institutional response under present water laws, policies, and management institutions. This task adapts and extends the optimization model developed by Booker for the Colorado Basin (Booker 1995). Despite similarities, there are several important differences between the Rio Grande and Colorado basins dealt with in the present study. For example, the Rio Grande Basin sees more substitution of groundwater for surface water in droughts, and the interstate water allocation specified by the Rio Grande Compact has no counterpart in the Colorado Basin. Moreover the Rio Grande has a much longer history of settlement and related agricultural water use than the Colorado, with the history of irrigation exceeding 400 years in the Las Cruces, New Mexico area alone.

### Hydrologic Model

The hydrology component of the overall model accounts for sources and uses of water from the San Luis Valley, Colorado to the El Paso, Texas area. This work was supervised by Dr. Phil King and Dr. Raghavan Srinivisan, with cooperation from Dr. Seiichi Miyamoto. The hydrologic model component was based on existing local hydrologic models and data. These include models developed by the U.S. Bureau of Reclamation, local irrigation districts, municipalities, the International Boundary and Water Commission, and the U.S. Geological Survey. The Soil and Water Assessment Tool (SWAT) developed by hydrologists at Texas A&M University is a basin-scale hydrologic/water quality model

(Arnold et al. 1993) developed by the U.S. Department of Agriculture-Agricultural Research Service and Texas Agricultural Experiment Station-Blackland Research Center. The SWAT model has been an important source of hydrologic data.

Many hydrology models are quite specialized and detailed. By contrast, this study focuses on the larger scale of the Rio Grande system, for which major sources and uses of water are accounted. Hydrologic performance characteristics relevant to this study were derived from existing work. Characteristics of the river system, such as reservoir capacities, stage-discharge and stage-surface area relationships, river conveyance and storage capacities, conveyance times, gains/losses, and diversions and return flows over seasonal time intervals has been derived in a simplified form from smaller scale more detailed models. Modeling system behavior at this level facilitated links to an economic damages model and to an institutional response model.

Modeling Consultant

Dr. James Booker, who completed a similar integrated hydrologic, economic, and legal drought management model in 1994 for the Colorado River Basin, originally worked as a consultant with Mr. Tom Lynch to build the model for the Rio Grande. In January 1999, after Mr. Lynch developed a prototype model and graduated from New Mexico State University, Dr. Booker completed the model. This model development work has consisted of several stages.

First, a strategic planning process was used to define the model design and components needed to achieve study objectives. A critical task was to identity the basic network structure, and appropriate spatial and temporal scales. Secondary areas included a conceptual design for linking groundwater use to surface flows, and implementing existing and prospective reservoir operations. The model treatment of native flows, withdrawals, consumptive use, and return flows will also be defined at this stage. The data structures designed for the Rio Grande modeling framework needed to be accessible to and supportive of other project needs while being easily applied within the GAMS (General Algebraic Modeling System) environment. GAMS is a mathematical optimization software package whose code is readable both by people and computers. Its readability by people was expected to be an advantage in peer review of the model, and its application to proposed water management plans.

Second, a prototype model that incorporates the model features defined at the strategic planning stage was developed. It has served two purposes. It served to validate initial design concepts and to identify at an early stage areas where design changes were necessary. It also provided early feedback to the full project team, serving as a vehicle to improve communication across disciplines and focus efforts on the critical areas needed to achieve overall objectives.

Third, implementing the completed Basin model to address institutions for adapting to drought required interaction among a number of project researchers. Possible water management scenarios were suggested based on preliminary results, and promising alternatives needed to be implemented. Defining such institutions within the model framework was not straightforward and was best accomplished with significant interaction among project researchers.

Finally, an important product of this project is an integrated modeling framework for the Rio Grande Basin that will be useful for water management and institutional analysis.

## Algorithm for Defining Water Use Patterns in Drought

Numerous water laws, court decisions, water rights patterns, and historical water use patterns as well as reservoir operating procedures in Colorado, New Mexico, and Texas, dictate the distribution of Rio Grande Basin water, both in normal and drought periods. Under the supervision of Dr. Charles DuMars the research group developed an algorithm incorporating the allocation of flows among all such parties. This algorithm will illustrate the allocation of flows during average years, when the river’s flows fulfill all claims as well as during low-flow years when the river’s waters are insufficient to meet all demands. The Rio Grande Compact is the major institution governing the allocation of these streamflows.

The current institutional and system operating response to drought-induced shortages was coded as a series of mathematical formulas, written in the GAMS language. The formulas were consistent with the response of the current operating systems to drought under current water management institutions. These formulas accounted for the water use priorities within each of the three Basin states. That is, the change in pattern of water diversions that occur during drought periods compared to normal periods are largely a function of the dates of priority and extent of use permitted to the various water right owners. Drought-induced changes in water use patterns also depend on what kind of water right is defined (e.g., diversion versus storage rights), location of the water right and water right owner, and extent of the right.

**Task 3: Develop an Economics Drought Damage Component**

This work component has analyzed the economic damages associated with selected drought scenarios by identifying the magnitude, location, and distribution of economic drought damages under present reservoir operating rules, policies, and management institutions.

Economic Impacts and Responses

A large body of theoretical and empirical literature has been developed that focuses on appropriate approaches for measuring direct economic impact of changes in water use levels (Young and Gray 1972; Gray and Young 1983; Gibbons 1986).

Estimating net willingness to pay for increments of water supply or for institutional adjustments that alter those increments of water supply is the accepted approach developed over many years in the economics scientific literature. Other monetary-based approaches include measures of value added, that is, income to primary regional resources (Young and Gray 1985), and gross revenue or sales per unit of water.

Three approaches for measuring net willingness to pay are available. The first approach employs statistical analysis of water use decisions by users. This approach is used primarily in the household and recreational sectors (Young 1973; Howe 1983; Daubert and Young 1981; Martin et al. 1984).

The second approach, change in net income, imputes residual changes in net business income to changes in water use. This approach is used primarily in evaluating agricultural and industrial water uses (Young and Gray 1972; Kelso et al. 1973).

The third approach, alternative cost, values water in terms of resource savings achieved by water intensive, rather than existing, production techniques.

## Drought Damage Assessment by Category of Use

### Agriculture

Direct economic damage to commercial agriculture resulting from drought is measured as the associated loss in net farm income. Income losses were estimated based on drought damage responses to water supply shortages for each of the major irrigated cropping regions in the basin. Major regions include the San Luis Valley in Colorado, the Middle Rio Grande Conservancy District near Socorro, New Mexico, Elephant Butte Irrigation District near Las Cruces, New Mexico, and the El Paso Water Conservation District #1 near El Paso, Texas.

Drought damage estimates for agriculture were based on crop-water yields, crop prices, and costs of agricultural production, including water delivery cost differentials between surface water and groundwater. The economic value of water in irrigation depends on opportunities for conservation, substitution, or reduced use of water in the face of increasing water scarcity (e.g., McGuckin et al. 1992).

Agronomic crop water yield response data are already available for many parts of the basin, and have been used to the extent possible. For crop prices and costs of production, data in crop enterprise budgets published by the Colorado, New Mexico, and Texas Agricultural Experiment Stations, the Bureau of Reclamation, and the individual irrigation districts were used. Examples include Lansford (1995) and Libbin (1995).

We conducted original research for all the important agricultural areas of the basin described above, in which linear programming models were used to replicate observed current and historical cropping patterns under various water supply conditions. For these models, agronomic yield response functions to water shortages were assembled in order to estimate impacts of water supply reductions on farm incomes. Equivalent methods are described in Booker and Colby (1995) and Booker and Young (1994).

Similar linear programming models have seen extensive previous development and use under the direction of Dr. Robert Young (e.g., Taylor and Young 1995) and Dr. Ron Lacewell (e.g., Bryant, et al. 1993). Dr. Robert Young and Dr. Marshall Frasier focused on agricultural areas in San Luis Valley, Colorado and in the Middle Rio Grande Conservancy District in New Mexico. A Ph.D. dissertation was completed by Mark Sperow at Colorado State University (1998), under supervision of Dr. Frasier, that examined agricultural sector response to drought in the San Luis Valley, Colorado. Dr. Ron Lacewell and Dr. John Ellis developed agricultural drought damages for the Middle Rio Grande Conservancy District and the Elephant Butte Irrigation District in New Mexico, and the El Paso Water Improvement District #1 in El Paso, Texas.

Municipal and Industrial (M&I)

The economic value of water used to meet M&I demands is based on water prices charged to customers, water use per household, and total numbers of households served. Albuquerque, Las Cruces, and El Paso are all large cities whose water use is connected to the Rio Grande. All are expected to experience considerable population growth in the years ahead, and their demand for water will likely increase. Dr. Tom McGuckin supervised the estimation of drought impacts for M&I uses, with assistance from Ms. Donna Stumpf.

Demand for water per household depends on average and incremental price per gallon, weather, income, size structure of household, and numerous demographic factors. Water use rates and the factors that influence those use rates, vary considerably by city, year, and seasons within a year. The total demand for water is demand per household times number of households. Data on population forecasts for these cities an important part of this study, have been obtained from census sources where possible.

Drought damage estimates for M&I water were developed from secondary sources. Numerous studies have been published on the economic value of water for M&I uses, some of which had application to the Rio Grande Basin. A small sample of these studies include Griffin and Chang (1991), Foster and Beattie (1979), Griffin (1990), Jones and Morris (1984), Opaluch (1982), Martin et al. (1984), Nieswiadomy (1992), and McKean et al. (1996), Taylor and Young (1995). Residential price elasticities of demand for water have also been estimated using contingent valuation methods (Thomas and Syme 1988).

Dr. McGuckin has developed data on residential water demand for Albuquerque and Las Cruces as well as El Paso from several previous studies, based on water use from 1980-1995. Household income, temperature, precipitation, number of service connections, and utility rate schedules have been included within a regression equation to estimate the effects that each have on historical residential water use. He has also explored the extent to which the presence of various non-price conservation programs (e.g., public information campaigns, odd-even watering schedules, low-flow toilet rebates) accompanying various rate schedules influences residential water use.

Hydroelectric Power

Streamflows, mostly from reservoir storage, produce hydroelectric power at a number of Basin dams, including El Vado, Abiquiu, and Elephant Butte reservoirs. Hydroelectric values of water are based on utility costs avoided by not having to supply power demands from alternative sources, such as thermal.

In the Rio Grande Basin, hydropower production occurs both during peak and base load periods, displacing base load (primarily coal) facilities and peak load (primarily gas turbine and oil) facilities. The cost of peaking power production is typically significantly greater than for base load production, so hydropower facilities could be operated to increase total production during peak demand periods, which is typically summertime in this region. However, competing demands for water in the Rio Grande Basin are considerable, so hydro production typically is not timed to occur during peak power demand periods.

Hydroelectric economic values of water were obtained where possible from regional and local utilities. For example, the Public Service Company of New Mexico supplies power for much of central New Mexico, while the El Paso Electric Company supplies power to southern New Mexico and west Texas.

Recreation

Water-based recreation is an important part of leisure activities of many residents of and visitors to the Rio Grande Basin, and water-related recreation opportunities contribute to tourism and related economic activities in much of the southwestern U.S.

Instream and reservoir-based recreation attract considerable numbers of visitors and both are affected negatively in a drought. Policy makers can make more informed decisions about stream and reservoir management if they know the economic benefits provided by streamflows and reservoir levels for recreation activities, such as fishing, boating, rafting, swimming, and sightseeing. Several studies have shown that recreational values of Basin reservoirs and streams are a declining function of reservoir contents and streamflows, respectively. Considerable work on recreation economic values of water has also been published by Daubert and Young (1981), Johnson and Walsh (1987), Sanders and others (1990), Ward (1987), Ward (1989), and Cole and Ward (1994). More recently, estimated recreational values of water have been observed in the range of $6 to $600 per acre-foot, depending on reservoir contents and other characteristics of the reservoir at which the recreation occurs (Ward et al. 1996).

Recent work has estimated recreational economic values of water in Lake Travis, Texas to be between $109 and $135 per acre-foot (Lansford and Jones 1995). Recreational economic values of water for coastal sites have also been estimated for Texas (Ozuna and Gomez 1994; Ozuna, et al. 1993). The present study has drawn from these and other sources of literature to develop estimates of recreation economic drought damages.

**Task 4: Identify Institutional Adjustments to Drought**

This study component identified how current water management institutions could be modified to alter the basin's current response to drought. It complements Task 3, which identifies only how current institutions affect the basin's response to shortage.

This study component aimed to predict how water use patterns of the Rio Grande Basin selected drought shortage scenarios would be altered by modified water management laws and institutions. It also predicted how economic damages would be altered by such institutional changes. The goal was to find institutional responses that would reduce the region's vulnerability to severe drought by reducing overall economic damages. A recently published study of sustained and severe drought in the Colorado River Basin identified several potential institutional responses to drought in that area (Booker 1995). Several of these responses had direct application to the present Rio Grande Basin analysis.

Professor Charles DuMars has studied most important institutions constituting the law of the river. The most important institution in this region is the Rio Grande Compact, with somewhat less emphasis on the Mexican Water Treaties of 1906 and 1944, federal reclamation law, the Pueblo Water

Rights Doctrine, and major environmental laws, including the Endangered Species Act and the Clean Water Act. His analysis included a brief summary of the state water law for each of the three Basin states.

DuMars has explained how each of the laws and institutions would function under different drought scenarios. To the degree these institutions stand as barriers to water transfer and use, these laws will be considered as constraints that must either be honored or altered through the political process.

The analysis began with an investigation of all of the above institutions through a literature search. After this research was completed, work focused on a matrix that illustrates the laws, their hierarchy, their potential impacts under different drought circumstances, and the degree of flexibility within each law to adjust to water scarcity.

After compiling the relevant laws, the agencies responsible for enforcing these laws were contacted in order to verify the actual application of the laws to the facts. As the data were developed, Professor DuMars worked closely with other team members to monitor their progress and indicate where and how the legal institutional principles compared with the factual information. This factual information was integrated into the overall report results as needed both as an individual chapter and as explanatory information needed to address fully related issues.

Because it is difficult to foretell what institutional changes will result from severe drought, the hydrology model component was designed to be flexible enough to represent the spectrum of possible operation rules. The model accommodates a large number of operating and allocation rules as well as overall systems of allocation.

**Task 5. Hydrologic-Economic-Legal Policy Analysis**

This task investigated the economic implications of alternative institutional arrangements for allocating Rio Grande Basin waters in times of shortage. The model was formulated as a mathematical program and solved for a variety of scenarios, including the 44-year period covering the 1950s drought, 1942-1985, and a 44-year period in which inflows were equal to average inflows defined for the period of record. In addition 50 and 100-year drought scenarios were developed, but time constraints prohibited complete integration of those scenarios into the final model.

Economic damages attributable to a severe drought for each region and sector were estimated by comparing the baseline long-run average flow results with the results for the 1950s drought scenario replicated for the next 44 years. Manipulations of the model permits analyses of institutional adjustments, such as carryover storage, increased irrigation efficiency, building new reservoirs, and water market development.

Numerous current institutional constraints set limits on how the river or its reservoirs can be operated. Three of the more important include the Rio Grande Compact, federal reservoir authorization, and contracts signed by various water users.

Potential institutional responses to drought include those that affect river management, changes to legal environments, and market-based responses such as water banks. A few examples below were originally considered, but modified as described in more detail subsequently in the results.

River Management

- Evaporation losses can be reduced by reallocating storage to high elevation reservoirs
- Reservoir operating rules might be evaluated to alter the balance between hydropower and different uses

Changes to Legal Environment

- Sale or lease of rental of water conserved due to investments made for water conservation; this is not currently permitted under New Mexico, Colorado, or Texas water law
- Proportional sharing of shortfalls; for rivers adjudicated in Colorado and New Mexico, the current seniority system of water rights produces an uneven pattern of sharing shortfalls

Market Based Operations

- Intrastate water banks: within a given state, institutions might be set up to reallocate that state's total drought-induced shortfall, using state water banks, or direct water marketing among users; interstate compacts such as The Rio Grande Compact would still be used to allocate shortfalls among states
- Interstate water banks: water banking or water marketing across state lines would be examined; if this occurred, the added benefits from water marketing may occur if state level transfers do not bring about similarly-valued water uses across states; implementing interstate water banks would need to account for the Compact through such measures as credits.
- Optioning contracts for temporary use of irrigation water (Young and Michelsen 1993); contracts for temporary use of irrigation water rights may be a low cost arrangement for providing drought insurance for urban areas, such as Albuquerque or El Paso

**Drought Scenarios for the Rio Grande Basin**

A major aim of this study was to develop scenarios for the 50-year and 100-year droughts in the Rio Grande Basin at the Rio Grande's headwaters in Colorado and New Mexico in addition to replicating the extended and severe drought of the 1950s. The following steps were taken to achieve this goal:

1) Identify the unimpaired gaging points in Rio Grande Basin, termed headwater flows, at which streamflow is essentially unaltered by human activities.
2) Statistically analyze drought durations and severity at the unimpaired gaging points.
3) Calculate monthly disaggregation coefficients for the annual streamflow series at the unimpaired gaging points, which characterize the monthly allocation of these annual flows.
4) Characterize 50-year and 100-year drought scenarios for those unimpaired gaging points.

The analysis described below was based on historical streamflow data from USGS gaging stations in the basin. These stations capture the majority of unimpaired inflows to the basin, and include both snowpack runoff and rainfall runoff dominated sub-basins. Additional basin inflows, ungaged flows, are characterized through correlations with the set of representative inflows. [1]

Selection of Unimpaired Gaging Points in Rio Grande Basin

In order to model the 50-year and 100-year droughts in the Rio Grande Basin, it was necessary to analyze the behavior of the system in terms of natural streamflow patterns. These natural streamflows could then be routed through the system, and management decisions could be made concerning reservoir releases and streamflow diversions. For this study, as shown in Figure 1-1 one gage was chosen on the following rivers as being representative of unimpaired streamflow in the river basin.

1) Rio Grande near Del Norte, CO
2) Conejos River Index Flows: (a) Conejos River at Mogote, CO plus (b) San Antonio River at Ortiz, CO plus (c) Los Pinos River near Ortiz, CO
3) Rio Chama near Chamita, NM
4) Jemez River below Jemez Canyon Dam, NM
5) Rio Puerco near Bernardo, NM
6) Rio Salado near San Acacia, NM

Each of these gages was chosen based on the criterion that no major management decisions upstream of the gage alters streamflow at that gage. Such management decisions might include reservoir operations, by which an increase in storage over a time period would decrease flow at the downstream gage or vice versa; a streamflow diversion to agricultural, municipal, or industrial water users, which

[1]For example ungaged inflows originating in northern New Mexico are calculated based on their correlation with historic Rio Grande flows measured at the Del Norte gage. Central New Mexico arroyo flows are estimated based on correlations with the Rio Salado. For the 50 and 100 year drought scenarios, these inflows represent flows associated with the kind of drought expected to occur once in 50 years or once in 100 years respectively.

would decrease the streamflow at the downstream gage; or a discharge into the river from water users, which would increase the streamflow at the gaging point.

For the Rio Grande, the gaging point near Del Norte, Colorado, was chosen to represent natural flow. Although this point is below the Rio Grande Reservoir, this reservoir was considered to have insignificant storage capacity relative to the monthly streamflow of the Rio Grande. Thus, impacts to the monthly streamflow due to changes in storage in the reservoir were considered negligible. This gaging point is also useful because it is the point on the Rio Grande on which Colorado's compact delivery requirement to New Mexico is based. Thus, the record of streamflow at this gage is long and consistent.

For the Rio Conejos, the gaging point near Mogote, Colorado, was chosen as representative of natural flow. This point is below Platoro Reservoir on the river, but again the effects of changes in reservoir storage were considered negligible due to the reservoir's small storage capacity. Colorado's compact delivery requirement to New Mexico from the Rio Conejos is determined by the flow at this gaging point plus flow of the San Antonio and Los Pinos rivers.

The unimpaired flow in the Rio Chama was modeled based on the flow at the gaging point near Chamita, New Mexico, after subtracting the flow in Willow Creek near Azotea Tunnel. This net Willow Creek flow represents the contribution to the Rio Grande Basin from the San Juan-Chama interbasin diversion project, which is considered a management decision.

Natural streamflow on the Rio Jemez was modeled according to the flow at the gaging point near Jemez, New Mexico. This gaging point is above the Jemez Canyon Reservoir and is considered representative of unimpaired flow in the river.

For the Rio Puerco and Rio Salado, the gaging points at their intersections with the Rio Grande were chosen to represent unimpaired flow. These gaging points are near Bernardo, New Mexico, and near San Acacia, New Mexico, respectively, and were selected because there are no reservoirs, diversion points, or discharge points above these gages.

Statistical Analysis of Drought Duration and Severity at Unimpaired Gaging Points

Based on the unimpaired streamflow points chosen for the Rio Grande and its tributaries, the next step was to determine the probabilistic distributions for the duration and severity of droughts at each of these points. To perform such an analysis, based on a limited record of annual streamflows at the gaging points, a Monte Carlo technique was employed. This involved the following four steps:

1) Determine the best-fitting frequency distributions for the annual streamflow time series at each of the six unimpaired gaging points and the parameters thereof.
2) Generate 10,000 years of synthetic streamflow data that use the best statistical distributions that are fit to actual historical flows.
3) Determine the best-fitting frequency distributions for drought duration.
4) Estimate the relationship between drought severity and drought duration at each unimpaired gaging point.

With these steps completed, the statistical characteristics of drought duration and the relationship of drought severity to drought duration is known for each of the unimpaired gaging points. This means the statistical behavior of droughts in terms of annual streamflow is known for each gaging point.

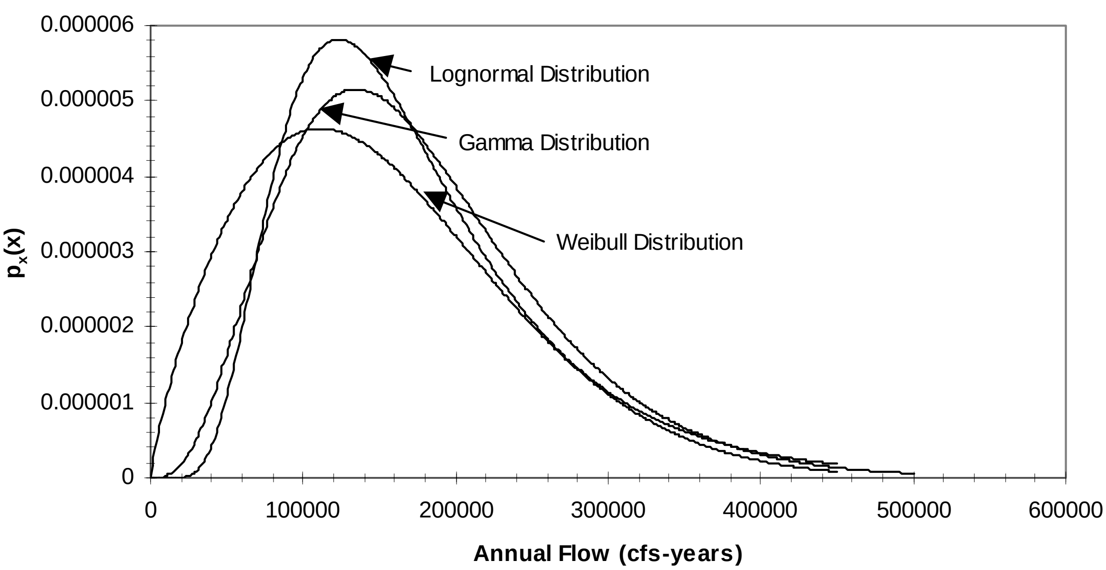
Frequency Distributions for Streamflow at Unimpaired Gaging Points

Probability distributions of drought parameters were identified by analyzing annual streamflow series at the unimpaired gaging points for the same. To do this, several candidate probability distributions were considered for each gaging point, each of which had an excellent potential of fitting the streamflow data. The distribution that best fit the original data was chosen to characterize the annual streamflow series at each point. The Gamma, Lognormal, and Extreme Value Type III Minimum (Weibull) were considered excellent candidates, because all have shapes that adapt to a wide range of annual streamflow water production. Figure 3-1 shows that each of these distributions has two added characteristics desirable for representing annual streamflow series: [2]

1) The distributions are bounded on their lower ends at zero.

2) The distributions allow for skewness about the mean.

**Figure 3-1**
**Rio Chama Annual Streamflow Probability Distributions**

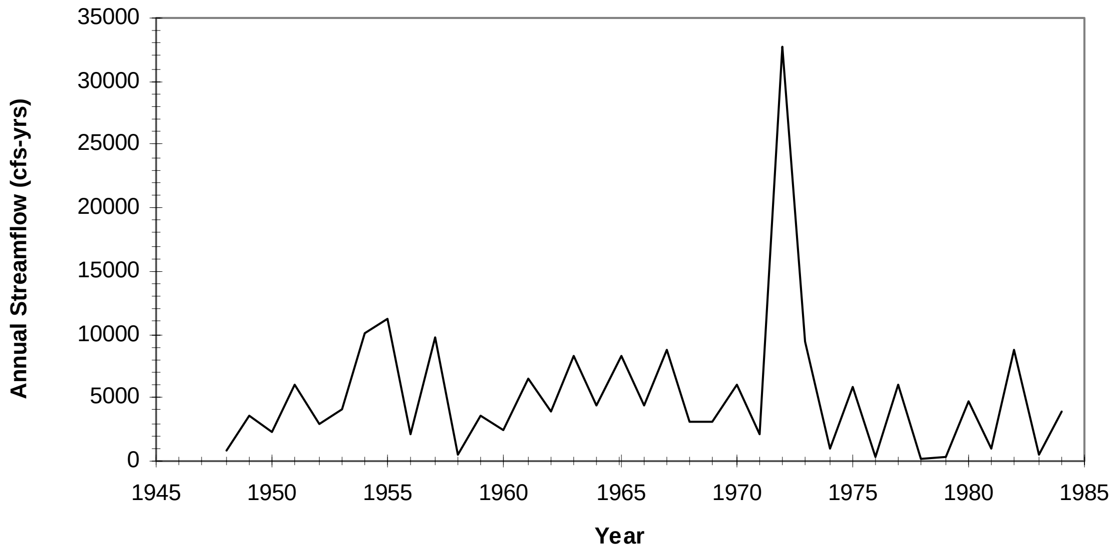



These two properties reflect the physical behavior of annual streamflow series. The first property is required because no streamflow series will have negative values. The second characteristic allows for the likelihood of either extremely high flows or extremely low flows, which fits well with the flashy

[2]In this section of the report dealing with developing drought scenarios for the Rio Grande Basin, streamflow is typically measured in the USGS format of cubic feet per second over a one-year period (cfs-years), except where otherwise noted. To translate cfs-years into acre-feet per year, multiply by 1.9837, a number slightly less than 2. For example, 20,000 cfs-years equals 20,000 times 1.9837 or 39,674 acre-feet per year.

nature of western rivers like those in the Rio Grande Basin. Figure 3-2 illustrates the characteristics of streamflows for the Rio Salado. While in 1958, 1978, and 1979, annual streamflow was almost zero, annual streamflow in 1972 was close to 33,000 cfs-years. This is more than six times the average annual streamflow for the Rio Salado. Clearly, the probability distribution used to model this series must allow extremely high or low flows to have a good chance of occurrence.

**Figure 3-2**
**Rio Salado Annual Streamflow**




The determination of the frequency distributions for the annual streamflow time series at each unimpaired gaging station in the Rio Grande Basin required the following steps:

1) For each river's annual streamflow series, estimate the distribution parameters for each of the candidate distributions.

2) Perform a Kolmogorov-Smirnov goodness of fit test to determine which of the candidate distributions best fits each annual streamflow series.

<u>Calculation of Distribution Parameters</u>

This section describes methods used to fit the gamma, lognormal, and Weibull distributions to the annual streamflow series for each stream reach. Each mathematical density function measures the probability that a given annual streamflow will occur, and is estimated based on analysis of past streamflow records.

The parameters for the gamma and lognormal distributions were calculated using the Microsoft Excel spreadsheet package (Microsoft 1996) and standard estimation techniques (Haan 1977). The parameters for the Weibull distribution were estimated using the SOLVER routine in the Excel spreadsheet, again using standard techniques. These calculations are described below.

Gamma Distribution. The gamma density (Haan 1977) function for a river's annual streamflow is given by:

$$p_x(x) = \lambda^{\eta} x^{\eta-1} e^{-\lambda x} / \Gamma(\eta) \qquad x, \lambda, \eta > 0 \tag{3.1}$$

where x is annual streamflow in cfs-years, $\lambda$ and $\eta$ are gamma distribution parameters that are estimated based on records of actual measured historical streamflow, as this streamflow varies from one year to the next. The expression $\Gamma(\eta)$ is the gamma function, which cannot be written in a simple form. However, its following properties can be used to compute it with any precision desired.

$$\Gamma(\eta) = (\eta - 1)! \quad \text{for } \eta = 1, 2, 3, \ldots$$

$$\Gamma(\eta + 1) = \eta\Gamma(\eta) \quad \text{for } \eta > 0 \tag{3.2}$$

$$\Gamma(1) = \Gamma(2) = 1$$

$$\Gamma(½) = (\pi)^{½}$$

Table 3-1 below shows values of $\Gamma(\eta)$ for a range of $\eta$ in which $1.0 \le \eta \le 2.0$. For other values of the parameter $\eta$, the equations above can be used.

| Table 3-1. Gamma Function Values for a River's Annual Streamflow in cfs-years | | | | | | | |
|---|---|---|---|---|---|---|---|
| η | gamma(η) | η | gamma(η) | η | gamma(η) | η | gamma(η) |
| 1.01 | 0.99433 | 1.26 | 0.90440 | 1.51 | 0.88659 | 1.76 | 0.92137 |
| 1.02 | 0.98884 | 1.27 | 0.90250 | 1.52 | 0.88704 | 1.77 | 0.92376 |
| 1.03 | 0.98355 | 1.28 | 0.90072 | 1.53 | 0.88757 | 1.78 | 0.92623 |
| 1.04 | 0.97844 | 1.29 | 0.89904 | 1.54 | 0.88818 | 1.79 | 0.92877 |
| 1.05 | 0.97350 | 1.30 | 0.89747 | 1.55 | 0.88887 | 1.80 | 0.93138 |
| 1.06 | 0.96874 | 1.31 | 0.89600 | 1.56 | 0.88964 | 1.81 | 0.93408 |
| 1.07 | 0.96415 | 1.32 | 0.89464 | 1.57 | 0.89049 | 1.82 | 0.93685 |
| 1.08 | 0.95973 | 1.33 | 0.89338 | 1.58 | 0.89142 | 1.83 | 0.93969 |
| 1.09 | 0.95546 | 1.34 | 0.89222 | 1.59 | 0.89243 | 1.84 | 0.94261 |
| 1.10 | 0.95135 | 1.35 | 0.89115 | 1.60 | 0.89352 | 1.85 | 0.94561 |
| 1.11 | 0.94739 | 1.36 | 0.89018 | 1.61 | 0.89468 | 1.86 | 0.94869 |
| 1.12 | 0.94359 | 1.37 | 0.88931 | 1.62 | 0.89592 | 1.87 | 0.95184 |
| 1.13 | 0.93993 | 1.38 | 0.88854 | 1.63 | 0.89724 | 1.88 | 0.95507 |
| 1.14 | 0.93642 | 1.39 | 0.88785 | 1.64 | 0.89864 | 1.89 | 0.95838 |
| 1.15 | 0.93304 | 1.40 | 0.88726 | 1.65 | 0.90012 | 1.90 | 0.96177 |
| 1.16 | 0.92980 | 1.41 | 0.88676 | 1.66 | 0.90167 | 1.91 | 0.96523 |
| 1.17 | 0.92670 | 1.42 | 0.88636 | 1.67 | 0.90330 | 1.92 | 0.96878 |
| 1.18 | 0.92373 | 1.43 | 0.88604 | 1.68 | 0.90500 | 1.93 | 0.97240 |
| 1.19 | 0.92088 | 1.44 | 0.88580 | 1.69 | 0.90678 | 1.94 | 0.97610 |
| 1.20 | 0.91817 | 1.45 | 0.88565 | 1.70 | 0.90864 | 1.95 | 0.97988 |
| 1.21 | 0.91558 | 1.46 | 0.88560 | 1.71 | 0.91057 | 1.96 | 0.98374 |
| 1.22 | 0.91311 | 1.47 | 0.88563 | 1.72 | 0.91258 | 1.97 | 0.98768 |
| 1.23 | 0.91075 | 1.48 | 0.88575 | 1.73 | 0.91466 | 1.98 | 0.99171 |
| 1.24 | 0.90852 | 1.49 | 0.88595 | 1.74 | 0.91683 | 1.99 | 0.99581 |
| 1.25 | 0.90640 | 1.50 | 0.88623 | 1.75 | 0.91906 | 2.00 | 1.00000 |

Separate parameters, $\lambda$ and $\eta$, were estimated using the relevant annual streamflow time series for each of the six headwater flows. It is a two-stage method, based on the method of maximum likelihood regression.

For the first stage the following calculations are made:

$$y = \ln(\text{avg}(x)) - \text{avg}(\ln(x))$$

$$\eta_{est} = [\,1 + (1 + 1.333y)^{1/2}\,] \;/\; 4y \qquad (3.3)$$

$$\lambda_{est} = \eta_{est} \,/\, \text{avg}(x),$$

where x is total annual streamflow in cfs-years.

For the second stage these values of $\lambda$ and $\eta$ were adjusted to gain greater precision using the following method:

$$E(\eta_{est} - \eta) = 3\eta_{est} / n$$

$$\eta_{cor} = \eta_{est} - E(\eta_{est} - \eta) \qquad (3.4)$$

$$\lambda_{cor} = \eta_{cor} / avg(x)$$

Demonstrating this method using the example of the time series on Rio Chama flows at Chamita, the calculations performed to calculate the gamma parameters are shown below:

| **Table 3-1a. Gamma Parameter Calculation, Rio Chama** |
|---|
| **Stage 1** |
| avg (x) = 176,785 = average annual flow (cfs-years) |
| avg (ln x) = 11.96 (3.4a) |
| ln (avg x) = 12.08 |
| y = 0.11794 |
| $\eta$ = 4.40 |
| $\lambda$ = 2.49E-05 |
| **Stage 2** |
| $E(\eta_{est}-\eta) = 3\,\eta_{est} / n$ = 0.22001 |
| $\eta_{cor}$ = 4.18 (3.4b) |
| $\lambda_{cor}$ = 2.36E-05 |
| $\Gamma(\eta)$ = 7.56 |

The gamma distribution parameters and the derived gamma distributions were estimated for each of the six headwater gages for the Rio Grande Basin.

Lognormal Distribution. The lognormal density function for annual streamflows is as follows:

$$p_X(x) = (2\pi x^2 \sigma_y^2)^{-1/2} \exp[-½(\ln x - \mu_y)^2/\sigma_y^2] \qquad x > 0 \qquad \text{(Haan 1977)} \qquad (3.5)$$

where x is annual streamflow, in cfs-years, and y = ln(x) is the natural logarithm of annual streamflow; $\mu_y$ and $\sigma_y^2$ are the mean and variance of y, respectively. Table 3-2 illustrates the estimation of the lognormal distribution parameters for annual streamflows on the Rio Conejos:

**Table 3-2. Estimated Parameters for Distribution of Rio Conejos Streamflows at Mogote gage, measured in cfs-years, Lognormal Distribution**

| Year | Streamflow = x | ln(Flow) = y | Year | Streamflow = x | ln(Flow) = y | Year | Streamflow = x | ln(Flow)= y |
|---|---|---|---|---|---|---|---|---|
| 1913 | 78,557 | 11.27 | 1940 | 77,283 | 11.26 | 1967 | 114,350 | 11.65 |
| 1914 | 125,127 | 11.74 | 1941 | 194,437 | 12.18 | 1968 | 117,866 | 11.68 |
| 1915 | 124,594 | 11.73 | 1942 | 142,769 | 11.87 | 1969 | 134,216 | 11.81 |
| 1916 | 174,988 | 12.07 | 1943 | 98,732 | 11.50 | 1970 | 121,021 | 11.70 |
| 1917 | 175,507 | 12.08 | 1944 | 148,433 | 11.91 | 1971 | 89,127 | 11.40 |
| 1918 | 112,676 | 11.63 | 1945 | 121,064 | 11.70 | 1972 | 61,029 | 11.02 |
| 1919 | 123,450 | 11.72 | 1946 | 72,420 | 11.19 | 1973 | 150,296 | 11.92 |
| 1920 | 216,689 | 12.29 | 1947 | 110,601 | 11.61 | 1974 | 81,953 | 11.31 |
| 1921 | 132,206 | 11.79 | 1948 | 145,624 | 11.89 | 1975 | 137,835 | 11.83 |
| 1922 | 154,323 | 11.95 | 1949 | 144,744 | 11.88 | 1976 | 110,041 | 11.61 |
| 1923 | 179,737 | 12.10 | 1950 | 85,563 | 11.36 | 1977 | 39,720 | 10.59 |
| 1924 | 152,678 | 11.94 | 1951 | 61,864 | 11.03 | 1978 | 91,304 | 11.42 |
| 1925 | 112,015 | 11.63 | 1952 | 186,842 | 12.14 | 1979 | 153,749 | 11.94 |
| 1926 | 131,657 | 11.79 | 1953 | 82,342 | 11.32 | 1980 | 147,169 | 11.90 |
| 1927 | 164,706 | 12.01 | 1954 | 68,183 | 11.13 | 1981 | 60,819 | 11.02 |
| 1928 | 105,584 | 11.57 | 1955 | 68,320 | 11.13 | 1982 | 158,120 | 11.97 |
| 1929 | 167,354 | 12.03 | 1956 | 84,909 | 11.35 | 1983 | 139,530 | 11.85 |
| 1930 | 107,958 | 11.59 | 1957 | 164,175 | 12.01 | 1984 | 124,222 | 11.73 |
| 1931 | 68,870 | 11.14 | 1958 | 126,576 | 11.75 | 1985 | 185,778 | 12.13 |
| 1932 | 186,221 | 12.13 | 1959 | 75,946 | 11.24 | 1986 | 170,622 | 12.05 |
| 1933 | 107,615 | 11.59 | 1960 | 105,000 | 11.56 | 1987 | 140,781 | 11.85 |
| 1934 | 55,393 | 10.92 | 1961 | 101,639 | 11.53 | 1988 | 82,305 | 11.32 |
| 1935 | 148,946 | 11.91 | 1962 | 128,721 | 11.77 | 1989 | 92,785 | 11.44 |
| 1936 | 111,980 | 11.63 | 1963 | 66,865 | 11.11 | 1990 | 78,569 | 11.27 |
| 1937 | 161,768 | 11.99 | 1964 | 78,397 | 11.27 | 1991 | 124,223 | 11.73 |
| 1938 | 158,456 | 11.97 | 1965 | 154,028 | 11.94 | 1992 | 89,531 | 11.40 |
| 1939 | 86,728 | 11.37 | 1966 | 120,465 | 11.70 | 1993 | 138,280 | 11.84 |
| | | | $\mu_y$ = 11.65 | | | $\sigma_y^2$ = 0.12 | | |

The lognormal distribution parameters were estimated for each of the six headwater gages using the methods described.

Weibull Distribution. The Weibull density function for a river's annual streamflows is given by:

$$p_X(x) = \alpha x^{\alpha-1} \beta^{-\alpha} \exp[-(x/\beta)^{\alpha}] \qquad x \geq 0; \alpha, \beta > 0 \text{ (Haan 1977)} \qquad (3.6)$$

where x is annual streamflow for the given stream, measured in cfs-years, and $\alpha$ and $\beta$ are Weibull distribution parameters. Its mean and variance are:

$$E(x) = \beta\, \Gamma(1 + 1/\alpha) \qquad (3.7)$$

$$Var(x) = \beta^2 [\Gamma(1 + 2/\alpha) - \Gamma^2(1 + 1/\alpha)]$$

The parameters, $\alpha$ and $\beta$, were estimated for each of the six headwater gages using observed historical annual streamflow. This method requires substituting the sample mean and variance for the unknown population mean and variance, respectively, and then solving both equations simultaneously to obtain an estimate of $\alpha$ and $\beta$. This solution was obtained using the SOLVER routine in Microsoft Excel. Table 3-3 illustrates estimation of the Weibull parameters, using the example of annual streamflow series for the Rio Grande at Del Norte.

**Table 3-3. Estimation of Weibull Distribution Parameters for Annual Rio Grande Headwater Streamflows, Del Norte gage (cfs-yrs)**

| | | | | | |
|---|---|---|---|---|---|
| $\mu$ = | 331,868 (cfs-yrs) | | $\mu_{gen}$ = | 268,647 (cfs-yrs) | $\Delta$ =4.00 E+09 |
| $\sigma^2$ = | 1.21E+10 | | $\sigma^2_{gen}$ = | 1.21E+10 | $\Delta$ = 2.93E+09 |
| $\alpha$ = | 2.6074 | | | SSR = | 6.93E+09 |
| $\beta$ = | 302,347 | | | | |
| $g_1$ = | $1+1/\alpha$ = | 1.3835263 | | | |
| $g_2$ = | $1+2/\alpha$ = | 1.7670527 | | | |
| $\Gamma(g_1)$ = | 0.88854 | | | | |
| $\Gamma(g_2)$ = | 0.92137 | | | | |

The SOLVER routine was used to minimize the sum of the squared residuals (SSR) between the sample and generated mean and the variance of the annual streamflow series by iteratively varying $\alpha$ an $\beta$.

Kolmogorov-Smirnov Goodness of Fit Test

The streamflow distribution with the best fit was chosen for each of the six headwater flow series using the Kolmogorov-Smrinov (K-S) test. This test compares the goodness of fit of a theoretical mathematical distribution with the distribution of sample streamflows based on the maximum deviation between the theoretical cumulative distribution function, $P_x(x)$, and the sample cumulative density function, S(x) (Haan 1977). The best fit among the three distributions is defined as the one whose maximum deviation is smallest. This maximum deviation, D, is defined by: $D = \max |P_X(x) - S(x)|$.

In order to conclude that a particular probability distribution fits a sample set with a significance level of ten percent, D must be less than the critical maximum deviation, $D_{crit}$, defined as follows:

$$D_{crit} = \frac{1.22}{\sqrt{n}} \tag{3.8}$$

where *n* is the sample size of the parameter to which the distribution is being fit.

For the gamma, lognormal, and Weibull distributions, the cumulative probability distribution functions are defined, respectively, as follows (Haan 1977):

$$P_X(x) = \int_0^x \lambda^\eta \, t^{\eta-1} e^{-\lambda t} / \Gamma(\eta) dt \qquad \text{(gamma)} \tag{3.9}$$

where x is annual streamflow, and $\lambda$ and $\eta$ are gamma distribution parameters defined previously.

$$P_X(x) = \int_0^x (2\pi \, t^2 \, \sigma_y^2)^{-1/2} \exp\,[-½ \, (\ln t - \mu_y)^2/\sigma_y^2] \qquad \text{(lognormal)} \tag{3.10}$$

where x is annual streamflow, and $\mu_y$ and $\sigma_y^2$ are the mean and variance of y, respectively, with y = ln(t).

$$P_X(x) = 1 - \exp\,[\,-(x/\beta)^\alpha\,] \qquad \text{(Weibull)} \tag{3.11}$$

where x is annual streamflow, and $\alpha$ and $\beta$ are Weibull distribution parameters defined previously.

The cumulative probability functions for each of the six stream gages were estimated using the GAMMADIST, LOGNORMDIST, and WEIBULL functions in Microsoft Excel. These functions derive the theoretical cumulative density functions for each annual streamflow series using, as input, the parameters calculated as previously described.

For each gage, the sample cumulative density function was generated using the HISTOGRAM function in Microsoft Excel. This function creates a histogram of a data set, based on selected class marks, and also calculates the sample cumulative density for the data set, at each class mark. The distribution with the lowest D, as defined above, was chosen to represent annual streamflow series at each gaging point. For each K-S test, the maximum deviation, D, was compared with $D_{crit}$ to confirm that the distribution chosen to represent the annual streamflow series fit the sample series with a significance level of ten percent or better.

The following pages show calculations involved in the K-S test to find the best fit distribution using the annual streamflow series of the Rio Puerco. Figure 3-3 shows the Rio Puerco's historical annual streamflow series. This is followed by K-S calculations, in Table 3-4, comparing the deviations between the sample and theoretical cumulative density functions. These steps were repeated for six headwater gages.

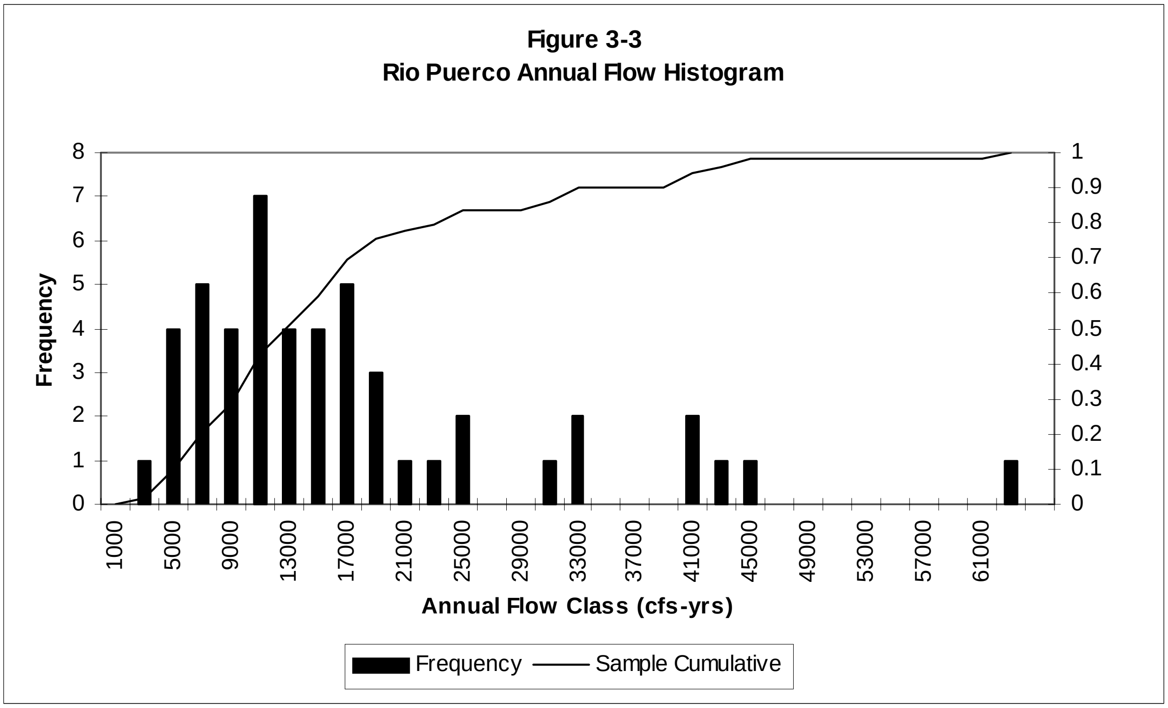


Figure 3-3
Rio Puerco Annual Flow Histogram
Frequency
0
1
2
3
4
5
6
7
8
0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0.9
1
1000
5000
9000
13000
17000
21000
25000
29000
33000
37000
41000
45000
49000
53000
57000
61000
Annual Flow Class (cfs-yrs)
Frequency
Sample Cumulative

| **Table 3-4. Goodness-of-Fit Test to Identify Distribution that Best Characterizes Annual Streamflow (cfs-years), Rio Puerco** | | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| Flow cfs-yrs | Freq. | Sample Cumul. | Gamma Cumul. | Gamma Deviation | Lognormal Cumul. | Lognormal Deviation | Weibull Cumul. | Weibull Deviation |
| 1000 | 0 | 0.000 | 0.007 | 0.007 | 0.000 | 0.000 | 0.036 | 0.036 |
| 3000 | 1 | 0.020 | 0.053 | 0.033 | 0.024 | 0.004 | 0.127 | 0.106 |
| 5000 | 4 | 0.102 | 0.127 | 0.025 | 0.102 | 0.000 | 0.222 | 0.120 |
| 7000 | 5 | 0.204 | 0.213 | 0.009 | 0.209 | 0.005 | 0.313 | 0.109 |
| 9000 | 4 | 0.286 | 0.304 | 0.018 | 0.321 | 0.035 | 0.398 | 0.112 |
| 11000 | 7 | 0.429 | 0.392 | 0.037 | 0.425 | 0.003 | 0.475 | 0.047 |
| 13000 | 4 | 0.510 | 0.475 | 0.035 | 0.516 | 0.006 | 0.545 | 0.035 |
| 15000 | 4 | 0.592 | 0.551 | 0.041 | 0.594 | 0.002 | 0.608 | 0.016 |
| 17000 | 5 | 0.694 | 0.618 | 0.076 | 0.659 | 0.035 | 0.663 | 0.031 |
| 19000 | 3 | 0.755 | 0.678 | 0.077 | 0.713 | 0.042 | 0.711 | 0.044 |
| 21000 | 1 | 0.776 | 0.729 | 0.046 | 0.758 | 0.018 | 0.754 | 0.022 |
| 23000 | 1 | 0.796 | 0.774 | 0.022 | 0.795 | 0.001 | 0.790 | 0.006 |
| 25000 | 2 | 0.837 | 0.812 | 0.025 | 0.826 | 0.011 | 0.822 | 0.015 |
| 27000 | 0 | 0.837 | 0.844 | 0.007 | 0.852 | 0.015 | 0.849 | 0.013 |
| 29000 | 0 | 0.837 | 0.871 | 0.034 | 0.873 | 0.037 | 0.873 | 0.036 |
| 31000 | 1 | 0.857 | 0.894 | 0.037 | 0.891 | 0.034 | 0.893 | 0.036 |
| 33000 | 2 | 0.898 | 0.913 | 0.015 | 0.906 | 0.009 | 0.910 | 0.012 |
| 35000 | 0 | 0.898 | 0.928 | 0.030 | 0.919 | 0.021 | 0.925 | 0.027 |
| 37000 | 0 | 0.898 | 0.941 | 0.043 | 0.930 | 0.032 | 0.937 | 0.039 |
| 39000 | 0 | 0.898 | 0.952 | 0.054 | 0.939 | 0.041 | 0.947 | 0.049 |
| 41000 | 2 | 0.939 | 0.961 | 0.022 | 0.947 | 0.008 | 0.956 | 0.017 |
| 43000 | 1 | 0.959 | 0.968 | 0.009 | 0.954 | 0.005 | 0.963 | 0.004 |
| 45000 | 1 | 0.980 | 0.974 | 0.005 | 0.960 | 0.020 | 0.970 | 0.010 |
| 47000 | 0 | 0.980 | 0.979 | 0.000 | 0.964 | 0.015 | 0.975 | 0.005 |
| 49000 | 0 | 0.980 | 0.983 | 0.003 | 0.969 | 0.011 | 0.979 | 0.000 |
| 51000 | 0 | 0.980 | 0.986 | 0.007 | 0.972 | 0.007 | 0.983 | 0.003 |
| 53000 | 0 | 0.980 | 0.989 | 0.009 | 0.976 | 0.004 | 0.986 | 0.006 |
| 55000 | 0 | 0.980 | 0.991 | 0.011 | 0.978 | 0.001 | 0.988 | 0.009 |
| 57000 | 0 | 0.980 | 0.993 | 0.013 | 0.981 | 0.001 | 0.990 | 0.011 |
| 59000 | 0 | 0.980 | 0.994 | 0.015 | 0.983 | 0.003 | 0.992 | 0.012 |
| 61000 | 0 | 0.980 | 0.995 | 0.016 | 0.985 | 0.005 | 0.993 | 0.014 |
| 63000 | 1 | 1.000 | 0.996 | 0.004 | 0.986 | 0.014 | 0.995 | 0.005 |
| | | | | | | | | |
| Max. Deviations | | | | 0.077 | | 0.042 | | 0.120 |
| Deviation $_{crit}$ = 0.174 | | | | | | | | |
| The lognormal distribution provides the best fit on the annual flow series for the Rio Puerco, because its maximum deviation between predicted and observed cumulative distribution is 0.042, whereas the Gamma and Weibull both have larger deviations | | | | | | | | |

Synthetic Streamflow for 10,000 Years

With the probabilistic distributions estimated for the unimpaired gages in the basin, Monte Carlo analysis is used to generate 10,000 years synthetic streamflow data for each of the six gaging points. At each gage, the 10,000 years synthetic streamflow have the identical statistical properties as the gage's relatively short period of historical observed streamflows. The considerably long series of synthetic streamflow data provides a much larger sampling period to analyze droughts at each gaging point and a more extensive view of the behavior of extremely wet or dry years at the gage than the much shorter observed streamflow data.

The cumulative probability function that is uniformly distributed over the interval of probability (0 to 1) is the basis for random generation of streamflows from a probability distribution (Haan 1977). If the cumulative probability function $P_X(x)$ for the streamflow, in cfs-years, is defined as:

$$P_X(x) = f(x) \tag{3.12}$$

then to generate a single random value x from $P_X(x)$, the following procedure is used:

1) Select a random number $R_u$ from a uniform distribution on the interval (0,1), in which all numbers have an equal probability of being selected.
2) Set $P_X(x) = R_u$., that is identify the cumulative probability associated with $R_u$.
3) Solve this equation for x, in this case, streamflow.

This procedure has the effect of transforming a cumulative probability, $R_u$, between 0 and 1 to the streamflow whose probability of being less than that flow equals that probability, $R_u$. This process is sometimes called obtaining the inverse transform of the streamflow probability distribution and is not possible for all distributions. The details of data analysis for the three distributions are described below.

Gamma Distribution. For the gamma distribution, the inverse transform cannot be obtained so other methods must be used (Haan 1977). A gamma random variable with a shape parameter on the interval (0,1) can be constructed as follows:

1) Let $R_{u1}$, $R_{u2}$, and $R_{u3}$ be independent uniform random variables on the interval (0,1).

2) Define $S_1 = R_{u1}^{1/\eta}$ and $S_2 = R_{u2}^{1/(1-\eta)}$.

3) If $S_1 + S_2 \leq 1.0$, define $Z = S_1/(S_1 + S_2)$ and $Y = -Z\ln(R_{u3})/\lambda$.

Then Y has a gamma distribution with shape parameter $\eta$ and scale parameter $\lambda$. If $S_1 + S_2 > 1.0$, then $R_{u1}$ and $R_{u2}$ are rejected, and new values are produced.

Finally, a gamma random variable with any shape parameter, $\eta$, can be constructed by adding a gamma variable with an integer value of $\eta$ and one with $\eta$ on (0,1). This is the method that was used for the study. The random uniform variables, $R_{u1}$, $R_{u2}$, and $R_{u3}$, were generated using the RAND(0,1) function within the Microsoft Excel spreadsheet, and the parameters were used to calculate the values for $S_1$, $S_2$, Z, $Y_{\eta-1}$, $R_{exp}$, $Y_{exp}$, and $Y_{gamma}$. The first 40 years of the 10,000 years of generated annual streamflow data for the Rio Salado near San Acacia, NM, are shown in Table 3-5. It should be noted that, in this case, $\eta$ =1.02. Therefore, $\eta$-1 is on the interval (0,1).

**Table 3-5. Generated Annual Streamflows (cfs yrs), first 40 of 10,000 years, Rio Salado Near San Acacia, NM, Gamma Distribution**

| Yr | $R_{u1}$ | $R_{u2}$ | $R_{u3}$ | $S_1$ | $S_2$ | $S_1+S_2$ | Z | $Y_{\eta-1}$ | $R_{exp}$ | $Y_{exp}$ | $Y_{gamma}$ (Streamflow) cfs-yrs |
|---|---|---|---|---|---|---|---|---|---|---|---|
| 1 | 0.154 | 0.1188 | 0.9306 | 0.0000 | 0.1129 | 0.1129 | 0.0000 | 0.0 | 0.2038 | 8105.1 | 8105.1 |
| 2 | 0.484 | 0.9233 | 0.5796 | 0.0000 | 0.9215 | 0.9215 | 0.0000 | 0.0 | 0.0084 | 24364.0 | 24364.0 |
| 3 | 0.303 | 0.1942 | 0.1973 | 0.0000 | 0.1867 | 0.1867 | 0.0000 | 0.0 | 0.9005 | 534.0 | 534.0 |
| 4 | 0.712 | 0.1357 | 0.0569 | 0.0000 | 0.1293 | 0.1293 | 0.0000 | 0.1 | 0.1383 | 10082.9 | 10083.0 |
| 5 | 0.086 | 0.5053 | 0.9074 | 0.0000 | 0.4971 | 0.4971 | 0.0000 | 0.0 | 0.7562 | 1424.0 | 1424.0 |
| 6 | 0.017 | 0.9986 | 0.4709 | 0.0000 | 0.9985 | 0.9985 | 0.0000 | 0.0 | 0.2906 | 6297.1 | 6297.1 |
| 7 | 0.750 | 0.0545 | 0.7147 | 0.0000 | 0.0508 | 0.0508 | 0.0001 | 0.2 | 0.6270 | 2379.0 | 2379.2 |
| 8 | 0.709 | 0.9069 | 0.4585 | 0.0000 | 0.9048 | 0.9048 | 0.0000 | 0.0 | 0.8223 | 996.7 | 996.7 |
| 9 | 0.507 | 0.9129 | 0.3557 | 0.0000 | 0.9109 | 0.9109 | 0.0000 | 0.0 | 0.6903 | 1888.9 | 1888.9 |
| 10 | 0.629 | 0.4950 | 0.5657 | 0.0000 | 0.4867 | 0.4867 | 0.0000 | 0.0 | 0.9515 | 253.5 | 253.5 |
| 11 | 0.336 | 0.3526 | 0.7784 | 0.0000 | 0.3439 | 0.3439 | 0.0000 | 0.0 | 0.4141 | 4493.2 | 4493.2 |
| 12 | 0.163 | 0.6559 | 0.3519 | 0.0000 | 0.6493 | 0.6493 | 0.0000 | 0.0 | 0.7184 | 1685.6 | 1685.6 |
| 13 | 0.099 | 0.4627 | 0.6560 | 0.0000 | 0.4542 | 0.4542 | 0.0000 | 0.0 | 0.3651 | 5134.9 | 5134.9 |
| 14 | 0.577 | 0.5413 | 0.7588 | 0.0000 | 0.5334 | 0.5334 | 0.0000 | 0.0 | 0.3310 | 5634.6 | 5634.6 |
| 15 | 0.558 | 0.7972 | 0.2910 | 0.0000 | 0.7929 | 0.7929 | 0.0000 | 0.0 | 0.9031 | 519.5 | 519.5 |
| 16 | 0.464 | 0.7831 | 0.7402 | 0.0000 | 0.7785 | 0.7785 | 0.0000 | 0.0 | 0.1085 | 11318.3 | 11318.3 |
| 17 | 0.307 | 0.860 | 0.4343 | 0.0000 | 0.8569 | 0.8569 | 0.0000 | 0.0 | 0.1400 | 10018.1 | 10018.1 |

| | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| 18 | 0.076 | 0.758 | 0.0202 | 0.0000 | 0.7534 | 0.7534 | 0.0000 | 0.0 | 0.7845 | 1236.7 | 1236.7 |
| 19 | 0.619 | 0.8363 | 0.7251 | 0.0000 | 0.8327 | 0.8327 | 0.0000 | 0.0 | 0.7515 | 1455.8 | 1455.8 |
| 20 | 0.247 | 0.8157 | 0.3838 | 0.0000 | 0.8117 | 0.8117 | 0.0000 | 0.0 | 0.5907 | 2682.8 | 2682.8 |
| 21 | 0.458 | 0.0076 | 0.2775 | 0.0000 | 0.0067 | 0.0067 | 0.0000 | 0.0 | 0.0152 | 21341.1 | 21341.1 |
| 22 | 0.311 | 0.5011 | 0.7601 | 0.0000 | 0.4928 | 0.4928 | 0.0000 | 0.0 | 0.2536 | 6991.7 | 6991.7 |
| 23 | 0.264 | 0.6482 | 0.5521 | 0.0000 | 0.6415 | 0.6415 | 0.0000 | 0.0 | 0.8270 | 967.7 | 967.7 |
| 24 | 0.111 | 0.3173 | 0.4521 | 0.0000 | 0.3086 | 0.3086 | 0.0000 | 0.0 | 0.9061 | 502.2 | 502.2 |
| 25 | 0.179 | 0.6966 | 0.6257 | 0.0000 | 0.6905 | 0.6905 | 0.0000 | 0.0 | 0.2155 | 7821.2 | 7821.2 |
| 26 | 0.626 | 0.2787 | 0.0670 | 0.0000 | 0.2703 | 0.2703 | 0.0000 | 0.0 | 0.8759 | 675.4 | 675.4 |
| 27 | 0.113 | 0.8982 | 0.9741 | 0.0000 | 0.8958 | 0.8958 | 0.0000 | 0.0 | 0.3982 | 4692.3 | 4692.3 |
| 28 | 0.338 | 0.5308 | 0.0112 | 0.0000 | 0.5228 | 0.5228 | 0.0000 | 0.0 | 0.5723 | 2843.8 | 2843.8 |
| 29 | 0.266 | 0.3578 | 0.6874 | 0.0000 | 0.3491 | 0.3491 | 0.0000 | 0.0 | 0.1137 | 11080.3 | 11080.3 |
| 30 | 0.840 | 0.7766 | 0.3067 | 0.0006 | 0.7718 | 0.7725 | 0.0008 | 4.8 | 0.2370 | 7337.6 | 7342.5 |
| 31 | 0.983 | 0.3681 | 0.8889 | 0.4823 | 0.3593 | 0.8416 | 0.5731 | 343.8 | 0.9401 | 314.8 | 658.6 |
| 32 | 0.986 | 0.1125 | 0.0557 | 0.5544 | 0.1067 | 0.6612 | 0.8386 | 12341.5 | 0.2865 | 6369.8 | 18711.2 |
| 33 | 0.057 | 0.3756 | 0.2205 | 0.0000 | 0.3669 | 0.3669 | 0.0000 | 0.0 | 0.3579 | 5236.0 | 5236.0 |
| 34 | 0.321 | 0.2544 | 0.8413 | 0.0000 | 0.2461 | 0.2461 | 0.0000 | 0.0 | 0.8382 | 899.6 | 899.6 |
| 35 | 0.274 | 0.6192 | 0.3466 | 0.0000 | 0.6121 | 0.6121 | 0.0000 | 0.0 | 0.8701 | 709.2 | 709.2 |
| 36 | 0.911 | 0.3878 | 0.1417 | 0.0198 | 0.3791 | 0.3989 | 0.0496 | 494.3 | 0.4395 | 4189.9 | 4684.2 |
| 37 | 0.789 | 0.6473 | 0.2730 | 0.0000 | 0.6406 | 0.6406 | 0.0001 | 0.5 | 0.8748 | 681.8 | 682.3 |
| 38 | 0.663 | 0.5689 | 0.6546 | 0.0000 | 0.5613 | 0.5613 | 0.0000 | 0.0 | 0.8083 | 1084.4 | 1084.4 |
| 39 | 0.770 | 0.1671 | 0.5758 | 0.0000 | 0.1601 | 0.1601 | 0.0001 | 0.3 | 0.5027 | 3504.4 | 3504.7 |
| 40 | 0.842 | 0.2573 | 0.6489 | 0.0007 | 0.2490 | 0.2497 | 0.0027 | 6.0 | 0.5519 | 3028.7 | 3034.7 |

Lognormal Distribution. The lognormal distribution is another case where an analytical inverse transform cannot be found (Haan 1977). However, a lognormal random variable, Y, can be generated according to the following function:

$$Y = \exp(\sigma_{\ln(x)} R_N + \mu_{\ln(x)}) \tag{3.13}$$

where $R_N$ is a random observation from a standard normal density distribution, and x represents the observed streamflow series, and the mean and variance of the log of the observed historical streamflow series are $\mu_{\ln(x)} = 9.44$ and $\sigma_{\ln(x)} = 0.7284$ respectively, where flow is measured in cfs-years. For this study random values of $R_N$ were generated using the Random Number Generation function in Microsoft Excel. The first 40 years of streamflow data generated for the Rio Puerco, for which the Lognormal fits well, are shown in Table 3-6:

| Table 3-6. Rio Puerco Generated Annual Streamflow, in cfs-yrs, first 40 of 10,000 years, lognormal distribution, in which $\mu_{ln(x)}$ = 9.44 and $\sigma_{ln(x)}$ = 0.7284 | | |
|---|---|---|
| Year | $R_N$ (random number from standard normal distribution with mean 0 and variance 1) | $Y_{lognormal}$ (streamflow, cfs-yrs) |
| 1 | 0.9227 | 24,720 |
| 2 | -0.7299 | 7,418 |
| 3 | 0.8891 | 24,123 |
| 4 | 2.5212 | 79,199 |
| 5 | 0.7564 | 21,901 |
| 6 | 0.0528 | 13,118 |
| 7 | -0.1344 | 11,446 |
| 8 | 1.1503 | 29,178 |
| 9 | 0.0610 | 13,197 |
| 10 | 0.4435 | 17,437 |
| 11 | -1.6051 | 3,921 |
| 12 | 1.1050 | 28,232 |
| 13 | 0.2419 | 15,056 |
| 14 | -0.0423 | 12,240 |
| 15 | -1.0010 | 6,088 |
| 16 | 1.7823 | 46,237 |
| 17 | -0.2154 | 10,790 |
| 18 | -1.2954 | 4,913 |
| 19 | 0.6193 | 19,818 |
| 20 | -0.0455 | 12,212 |
| 21 | 0.2244 | 14,865 |
| 22 | 0.2997 | 15,702 |
| 23 | 0.0264 | 12,868 |
| 24 | 2.6145 | 84,774 |
| 25 | -0.4176 | 9,312 |
| 26 | 0.6106 | 19,693 |
| 27 | -0.4918 | 8,823 |
| 28 | 1.5141 | 38,031 |
| 29 | 1.0614 | 27,348 |
| 30 | -0.0260 | 12,386 |
| 31 | 0.4674 | 17,742 |
| 32 | -0.4836 | 8,875 |
| 33 | -1.1566 | 5,436 |
| 34 | -1.0262 | 5,978 |
| 35 | 1.5636 | 39,428 |
| 36 | -0.7806 | 7,149 |
| 37 | 0.2193 | 14,809 |
| 38 | -1.0159 | 6,023 |
| 39 | 1.0292 | 26,715 |
| 40 | 0.0589 | 13,176 |

Weibull Distribution. Of the three distributions used in this study, the Weibull is the only one that has an analytical inverse transform. The inverse transform for the Weibull distribution is as follows:

$$x = -\beta\, [\ln(1-R_u)]^{1/\alpha} \qquad \text{(Haan 1977)} \qquad (3.14)$$

$R_U$ can be generated using the RAND (0,1) function in Microsoft Excel.The result is to assign a streamflow any value of $R_u$ generated randomly over the cumulative probability interval 0-1.

Comparison of Headwater Flows. The gamma distribution fit best for all headwater gages except the Rio Puerco. For the Rio Puerco, the lognormal fit best. The Weibull did not fit best for any of the six.

## Determination of Frequency Distributions for Drought Duration

From the 10,000 years of synthetic annual streamflow data, the characteristics of the drought parameters, severity and duration, at each unimpaired gaging point were then evaluated. The statistical behavior, relative to annual streamflow, of droughts at each of the unimpaired gaging points would then be known. From this information, 50-year and 100-year drought scenarios were generated for each of the gages, as described in detail below.

The large sample set of streamflow data with the same statistical properties as the historical streamflow data provided a large sample of droughts in the Rio Grande Basin. From this, the drought events were identified throughout the streamflow series as described below.

Exponential, gamma, lognormal, and Weibull probability distributions were fit to the drought duration and severity(not streamflow),and goodness of fit tests were then performed to determine the best fit distributions.

Identification of Drought Events. This section describes principles and procedures underlying runs theory, as used to characterize the drought events for the 10,000 years of synthetic streamflows for each of the six unimpaired flow gages. The following steps were taken in this process:

1) Assign a known percentage of mean annual streamflow, at each gaging point, to correspond to a drought, defined as the "critical streamflow." For this investigation, critical streamflow level was assigned a value of 75% of the long-term annual average streamflow.

2) Set initial storage deficit at zero. As long as annual streamflow remains at or above the critical streamflow, the storage deficit remains at zero.

3) If annual streamflow falls below the critical streamflow for a year, add that year’s flow shortfall to the storage deficit using the equation:

$$deficit_{i} = deficit_{i-1} + (streamflow_{crit} - streamflow_{obs}) \qquad (3.15)$$

where $deficit_i$ is the storage deficit at the end of the given time step, $deficit_{i-1}$ is the storage deficit at the end of the previous time step, $streamflow_{crit}$ is the critical annual streamflow, and $streamflow_{obs}$ is the observed annual streamflow during the given time step.

4) Continue to track the storage deficit using the equation above until the deficit returns to zero. At this point the drought has ended. Note that the storage deficit cannot go below zero.

The first 40 years of generated annual streamflows, and the associated droughts, at the unimpaired gaging point on the Rio Grande are shown in Table 3-7.

| Table 3-7. Analysis of Drought Deficits, based on first 40 years of 10,000 years synthetic streamflow, Rio Grande at Del Norte gage, (cfs-years) | | | | | |
|---|---|---|---|---|---|
| Average Annual Flow (cfs-yrs) = 332,507<br>75% Average Annual flow = 249,380 | | | | | |
| Year | Annual Flow<br><br>(cfs-yrs) | 75% ave annual flow<br>(cfs-yrs) | Storage Deficit<br><br>(cfs-yrs) | Cumulative Deficit<br><br>(cfs-yrs) | Drought Deficit<br><br>(cfs-yrs) |
| 1 | 379,571 | 249,380 | 0 | 0 | 0 |
| 2 | 258,081 | 249,380 | 0 | 0 | 0 |
| 3 | 151,103 | 249,380 | 98,278 | 98,278 | 98,278 |
| 4 | 699,228 | 249,380 | 0 | 0 | 0 |
| 5 | 37,261 | 249,380 | 212,119 | 212,119 | 0 |
| 6 | 356,816 | 249,380 | 104,684 | 316,804 | 316,804 |
| 7 | 940,750 | 249,380 | 0 | 0 | 0 |
| 8 | 161,563 | 249,380 | 87,818 | 87,818 | 87,818 |
| 9 | 451,292 | 249,380 | 0 | 0 | 0 |
| 10 | 8,705 | 249,380 | 240,675 | 240,675 | 0 |
| 11 | 270,485 | 249,380 | 219,571 | 460,246 | 460,246 |
| 12 | 555,126 | 249,380 | 0 | 0 | 0 |
| 13 | 620,381 | 249,380 | 0 | 0 | 0 |
| 14 | 1,271,655 | 249,380 | 0 | 0 | 0 |
| 15 | 472,702 | 249,380 | 0 | 0 | 0 |
| 16 | 103,389 | 249,380 | 145,992 | 145,992 | 0 |
| 17 | 201,162 | 249,380 | 194,210 | 340,201 | 0 |
| 18 | 396,375 | 249,380 | 47,216 | 387,417 | 0 |
| 19 | 208,386 | 249,380 | 88,210 | 475,628 | 0 |
| 20 | 227,493 | 249,380 | 110,098 | 585,725 | 0 |
| 21 | 222,983 | 249,380 | 136,495 | 722,220 | 0 |
| 22 | 57,274 | 249,380 | 328,601 | 1,050,822 | 1,050,822 |
| 23 | 794,463 | 249,380 | 0 | 0 | 0 |
| 24 | 889,303 | 249,380 | 0 | 0 | 0 |
| 25 | 390,543 | 249,380 | 0 | 0 | 0 |
| 26 | 240,460 | 249,380 | 8,921 | 8,921 | 8,921 |
| 27 | 1,038,200 | 249,380 | 0 | 0 | 0 |
| 28 | 52,458 | 249,380 | 196,922 | 196,922 | 0 |
| 29 | 304,495 | 249,380 | 141,808 | 338,730 | 0 |
| 30 | 111,891 | 249,380 | 279,298 | 618,027 | 0 |
| 31 | 84,944 | 249,380 | 443,735 | 1,061,762 | 0 |
| 32 | 53,859 | 249,380 | 639,256 | 1,701,018 | 1,701,018 |
| 33 | 1,738,162 | 249,380 | 0 | 0 | 0 |
| 34 | 40,999 | 249,380 | 208,381 | 208,381 | 0 |
| 35 | 31,218 | 249,380 | 426,544 | 634,926 | 634,926 |
| 36 | 1,293,570 | 249,380 | 0 | 0 | 0 |
| 37 | 159,168 | 249,380 | 90,213 | 90,213 | 0 |
| 38 | 65,366 | 249,380 | 274,228 | 364,441 | 0 |
| 39 | 201,204 | 249,380 | 322,405 | 686,845 | 686,845 |
| 40 | 623,854 | 249,380 | 0 | 0 | 0 |

This forty-year stretch of synthesized flows at the Rio Grande gage resulted in nine droughts, which have the following characteristics shown in Table 3-8.

**Table 3-8. Drought Duration and Deficits, Rio Grande at Del Norte, CO**

| Drought Duration (years), x | Drought deficit in year before drought ends (cfs-yrs) |
|---|---|
| 1 | 98,278 |
| 2 | 316,804 |
| 1 | 87,818 |
| 2 | 460,246 |
| 7 | 1,050,822 |
| 1 | 8,921 |
| 5 | 1,701,018 |
| 2 | 634,926 |
| 3 | 686,845 |

For the Rio Grande at Del Norte, CO,a total of 1297 droughts of varying durations were identified within the 10,000 years of synthesized streamflow. This table shows that a drought of 'x' years' duration is defined as 'x' consecutive years in which the cumulative deficit exceeds zero. Similar methods were used to synthesize droughts of varying severity and duration for the other headwater gages.

Estimation of Parameters for Drought Severity and Duration. With the drought events identified, using the method described above, four distributions were fit to the time series of drought durations. The four distributions included the exponential as well as the gamma, lognormal, and Weibull distributions. Like the other three distributions, the exponential distribution is bounded by zero on the low end and adapts to skewness about the mean. Thus, this distribution was considered a good candidate to describe the drought duration time series.

The single parameter for the exponential distribution, $\lambda$, was estimated using the Microsoft Excel spreadsheet package and standard estimation techniques. The exponential density function for drought duration is given by:

$$p_X(x) = \lambda e^{-\lambda x} \qquad x, \lambda > 0 \quad \text{(Haan 1977)} \tag{3.16}$$

where x is the drought duration (not annual streamflow), $p_X(x)$ is the frequency in which a drought of that duration occurs. The exponential parameter $\lambda$ is estimated to minimize the difference between the actual drought duration and its value predicted by the exponential distribution. The 'observed' drought frequency comes from sampling the 10,000 years of synthetic streamflow. The predicted drought frequency comes from random sampling from the relevant cumulative distribution. The estimate of $\lambda$ is:

$$\lambda = 1/\text{avg}(x) \tag{3.17}$$

The parameters for the gamma, lognormal, and Weibull distributions were estimated as described previously. The estimated distribution parameters for the Rio Grande Del Norte, CO drought duration series are shown below:

| **Table 3-8a. Rio Grande at Del Norte, CO Drought Duration Distribution Parameters** | | |
|---|---|---|
| EXPONENTIAL PARAMETERS: | | |
| | avg (x) = | 5.76 (years drought duration) |
| | $\lambda$ = | 0.17 |
| GAMMA PARAMETERS: | | |
| | avg (ln x) = | 1.10 |
| | ln (avg x) = | 1.75 |
| | y = | 0.65 |
| | $\eta$ = | 0.91 |
| | $\lambda$ = | 0.158 |
| Correcting for bias: | | |
| | E ($\eta_{est}$-$\eta$) = | 0.0021 |
| | $\eta_{cor}$ = | 0.91 |
| | $\lambda_{cor}$ = | 0.158 |
| LOGNORMAL PARAMETERS | | |
| | avg(ln x) = | 1.1 |
| | stdev (ln x)= | 1.04 |
| WEIBULL PARAMETERS | | |
| | $\alpha$= | 0.73 |
| | $\beta$= | 5.78 |

A similar estimation of drought duration parameters was peformed for the other 5 headwater gages. Results are shown in Figure 3-4 and Table 3-9 for the 10,000 years of synthetic streamflow for the Rio Grande at Del Norte, CO.

**Figure 3-4**
**Drought Duration Histogram, Rio Grande at Del Norte, CO**

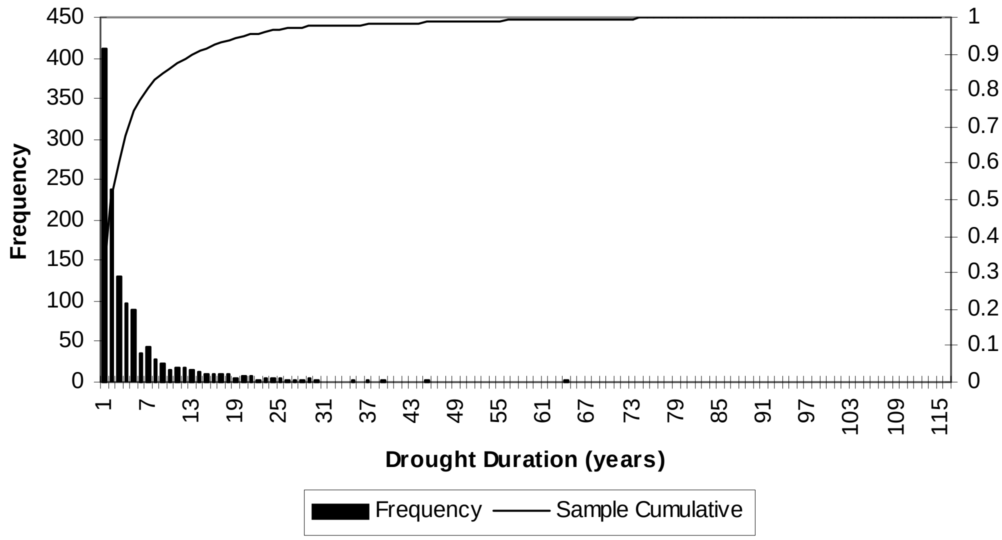


**Table 3-9. Distribution of Drought Durations, 10,000 years of synthetic streamflow, Rio Grande Del Norte, CO headwater flows with 50 and 100-year drought events indicated in bold font**

| Drought Duration | Sample Freq | Sample Cum. | Exponential Cum. | Gamma Cum. | Lognorm Cum. | Weibull Cum. | Exponential Dev. | Gamma Dev. | Lognorm Dev. | Weibull Dev. |
|---|---|---|---|---|---|---|---|---|---|---|
| 1 | 412 | 0.318 | 0.159 | 0.180 | 0.144 | 0.242 | 0.158 | 0.138 | 0.174 | 0.076 |
| 2 | 238 | 0.501 | 0.293 | 0.314 | 0.347 | 0.369 | 0.208 | 0.187 | 0.154 | 0.133 |
| 3 | 130 | 0.601 | 0.406 | 0.424 | 0.499 | 0.461 | 0.195 | 0.178 | 0.102 | 0.140 |
| 4 | 97 | 0.676 | 0.501 | 0.514 | 0.609 | 0.534 | 0.175 | 0.162 | 0.067 | 0.142 |
| 5 | 90 | 0.746 | 0.580 | 0.589 | 0.688 | 0.593 | 0.165 | 0.156 | 0.057 | 0.152 |
| 6 | 36 | 0.773 | 0.647 | 0.653 | 0.748 | 0.642 | 0.126 | 0.121 | 0.026 | 0.131 |
| 7 | 44 | 0.807 | 0.703 | 0.706 | 0.793 | 0.684 | 0.104 | 0.101 | 0.014 | 0.124 |
| 8 | 29 | 0.830 | 0.751 | 0.751 | 0.828 | 0.719 | 0.079 | 0.079 | 0.002 | 0.111 |
| 9 | 22 | 0.847 | 0.790 | 0.789 | 0.855 | 0.749 | 0.056 | 0.058 | 0.009 | 0.097 |
| 10 | 16 | 0.859 | 0.824 | 0.821 | 0.877 | 0.776 | 0.035 | 0.038 | 0.018 | 0.083 |
| 11 | 18 | 0.873 | 0.852 | 0.848 | 0.895 | 0.799 | 0.021 | 0.025 | 0.022 | 0.074 |
| 12 | 18 | 0.887 | 0.876 | 0.871 | 0.909 | 0.819 | 0.011 | 0.016 | 0.023 | 0.068 |
| 13 | 15 | 0.898 | 0.895 | 0.890 | 0.921 | 0.837 | 0.003 | 0.008 | 0.023 | 0.062 |
| 14 | 14 | 0.909 | 0.912 | 0.907 | 0.931 | 0.852 | 0.003 | 0.002 | 0.022 | 0.057 |
| 15 | 9 | 0.916 | 0.926 | 0.921 | 0.940 | 0.866 | 0.010 | 0.005 | 0.024 | 0.050 |
| 16 | 11 | 0.924 | 0.938 | 0.933 | 0.947 | 0.879 | 0.013 | 0.008 | 0.022 | 0.046 |
| 17 | 9 | 0.931 | 0.948 | 0.943 | 0.953 | 0.890 | 0.016 | 0.011 | 0.021 | 0.042 |
| 18 | 10 | 0.939 | 0.956 | 0.951 | 0.958 | 0.900 | 0.017 | 0.012 | 0.019 | 0.039 |
| 19 | 5 | 0.943 | 0.963 | 0.958 | 0.963 | 0.909 | 0.020 | 0.016 | 0.020 | 0.034 |
| 20 | 8 | 0.949 | 0.969 | 0.965 | 0.966 | 0.917 | 0.020 | 0.016 | 0.017 | 0.033 |
| 21 | 7 | 0.955 | 0.974 | 0.970 | 0.970 | 0.924 | 0.019 | 0.015 | 0.015 | 0.031 |
| 22 | 2 | 0.956 | 0.978 | 0.974 | 0.973 | 0.930 | 0.022 | 0.018 | 0.017 | 0.026 |
| 23 | 6 | 0.961 | 0.982 | 0.978 | 0.975 | 0.936 | 0.021 | 0.018 | 0.015 | 0.025 |
| 24 | 5 | 0.965 | 0.985 | 0.981 | 0.978 | 0.941 | 0.020 | 0.017 | 0.013 | 0.023 |
| 25 | 4 | 0.968 | 0.987 | 0.984 | 0.980 | 0.946 | 0.019 | 0.017 | 0.012 | 0.021 |
| 26 | 2 | 0.969 | 0.989 | 0.987 | 0.981 | 0.951 | 0.020 | 0.017 | 0.012 | 0.018 |
| 27 | 2 | 0.971 | 0.991 | 0.989 | 0.983 | 0.955 | 0.020 | 0.018 | 0.012 | 0.016 |
| 28 | 3 | 0.973 | 0.992 | 0.990 | 0.984 | 0.958 | 0.019 | 0.017 | 0.011 | 0.015 |
| 29 | 4 | 0.976 | 0.993 | 0.992 | 0.986 | 0.962 | 0.017 | 0.016 | 0.010 | 0.014 |
| 30 | 2 | 0.978 | 0.995 | 0.993 | 0.987 | 0.965 | 0.017 | 0.015 | 0.009 | 0.013 |
| 31 | 0 | 0.978 | 0.995 | 0.994 | 0.988 | 0.967 | 0.018 | 0.016 | 0.010 | 0.010 |
| 32 | 1 | 0.978 | 0.996 | 0.995 | 0.989 | 0.970 | 0.018 | 0.016 | 0.010 | 0.008 |
| 33 | 0 | 0.978 | 0.997 | 0.996 | 0.990 | 0.972 | 0.018 | 0.017 | 0.011 | 0.006 |
| 34 | 0 | 0.978 | 0.997 | 0.996 | 0.990 | 0.974 | 0.019 | 0.018 | 0.012 | 0.004 |
| 35 | 2 | 0.980 | 0.998 | 0.997 | 0.991 | 0.976 | 0.018 | 0.017 | 0.011 | 0.004 |
| **36 (50 yr)** | **0** | **0.980** | **0.998** | **0.997** | **0.992** | **0.978** | **0.018** | **0.017** | **0.012** | **0.002** |
| 37 | 2 | 0.981 | 0.998 | 0.998 | 0.992 | 0.980 | 0.017 | 0.016 | 0.011 | 0.002 |
| 38 | 0 | 0.981 | 0.999 | 0.998 | 0.993 | 0.981 | 0.017 | 0.017 | 0.011 | 0.000 |

| | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| 39 | 2 | 0.983 | 0.999 | 0.998 | 0.993 | 0.983 | 0.016 | 0.015 | 0.010 | 0.000 |
| 40 | 1 | 0.984 | 0.999 | 0.999 | 0.994 | 0.984 | 0.015 | 0.015 | 0.010 | 0.000 |
| 41 | 0 | 0.984 | 0.999 | 0.999 | 0.994 | 0.985 | 0.015 | 0.015 | 0.010 | 0.001 |
| 42 | 1 | 0.985 | 0.999 | 0.999 | 0.995 | 0.986 | 0.015 | 0.014 | 0.010 | 0.002 |
| 43 | 0 | 0.985 | 0.999 | 0.999 | 0.995 | 0.987 | 0.015 | 0.015 | 0.010 | 0.003 |
| 44 | 0 | 0.985 | 1.000 | 0.999 | 0.995 | 0.988 | 0.015 | 0.015 | 0.011 | 0.003 |
| 45 | 3 | 0.987 | 1.000 | 0.999 | 0.996 | 0.989 | 0.013 | 0.012 | 0.009 | 0.002 |
| 46 | 1 | 0.988 | 1.000 | 0.999 | 0.996 | 0.990 | 0.012 | 0.012 | 0.008 | 0.002 |
| 47 | 1 | 0.988 | 1.000 | 1.000 | 0.996 | 0.990 | 0.011 | 0.011 | 0.008 | 0.002 |
| 48 | 1 | 0.989 | 1.000 | 1.000 | 0.996 | 0.991 | 0.011 | 0.010 | 0.007 | 0.002 |
| 49 | 0 | 0.989 | 1.000 | 1.000 | 0.996 | 0.992 | 0.011 | 0.010 | 0.007 | 0.002 |
| 50 | 0 | 0.989 | 1.000 | 1.000 | 0.997 | 0.992 | 0.011 | 0.011 | 0.007 | 0.003 |
| 51 | 0 | 0.989 | 1.000 | 1.000 | 0.997 | 0.993 | 0.011 | 0.011 | 0.008 | 0.004 |
| **52 (100 yr)** | **1** | **0.990** | **1.000** | **1.000** | **0.997** | **0.993** | **0.010** | **0.010** | **0.007** | **0.003** |
| 53 | 1 | 0.991 | 1.000 | 1.000 | 0.997 | 0.994 | 0.009 | 0.009 | 0.006 | 0.003 |
| 54 | 0 | 0.991 | 1.000 | 1.000 | 0.997 | 0.994 | 0.009 | 0.009 | 0.007 | 0.003 |
| 55 | 0 | 0.991 | 1.000 | 1.000 | 0.997 | 0.995 | 0.009 | 0.009 | 0.007 | 0.004 |
| 56 | 1 | 0.992 | 1.000 | 1.000 | 0.998 | 0.995 | 0.008 | 0.008 | 0.006 | 0.003 |
| 57 | 0 | 0.992 | 1.000 | 1.000 | 0.998 | 0.995 | 0.008 | 0.008 | 0.006 | 0.004 |
| 58 | 0 | 0.992 | 1.000 | 1.000 | 0.998 | 0.996 | 0.008 | 0.008 | 0.006 | 0.004 |
| 59 | 0 | 0.992 | 1.000 | 1.000 | 0.998 | 0.996 | 0.008 | 0.008 | 0.006 | 0.004 |
| 60 | 0 | 0.992 | 1.000 | 1.000 | 0.998 | 0.996 | 0.008 | 0.008 | 0.007 | 0.005 |
| 61 | 0 | 0.992 | 1.000 | 1.000 | 0.998 | 0.996 | 0.008 | 0.008 | 0.007 | 0.005 |
| 62 | 0 | 0.992 | 1.000 | 1.000 | 0.998 | 0.997 | 0.008 | 0.008 | 0.007 | 0.005 |
| 63 | 0 | 0.992 | 1.000 | 1.000 | 0.998 | 0.997 | 0.008 | 0.008 | 0.007 | 0.005 |
| 64 | 2 | 0.993 | 1.000 | 1.000 | 0.998 | 0.997 | 0.007 | 0.007 | 0.005 | 0.004 |
| 65 | 1 | 0.994 | 1.000 | 1.000 | 0.999 | 0.997 | 0.006 | 0.006 | 0.005 | 0.003 |
| 66 | 0 | 0.994 | 1.000 | 1.000 | 0.999 | 0.997 | 0.006 | 0.006 | 0.005 | 0.004 |
| 67 | 1 | 0.995 | 1.000 | 1.000 | 0.999 | 0.998 | 0.005 | 0.005 | 0.004 | 0.003 |
| 68 | 1 | 0.995 | 1.000 | 1.000 | 0.999 | 0.998 | 0.005 | 0.005 | 0.003 | 0.002 |
| 69 | 1 | 0.996 | 1.000 | 1.000 | 0.999 | 0.998 | 0.004 | 0.004 | 0.003 | 0.002 |
| 70 | 0 | 0.996 | 1.000 | 1.000 | 0.999 | 0.998 | 0.004 | 0.004 | 0.003 | 0.002 |
| 71 | 0 | 0.996 | 1.000 | 1.000 | 0.999 | 0.998 | 0.004 | 0.004 | 0.003 | 0.002 |
| 72 | 1 | 0.997 | 1.000 | 1.000 | 0.999 | 0.998 | 0.003 | 0.003 | 0.002 | 0.001 |
| 73 | 0 | 0.997 | 1.000 | 1.000 | 0.999 | 0.998 | 0.003 | 0.003 | 0.002 | 0.001 |
| 74 | 1 | 0.998 | 1.000 | 1.000 | 0.999 | 0.998 | 0.002 | 0.002 | 0.001 | 0.001 |
| 75 | 0 | 0.998 | 1.000 | 1.000 | 0.999 | 0.999 | 0.002 | 0.002 | 0.001 | 0.001 |
| 76 | 0 | 0.998 | 1.000 | 1.000 | 0.999 | 0.999 | 0.002 | 0.002 | 0.001 | 0.001 |
| 77 | 0 | 0.998 | 1.000 | 1.000 | 0.999 | 0.999 | 0.002 | 0.002 | 0.001 | 0.001 |
| 78 | 0 | 0.998 | 1.000 | 1.000 | 0.999 | 0.999 | 0.002 | 0.002 | 0.001 | 0.001 |
| 79 | 0 | 0.998 | 1.000 | 1.000 | 0.999 | 0.999 | 0.002 | 0.002 | 0.002 | 0.001 |
| 80 | 0 | 0.998 | 1.000 | 1.000 | 0.999 | 0.999 | 0.002 | 0.002 | 0.002 | 0.001 |
| 81 | 0 | 0.998 | 1.000 | 1.000 | 0.999 | 0.999 | 0.002 | 0.002 | 0.002 | 0.001 |

| | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| 82 | 0 | 0.998 | 1.000 | 1.000 | 0.999 | 0.999 | 0.002 | 0.002 | 0.002 | 0.001 |
| 83 | 0 | 0.998 | 1.000 | 1.000 | 0.999 | 0.999 | 0.002 | 0.002 | 0.002 | 0.001 |
| 84 | 0 | 0.998 | 1.000 | 1.000 | 0.999 | 0.999 | 0.002 | 0.002 | 0.002 | 0.001 |
| 85 | 0 | 0.998 | 1.000 | 1.000 | 0.999 | 0.999 | 0.002 | 0.002 | 0.002 | 0.002 |
| 86 | 0 | 0.998 | 1.000 | 1.000 | 0.999 | 0.999 | 0.002 | 0.002 | 0.002 | 0.002 |
| 87 | 0 | 0.998 | 1.000 | 1.000 | 0.999 | 0.999 | 0.002 | 0.002 | 0.002 | 0.002 |
| 88 | 0 | 0.998 | 1.000 | 1.000 | 0.999 | 0.999 | 0.002 | 0.002 | 0.002 | 0.002 |
| 89 | 0 | 0.998 | 1.000 | 1.000 | 0.999 | 0.999 | 0.002 | 0.002 | 0.002 | 0.002 |
| 90 | 0 | 0.998 | 1.000 | 1.000 | 0.999 | 0.999 | 0.002 | 0.002 | 0.002 | 0.002 |
| 91 | 1 | 0.998 | 1.000 | 1.000 | 1.000 | 0.999 | 0.002 | 0.002 | 0.001 | 0.001 |
| 92 | 0 | 0.998 | 1.000 | 1.000 | 1.000 | 0.999 | 0.002 | 0.002 | 0.001 | 0.001 |
| 93 | 0 | 0.998 | 1.000 | 1.000 | 1.000 | 1.000 | 0.002 | 0.002 | 0.001 | 0.001 |
| 94 | 0 | 0.998 | 1.000 | 1.000 | 1.000 | 1.000 | 0.002 | 0.002 | 0.001 | 0.001 |
| 95 | 0 | 0.998 | 1.000 | 1.000 | 1.000 | 1.000 | 0.002 | 0.002 | 0.001 | 0.001 |
| 96 | 0 | 0.998 | 1.000 | 1.000 | 1.000 | 1.000 | 0.002 | 0.002 | 0.001 | 0.001 |
| 97 | 0 | 0.998 | 1.000 | 1.000 | 1.000 | 1.000 | 0.002 | 0.002 | 0.001 | 0.001 |
| 98 | 1 | 0.999 | 1.000 | 1.000 | 1.000 | 1.000 | 0.001 | 0.001 | 0.000 | 0.000 |
| 99 | 0 | 0.999 | 1.000 | 1.000 | 1.000 | 1.000 | 0.001 | 0.001 | 0.000 | 0.000 |
| 100 | 0 | 0.999 | 1.000 | 1.000 | 1.000 | 1.000 | 0.001 | 0.001 | 0.000 | 0.000 |
| 101 | 0 | 0.999 | 1.000 | 1.000 | 1.000 | 1.000 | 0.001 | 0.001 | 0.000 | 0.000 |
| 102 | 0 | 0.999 | 1.000 | 1.000 | 1.000 | 1.000 | 0.001 | 0.001 | 0.000 | 0.000 |
| 103 | 0 | 0.999 | 1.000 | 1.000 | 1.000 | 1.000 | 0.001 | 0.001 | 0.000 | 0.001 |
| 104 | 0 | 0.999 | 1.000 | 1.000 | 1.000 | 1.000 | 0.001 | 0.001 | 0.000 | 0.001 |
| 105 | 0 | 0.999 | 1.000 | 1.000 | 1.000 | 1.000 | 0.001 | 0.001 | 0.000 | 0.001 |
| 106 | 0 | 0.999 | 1.000 | 1.000 | 1.000 | 1.000 | 0.001 | 0.001 | 0.000 | 0.001 |
| 107 | 0 | 0.999 | 1.000 | 1.000 | 1.000 | 1.000 | 0.001 | 0.001 | 0.000 | 0.001 |
| 108 | 0 | 0.999 | 1.000 | 1.000 | 1.000 | 1.000 | 0.001 | 0.001 | 0.000 | 0.001 |
| 109 | 0 | 0.999 | 1.000 | 1.000 | 1.000 | 1.000 | 0.001 | 0.001 | 0.001 | 0.001 |
| 110 | 0 | 0.999 | 1.000 | 1.000 | 1.000 | 1.000 | 0.001 | 0.001 | 0.001 | 0.001 |
| 111 | 0 | 0.999 | 1.000 | 1.000 | 1.000 | 1.000 | 0.001 | 0.001 | 0.001 | 0.001 |
| 112 | 0 | 0.999 | 1.000 | 1.000 | 1.000 | 1.000 | 0.001 | 0.001 | 0.001 | 0.001 |
| 113 | 0 | 0.999 | 1.000 | 1.000 | 1.000 | 1.000 | 0.001 | 0.001 | 0.001 | 0.001 |
| 114 | 0 | 0.999 | 1.000 | 1.000 | 1.000 | 1.000 | 0.001 | 0.001 | 0.001 | 0.001 |
| 115 | 1 | 1.000 | 1.000 | 1.000 | 1.000 | 1.000 | 0.000 | 0.000 | 0.000 | 0.000 |
| Deviations @ S(x) = 0.980 (50 year drought) | | | | | | | 0.018 | 0.017 | 0.011 | 0.004 |
| Deviations @ S(x) = 0.985 (67 year drought) | | | | | | | 0.015 | 0.014 | 0.010 | 0.002 |
| Deviations @ S(x) = 0.990 (100-year drought) | | | | | | | 0.010 | 0.010 | 0.007 | 0.003 |
| Critical Deviation = 0.034 | | | | | | | | | | |
| The Weibull distribution best fits the drought duration series for the Rio Grande at Del Norte, CO. | | | | | | | | | | |

Table 3-10 below shows the estimated probability distributions for each of four distributions for drought durations for each of the six Rio Grande Basin headwater gages. As shown on the bottom row, the Weibull distribution provides the best fit for each of the six gages. The Weibull was therefore used to generate the drought scenarios for both the 50 and 100-year drought events.

**Table 3-10. Estimated Drought Duration Parameters, Four Probability Distributions, Six Headwater Gages, Rio Grande Basin**

| Distribution | Rio Chama at Chamita | Conejos River at Mogote | Rio Grande at Del Norte | Jemez River below Jemez Canyon Dam | Rio Puerco near Bernardo, NM | Rio Salado near San Acacia NM |
|---|---|---|---|---|---|---|
| EXPONENTIAL | | | | | | |
| avg(x) | 5.7300 | 5.1662 | 5.7587 | 5.0701 | 4.4208 | 5.5322 |
| $\lambda$ | 0.1700 | 0.1936 | 0.1737 | 0.1972 | 0.2262 | 0.1808 |
| GAMMA | | | | | | |
| Stage 1 | | | | | | |
| avg (ln x) | 1.1400 | 1.0724 | 1.1006 | 1.0614 | 0.9832 | 1.0806 |
| ln (avg x) | 1.7500 | 1.6421 | 1.7507 | 1.6234 | 1.4863 | 1.7106 |
| y | 0.6100 | 0.5697 | 0.6501 | 0.5620 | 0.5032 | 0.6300 |
| $\eta$ | 0.9600 | 1.0209 | 0.9100 | 1.0333 | 1.1391 | 0.9351 |
| $\lambda$ | 0.1680 | 0.1976 | 0.1580 | 0.2038 | 0.2577 | 0.1690 |
| Stage 2, Correcting for bias | | | | | | |
| $E(\eta_{est} - \eta)$ | 0.0022 | 0.0022 | 0.0021 | 0.0022 | 0.0022 | 0.0021 |
| $\eta_{corr}$ | 0.9600 | 1.0187 | 0.9079 | 1.0311 | 1.1369 | 0.9330 |
| $\lambda_{corr}$ | 0.1680 | 0.1972 | 0.1577 | 0.2034 | 0.2572 | 0.1686 |
| LOGNORMAL | | | | | | |
| avg (ln x) = | 1.1400 | 1.0724 | 1.1006 | 1.0614 | 0.9832 | 1.0806 |
| stdev (ln x) = | 1.0500 | 0.9984 | 1.0355 | 0.9872 | 0.9348 | 1.0170 |
| WEIBULL | | | | | | |
| $\alpha$ | 0.7900 | 0.8000 | 0.7326 | 0.7634 | 0.9950 | 0.5051 |
| $\beta$ | 5.6500 | 5.0920 | 5.7783 | 4.5755 | 5.7717 | 2.2712 |
| | | | | | | |
| Best Fit of 4 distributions | Weibull | Weibull | Weibull | Weibull | Weibull | Weibull |

Goodness of Fit Test to Identify Best Distribution. The Kolmogorov-Smirnov (K-S) test was used to identify which of the candidate distributions best fit the sample distribution of drought durations at each of the six unimpaired gaging stations. The candidate distribution with the lowest deviation at the point where the probability of a longer duration drought, S(x) = 0.985 was selected as the best fit. This definition of best fit assures that the selected candidate distribution fit the sample data well in the region of particular interest for 50-year and 100-year drought events. A 50-year event is defined as a drought with a probability of a longer drought equal to 1/50, which is 0.02. In terms of cumulative probability, this means S(x) is 0.980. A 100-year drought means S(x) = 0.990. The exponential cumulative density function, S(x), was generated using the EXPONDIST function in Microsoft Excel.

The following pages illustrate the calculations involved in the K-S test for the theoretical probability distributions for the drought duration series of the Rio Grande at Del Norte, CO. The K-S calculations compare deviations between the sample and theoretical cumulative density functions. Similar tests were performed for all six headwater gages.

Analysis of Drought Severity vs. Drought Duration. With the probability distributions for drought durations at the unimpaired gaging stations characterized, the relationship between drought severity (defined as average cumulative drought deficit) and duration (number of years a drought event lasts) was analyzed using linear regression techniques in Microsoft Excel. These analyses then complete the picture concerning the behavior of droughts, relative to annual streamflow, at the unimpaired gaging points in the Rio Grande Basin. It should be noted that, for each station, the correlation coefficient for the drought duration and deficit series was calculated using the CORREL function in Microsoft Excel in order to measure linear dependence between the two series.

From the probability distribution that best fit the drought duration series, the durations at which the cumulative probability, P(x), was equal to 0.98 and 0.99 represented the 50-year and 100-year droughts, respectively. These durations were then matched to the 50-year and 100-year deficits based on the linear regression. The 50-year and 100-year drought durations and deficits were identified. A part of the information concerning the relationship of drought duration to drought deficit for the Rio Grande is shown below in Table 3-11.

**Table 3-11. Sample of Rio Grande Drought Durations vs. Water Deficits**

| Regression Statistics | |
|---|---|
| Multiple R | 0.847 |
| $R^2$ | 0.717 |
| Adjusted $R^2$ | 0.716 |
| Standard Error | 6,574,162 |
| Observations | 1297 |
| Intercept | 0 |
| X Variable 1 | 964,976 |

| Regression Plot Series | |
|---|---|
| Drought Duration | Drought Deficit (cfs-yrs) |
| 1 | 964,976 |
| 2 | 1,929,952 |
| 3 | 2,894,928 |
| 4 | 3,859,904 |
| 5 | 4,824,880 |
| 6 | 5,789,856 |
| 8 | 7,719,808 |
| 9 | 8,684,784 |
| 10 | 9,649,760 |

Estimation of 50-year and 100-year Droughts at Unimpaired Gages

Fifty and one-hundred year drought scenarios are shown for each of the six headwater gages in four tables below. Table 3-12 shows annual values of total streamflow for 50-year drought scenarios, in total water production, cfs-years. The 50-year drought duration of longest duration is for the Rio Grande at Del Norte, CO, at 38 years. The shortest duration 50-year drought is for the Rio Puerco near Bernardo NM, at 25 years.

Table 3-13 shows total cumulative storage deficits as defined previously for each year at each of the six headwater gages. The drought is defined as ending when total storage deficit falls to zero.

Tables 3-14 and 3-15 show similar drought scenarios and storage deficits for the 100-year droughts.  The longest duration 100-year drought occurs for the Rio Grande at Del Norte, CO and Rio Salado near San Acacia, at 47 years, while the shortest duration is for the Rio Puerco near Bernardo, NM at 28 years.

| **Table 3.12. 50-Year Drought Scenarios, Six Headwater Gages, Rio Grande Basin, Total Annual Streamflows, in cfs-years.** | | | | | | |
|---|---|---|---|---|---|---|
| | Rio Chama | Rio Grande | Rio Salado | Conejos River[3] | Rio Puerco | Jemez River |
| Ave flow | 175,791 | 332,508 | 5,122 | 119,485 | 16,428 | 29,080 |
| Critical flow | 131,844 | 249,381 | 3,841 | 89,613 | 12,321 | 21,810 |
| Year | | | | | | |
| 1 | 78,802 | 81,263 | 1,123 | 53,465 | 7,783 | 2,491 |
| 2 | 140,210 | 8,234 | 1,121 | 59,411 | 15,634 | 11,562 |
| 3 | 38,741 | 2,053 | 5,868 | 25,632 | 8,059 | 19,447 |
| 4 | 35,147 | 577,582 | 3,719 | 55,692 | 12,319 | 22,227 |
| 5 | 53,473 | 129,288 | 2,625 | 93,017 | 12,502 | 20,327 |
| 6 | 107,666 | 77,197 | 4,988 | 90,033 | 5,188 | 6,749 |
| 7 | 358,023 | 376,162 | 4,004 | 147,041 | 6,894 | 6,239 |
| 8 | 1,521 | 59,047 | 1,994 | 32,253 | 12,674 | 19,825 |
| 9 | 158,821 | 138,692 | 1,529 | 85,445 | 12,456 | 22,350 |
| 10 | 38,237 | 269,495 | 5,910 | 43,147 | 6,522 | 66,705 |
| 11 | 119,968 | 430,264 | 7,836 | 65,276 | 19,578 | 17,763 |
| 12 | 67,014 | 219,778 | 5,338 | 30,948 | 5,515 | 10,259 |
| 13 | 88,876 | 242,119 | 904 | 52,051 | 11,459 | 7,467 |
| 14 | 60,599 | 242,401 | 3,339 | 191,456 | 3,633 | 32,948 |
| 15 | 257,241 | 243,592 | 1,477 | 132,977 | 2,590 | 4,998 |

[3]In this table and the following three tables, Conejos River flows include the Mogote gage only. The two other significant gages on the Conejos, for the Rio Grande Compact, are the Los Pinos and San Antonio. Drought scenarios for the sum of the three index gage flows can be estimated based on these tabled flows. Based on the period 1941-1985, multiplying flows at the Mogote gage by 0.375 explains 98.5 percent of the variance in Los Pinos gage flows. Multiplying Mogote gage flows by 0.088 explains 93.4 percent of the variance in San Antonio gage flows. So, multiplying Conejos column flows in this table by (1 + 0.375 + 0.088) = 1.463, produces drought scenarios for the three Conejos River index gages. Average total flow of the three Conejos Index flows, in acre feet per year, is computed as 119,485 (from the table) x 1.463 (three index flows based on Mogote flows) x 1.9837 (annual acre feet per cfs), which is just under 347,000.

| | | | | | | |
|---|---|---|---|---|---|---|
| 16 | 50,093 | 171,531 | 613 | 130,028 | 39,282 | 7,367 |
| 17 | 31,230 | 434,976 | 4,854 | 81,218 | 9,319 | 6,186 |
| 18 | 88,746 | 13,195 | 5,352 | 76,170 | 19,417 | 17,276 |
| 19 | 70,476 | 131,570 | 1,324 | 115,966 | 2,136 | 8,123 |
| 20 | 85,132 | 160,383 | 7,430 | 60,162 | 13,367 | 13,937 |
| 21 | 228,216 | 38,190 | 7,400 | 11,906 | 12,981 | 51,535 |
| 22 | 23,244 | 162,823 | 193 | 116,316 | 4,989 | 61,055 |
| 23 | 51,960 | 263,015 | 1,080 | 1,571 | 22,685 | 7,465 |
| 24 | 229,734 | 51,287 | 3,190 | 133,033 | 3,225 | 2,535 |
| 25 | 279,495 | 1,125,814 | 2,628 | 161,830 | 63,622 | 18,005 |
| 26 | 230,649 | 107,771 | 242 | 92,710 | | 9,818 |
| 27 | 181,442 | 514,983 | 916 | 215,203 | | 50,503 |
| 28 | 74,544 | 522,610 | 2,986 | 126,911 | | 109,198 |
| 29 | 27,986 | 235,306 | 9,117 | 334,250 | | |
| 30 | 96,276 | 359,288 | 4,251 | | | |
| 31 | 187,839 | 15,949 | 2,162 | | | |
| 32 | 1,031,389 | 48,697 | 6,995 | | | |
| 33 | | 303,632 | 5,045 | | | |
| 34 | | 9,167 | 8,987 | | | |
| 35 | | 72,031 | 4,233 | | | |
| 36 | | 36,062 | 12,628 | | | |
| 37 | | 164,073 | | | | |
| 38 | | 1,611,490 | | | | |

| **Table 3-13. 50-Year Drought Scenarios, Six Headwater Gages, Rio Grande Basin, Cumulative Storage Deficits, cfs-Years, Since Drought Onset.** | | | | | | |
|---|---|---|---|---|---|---|
| Year | Rio Chama | Rio Grande | Rio Salado | Rio Conejos | Rio Puerco | Rio Jemez |
| 1 | 78,802 | 168,118 | 2,719 | 36,149 | 4,539 | 19,320 |
| 2 | 140,210 | 409,265 | 5,440 | 66,351 | 1,225 | 29,568 |
| 3 | 38,741 | 656,593 | 3,415 | 130,334 | 5,488 | 31,932 |
| 4 | 35,147 | 328,391 | 3,538 | 164,255 | 5,490 | 31,515 |
| 5 | 53,473 | 448,484 | 4,755 | 160,852 | 5,309 | 32,998 |
| 6 | 107,666 | 620,668 | 3,609 | 160,433 | 12,443 | 48,059 |
| 7 | 358,023 | 493,887 | 3,446 | 103,006 | 17,870 | 63,631 |
| 8 | 1,521 | 684,221 | 5,294 | 160,366 | 17,518 | 65,617 |
| 9 | 158,821 | 794,909 | 7,607 | 164,536 | 17,383 | 65,077 |
| 10 | 38,237 | 774,794 | 5,539 | 211,002 | 23,183 | 20,183 |
| 11 | 119,968 | 593,911 | 1,545 | 235,341 | 15,926 | 24,230 |
| 12 | 67,014 | 623,514 | 49 | 294,006 | 22,732 | 35,781 |
| 13 | 88,876 | 630,776 | 2,987 | 331,570 | 23,594 | 50,125 |
| 14 | 60,599 | 637,756 | 3,490 | 229,728 | 32,282 | 38,987 |
| 15 | 257,241 | 643,545 | 5,856 | 186,365 | 42,013 | 55,799 |
| 16 | 50,093 | 721,394 | 9,084 | 145,951 | 15,053 | 70,242 |
| 17 | 31,230 | 535,799 | 8,072 | 154,346 | 18,055 | 85,867 |
| 18 | 88,746 | 771,985 | 6,562 | 167,791 | 10,958 | 90,401 |
| 19 | 70,476 | 889,795 | 9,080 | 141,438 | 21,144 | 104,088 |
| 20 | 85,132 | 978,793 | 5,492 | 170,890 | 20,098 | 111,962 |
| 21 | 228,216 | 1,189,984 | 1,934 | 248,598 | 19,439 | 82,237 |
| 22 | 23,244 | 1,276,542 | 5,582 | 221,896 | 26,771 | 42,993 |
| 23 | 51,960 | 1,262,907 | 8,344 | 309,939 | 16,408 | 57,338 |
| 24 | 229,734 | 1,461,001 | 8,996 | 266,520 | 25,503 | 76,614 |

| | | | | | | |
|---|---|---|---|---|---|---|
| 25 | 279,495 | 584,568 | 10,210 | 194,305 | 0 | 80,418 |
| 26 | 230,649 | 726,178 | 13,810 | 191,208 | | 92,411 |
| 27 | 181,442 | 460,576 | 16,735 | 65,619 | | 63,718 |
| 28 | 74,544 | 187,347 | 17,591 | 28,323 | | 0 |
| 29 | 27,986 | 201,422 | 12,316 | 0 | | |
| 30 | 96,276 | 91,515 | 11,906 | | | |
| 31 | 187,839 | 324,946 | 13,586 | | | |
| 32 | 1,031,389 | 525,630 | 10,433 | | | |
| 33 | 0 | 471,378 | 9,230 | | | |
| 34 | | 711,592 | 4,085 | | | |
| 35 | | 888,941 | 3,694 | | | |
| 36 | | 1,102,260 | 0 | | | |
| 37 | | 1,187,567 | | | | |
| 38 | | 0 | | | | |

| Table 3-14. 100-Year Drought Scenarios, Six Headwater Gages, Rio Grande Basin, Total Annual Streamflows, cfs-Years. | | | | | | |
|---|---|---|---|---|---|---|
| | Rio Chama | Rio Grande | Rio Salado | Rio Conejos | Rio Puerco | Rio Jemez |
| Ave. Flow | 175,791 | 332,508 | 5,122 | 119,485 | 16,428 | 29,080 |
| Critical Flow | 131,844 | 249,381 | 3,841 | 89,613 | 12,321 | 21,810 |
| Year | | | | | | |
| 1 | 34,914 | 53,472 | 1,775 | 18,058 | 12,071 | 6,181 |
| 2 | 113,412 | 71,100 | 3,140 | 141,815 | 8,858 | 25,011 |
| 3 | 37,522 | 70,618 | 3,933 | 60,491 | 5,155 | 5,462 |
| 4 | 46,005 | 388,368 | 2,929 | 79,026 | 4,898 | 37,988 |
| 5 | 184,885 | 137,318 | 3,746 | 49,787 | 13,996 | 13,600 |
| 6 | 81,394 | 152,001 | 5,710 | 16,175 | 7,986 | 10,060 |
| 7 | 23,395 | 155,365 | 2,805 | 21,322 | 6,989 | 46,650 |
| 8 | 66,080 | 247,501 | 1,320 | 5,605 | 7,062 | 15,514 |
| 9 | 58,117 | 150,309 | 1,191 | 25,782 | 8,347 | 8,582 |
| 10 | 95,318 | 154,929 | 702 | 205,190 | 5,604 | 14,226 |
| 11 | 82,786 | 512,305 | 5,187 | 119,105 | 6,599 | 4,495 |
| 12 | 157,282 | 112,820 | 3,522 | 122,868 | 20,933 | 14,419 |
| 13 | 7,733 | 85,989 | 4,748 | 157,710 | 16,945 | 20,162 |
| 14 | 16,938 | 15,139 | 535 | 50,224 | 9,495 | 35,710 |
| 15 | 58,903 | 113,448 | 5,793 | 33,837 | 5,522 | 17,846 |
| 16 | 258,787 | 92,165 | 1,159 | 80,422 | 48,023 | 25,331 |
| 17 | 13,898 | 138,730 | 6,136 | 73,569 | 6,179 | 19,526 |
| 18 | 16,172 | 281,916 | 1,621 | 169,065 | 11,915 | 25,153 |
| 19 | 69,306 | 54,091 | 5,472 | 92,098 | 18,147 | 7,704 |
| 20 | 214,488 | 585,657 | 2,741 | 21,774 | 6,681 | 6,017 |
| 21 | 45,320 | 135,331 | 1,750 | 103,725 | 25,477 | 52,655 |
| 22 | 153,904 | 411,166 | 274 | 15,258 | 6,267 | 3,813 |

| | | | | | | |
|---|---|---|---|---|---|---|
| 23 | 167,256 | 490,052 | 7,251 | 37,694 | 2,310 | 43,115 |
| 24 | 272,000 | 180,391 | 7,430 | 118,690 | 4,806 | 50,027 |
| 25 | 373,948 | 351,569 | 2,912 | 36,745 | 15,577 | 25,928 |
| 26 | 194,894 | 251,415 | 679 | 77,218 | 9,364 | 9,089 |
| 27 | 211,630 | 183,559 | 7,888 | 21,017 | 6,741 | 30,795 |
| 28 | 6,560 | 293,275 | 4,492 | 367,939 | 52,518 | 22,121 |
| 29 | 179,814 | 12,241 | 4,035 | 131,245 | | 14,244 |
| 30 | 51,902 | 372,304 | 690 | 28,917 | | 18,524 |
| 31 | 164,592 | 234,222 | 10,187 | 23,730 | | 19,577 |
| 32 | 67,032 | 204,214 | 3,321 | 36,029 | | 7,359 |
| 33 | 389,769 | 689,689 | 2,331 | 92,222 | | 32,106 |
| 34 | 20,420 | 620,910 | 875 | 212,936 | | 42,594 |
| 35 | 22,692 | 38,468 | 3,528 | 451,619 | | 32,924 |
| 36 | 216,709 | 20,629 | 1,287 | | | |
| 37 | 9,650 | 1,026,553 | 6,290 | | | |
| 38 | 79,099 | 276,608 | 4,349 | | | |
| 39 | 262,736 | 87,166 | 5,325 | | | |
| 40 | 822,940 | 155,564 | 4,301 | | | |
| 41 | | 567,731 | 8,282 | | | |
| 42 | | 213,582 | 2,755 | | | |
| 43 | | 55,354 | 1,777 | | | |
| 44 | | 201,584 | 7,339 | | | |
| 45 | | 127,084 | 163 | | | |
| 46 | | 484,593 | 10,408 | | | |
| 47 | | 885,320 | 8,331 | | | |

| Table 3-15. 100-Year Drought Scenarios, Six Headwater Gages, Rio Grande Basin, Cumulative Storage Deficits, cfs-Years, Since Drought Onset | | | | | | |
|---|---|---|---|---|---|---|
| | Rio Chama | Rio Grande | Rio Salado | Rio Conejos | Rio Puerco | Rio Jemez |
| Ave. Flow | 175,791 | 332,508 | 5,122 | 119,485 | 16,428 | 29,080 |
| Critical Flow | 131,844 | 249,381 | 3,841 | 89,613 | 12,321 | 21,810 |
| Year | | | | | | |
| 1 | 96,929 | 195,909 | 2,067 | 71,556 | 251 | 15,629 |
| 2 | 115,361 | 374,189 | 2,769 | 19,354 | 3,714 | 12,428 |
| 3 | 209,682 | 552,952 | 2,678 | 48,477 | 10,880 | 28,777 |
| 4 | 295,521 | 413,964 | 3,591 | 59,066 | 18,303 | 12,599 |
| 5 | 242,480 | 526,027 | 3,687 | 98,893 | 16,629 | 20,809 |
| 6 | 292,929 | 623,407 | 1,818 | 172,331 | 20,964 | 32,559 |
| 7 | 401,377 | 717,423 | 2,856 | 240,624 | 26,296 | 7,720 |
| 8 | 467,142 | 719,302 | 5,378 | 324,632 | 31,556 | 14,016 |
| 9 | 540,869 | 818,374 | 8,029 | 388,465 | 35,530 | 27,245 |
| 10 | 577,394 | 912,826 | 11,169 | 272,889 | 42,247 | 34,829 |
| 11 | 626,452 | 649,902 | 9,824 | 243,397 | 47,970 | 52,145 |
| 12 | 601,013 | 786,462 | 10,144 | 210,144 | 39,359 | 59,536 |
| 13 | 725,124 | 949,854 | 9,237 | 142,048 | 34,735 | 61,184 |
| 14 | 840,030 | 1,184,096 | 12,544 | 181,438 | 37,562 | 47,285 |
| 15 | 912,971 | 1,320,029 | 10,593 | 237,214 | 44,362 | 51,249 |
| 16 | 786,028 | 1,477,245 | 13,276 | 246,406 | 8,660 | 47,729 |
| 17 | 903,974 | 1,587,895 | 10,982 | 262,451 | 14,803 | 50,013 |
| 18 | 1,019,646 | 1,555,359 | 13,203 | 183,001 | 15,209 | 46,670 |
| 19 | 1,082,184 | 1,750,649 | 11,573 | 180,516 | 9,384 | 60,777 |
| 20 | 999,540 | 1,414,373 | 12,674 | 248,356 | 15,024 | 76,570 |
| 21 | 1,086,063 | 1,528,422 | 14,766 | 234,246 | 1,869 | 45,726 |
| 22 | 1,064,003 | 1,366,637 | 18,334 | 308,602 | 7,924 | 63,723 |

| | | | | | | |
|---|---|---|---|---|---|---|
| 23 | 1,028,591 | 1,125,965 | 14,925 | 360,523 | 17,935 | 42,419 |
| 24 | 888,434 | 1,194,955 | 11,337 | 331,447 | 25,450 | 14,203 |
| 25 | 646,330 | 1,092,766 | 12,267 | 384,315 | 22,194 | 10,085 |
| 26 | 583,279 | 1,090,732 | 15,430 | 396,712 | 25,152 | 22,806 |
| 27 | 503,492 | 1,156,553 | 11,384 | 465,308 | 30,732 | 13,821 |
| 28 | 628,776 | 1,112,659 | 10,734 | 186,983 | 0 | 13,510 |
| 29 | 580,806 | 1,349,799 | 10,541 | 145,352 | | 21,076 |
| 30 | 660,747 | 1,226,875 | 13,693 | 206,049 | | 24,362 |
| 31 | 627,999 | 1,242,034 | 7,348 | 271,933 | | 26,595 |
| 32 | 692,810 | 1,287,201 | 7,870 | 325,518 | | 41,046 |
| 33 | 434,885 | 846,893 | 9,380 | 322,910 | | 30,751 |
| 34 | 546,308 | 475,364 | 12,347 | 199,588 | | 9,967 |
| 35 | 655,460 | 686,276 | 12,660 | 0 | | 0 |
| 36 | 570,594 | 915,028 | 15,215 | | | |
| 37 | 692,788 | 137,856 | 12,767 | | | |
| 38 | 745,533 | 110,629 | 12,259 | | | |
| 39 | 614,640 | 272,844 | 10,776 | | | |
| 40 | 0 | 366,660 | 10,317 | | | |
| 41 | | 48,310 | 5,877 | | | |
| 42 | | 84,109 | 6,964 | | | |
| 43 | | 278,135 | 9,029 | | | |
| 44 | | 325,932 | 5,532 | | | |
| 45 | | 448,229 | 9,211 | | | |
| 46 | | 213,017 | 2,645 | | | |
| 47 | | 0 | 0 | | | |

## Economic Analysis of Farm Response to Drought in the San Luis Valley, Colorado[4]

Summary

An optimization model was developed that estimates net returns from cropping activities in the San Luis Valley, Colorado based on available surface and groundwater for agriculture. Results of the analysis indicate that crop production activities depend more on available groundwater than on surface water diversions from the Rio Grande.

Introduction

Agriculture accounts for nearly 90% of consumptive water use in the western United States (Gibbons 1986). Agricultural producers continue to experience increased competition for limited water resources with growing urban populations. Brajer and Martin (1990) state that water is not becoming scarce, but rather cheap water is becoming scarce as water markets develop.

Agricultural producers adapt to increased groundwater pumping costs, higher market values for voluntary water transfers, and environmental constraints on water through improved irrigation efficiency and reduced consumption (Moore, et. al. 1992). Surface water, with flows that are uncertain from year to year and groundwater from aquifers with declining water levels, represent the primary source of irrigation water for agricultural production. Sustained and severe drought conditions impact surface and groundwater supplies, adding an additional element of uncertainty to agricultural production.

Most institutional arrangements for water allocation in the west are based on the Doctrine of Prior Appropriation whereby the first person or organization that puts water to a beneficial use obtains a

[4]Considerably more detailed analysis was done for Colorado than for New Mexico or west Texas agriculture. A Ph.D. dissertation completed at Colorado State University focused exclusively on San Luis Valley agriculture (Sperow, 1998). In it the author developed detailed data sources and empirical relations regarding water use and crop production. By contrast, relations regarding crop production and water use are scarce in New Mexico and west Texas. Also the New Mexico-Texas section of the study required analysis of three irrigation districts, while detailed analysis in Colorado focused on one.

decree amount and the highest priority right to that water through adjudication in water courts where they exist. The Doctrine of Prior Appropriation is said by some economists to be economically inefficient because it fails to promote water conservation in the face of growing scarcity (e.g., Burness and Quirk 1979). In general, water markets that could, in principle, allocate water to higher economic valued uses are poorly organized. So market signals that have the potential to promote higher economic valued end uses are weak. Brajer and Martin (1990) contend that water is a social good and vital necessity with attributes beyond its commercial value, so it should not be treated as a normal commodity.

Much of the current competition for water in the San Luis Valley of Colorado comes from increasing urban populations along the Front Range that seek additional water sources. The competition for water in southern Colorado is much the same as in the case of New Mexico and Texas, additional water is needed to meet growing demands for uses outside agriculture, including endangered species habitat. Irrigated agriculture could provide a source for transferring water supplies to meet these growing demands since it typically absorbs the greatest amount of water in its use, and is of low economic value at the margin for many crops. The value of water to agricultural production and how agricultural producers respond to decreased water supplies in the face of drought by changing the mix of crops produced is an important issue in the west for water policy analysis.

This section of the report develops a model that simulates the Doctrine of Prior Appropriation in Colorado, identifies producer response to restricted water supplies, and estimates the value of water to agriculture in the study area. This study provides a foundation for studies into the relaxation of institutional constraints by developing an analytical method for identifying the value of irrigation water for agricultural production. The area of study is the Closed Basin portion of the San Luis Valley in south-central Colorado. The primary focus of the study is on changing surface water flows, however an extensive aquifer is also accounted for in the analysis. A model addressing the major surface and groundwater hydrologic features and the cropping patterns of producers in the region is developed. By analyzing income changes due to low-water flows, the value of irrigation water to agricultural production in the study area may be determined.

## Background

Rio Grande flow at the Colorado-New Mexico state line depends on snowpack, administration of the Rio Grande Compact, and behavior of Colorado agricultural producers. What ends up at the Colorado-New Mexico state line at the Lobatos gage depends on streamflow at Del Norte, Colorado, the amount of water diverted for agriculture in Colorado, and the delivery requirements specified in the Rio Grande Compact of 1938. The Rio Grande water has been over-appropriated. That is, more water has been allocated to users than is generally available from the river. Junior rights may not receive water during the growing season when surface water flows are low because senior rights, especially Rio Grande Compact requirements, take precedence.

The San Luis Valley in Colorado consists of approximately 3,200 square miles with an average elevation of about 7,700 feet. The Valley receives more water than most deserts in the country. The average annual rainfall is 7 to 10 inches, with more than half of the precipitation occurring between July and September. Crop production is difficult without supplemental water for irrigation. The short growing season of 90-120 days also limits the choice of crops (Doesken and McKee 1989).

Conjunctive use of surface and groundwater provides the water necessary to irrigate crops in the San Luis Valley. Groundwater in the San Luis Valley is obtained from an Unconfined Aquifer and a deeper confined aquifer, which are separated from another confined aquifer by a series of clay formations 10 to 700 feet thick. The study area is in the northern portion of the Valley that is referred to as the Closed Basin because it is internally drained. An alluvial divide prevents water in the Closed Basin from draining into the Rio Grande. Irrigation water diverted from the Rio Grande or pumped from the aquifer within the Closed Basin that is not consumed by evapotranspiration does not return to the Rio Grande, but recharges the Unconfined Aquifer within the Closed Basin.

Econometric (Nieswiadomy 1985; Ogg and Gollehon 1989; Moore and Negri 1992) and mathematical (Bryant et. al. 1993; Kulshreshtha and Tewari 1991) techniques have been used to describe water use by agricultural producers and to derive the value of water to crop production. Existing models that address river diversions for agriculture have excessive data requirements and many do not consider the Doctrine of Prior Appropriation. Wurbs and Walls (1989) developed a model that addresses prior appropriation by accounting for water rights assigned to reservoir storage facilities in Texas. Bredehoeft and Young (1983) analyzed a river basin delivering water to a single irrigation ditch for three areas with hypothetical rights and decrees allocated. A mathematical model is developed for the analysis that explicitly accounts for the Doctrine of Prior Appropriation, that is, economic returns from water are maximized subject to priorities defined by seniority of water rights.

## Analysis

The economic value of water to the San Luis Valley is determined using a two-stage optimization model that accounts for river flow, groundwater pumping, and effective rainfall. The Doctrine of Prior Appropriation is addressed in the first stage of the model to allocate river water from the Rio Grande to the irrigation ditches and canals holding the highest priorities. Rio Grande Compact requirements are calculated outside the model so all river flow within the model may be diverted for agricultural production. Municipal and industrial uses are not considered in the analysis because agriculture accounts for 97% of water use in the San Luis Valley. The amount of water diverted represents the amount of water available for crop irrigation. The area includes eight storage reservoirs that provide some water for agricultural production, but are not considered in the analysis because they are small and have junior water rights. Cropping and irrigation decisions are dependent upon the amount of surface water that is available and whether groundwater rights are owned by the producer. Cropping patterns and the associated net returns from irrigation water are estimated in the second stage of the model based upon crop production functions and costs of production for the primary crops produced in the study area.

The impact of decreased water supplies on crop production is analyzed by parametrically decreasing the amount of river flow and volume of available aquifer water and estimating the change in the value of crop production. The proportion of groundwater in the aquifer that may be pumped economically is not known with certainty. By parametrically decreasing available groundwater and surface water, the relative importance of groundwater pumping and surface water sources will be identified.

The Colorado Division of Water Resources has partitioned the state into seven water divisions organized around major drainage basins or series of rivers. The Rio Grande is in Water Division Three. River flow and diversion records are maintained by Water Districts, representing river basins. The San Luis Valley has six Water Districts with Water District 20 representing the Rio Grande Basin. The Rio Grande accounts for 70.1% of diversion rights in Water District 20 where 91 other sources (creeks and streams) also provide water. The Rio Grande accounts for 337 of the 861 water rights in Water District 20. Historical diversion records indicate that the Rio Grande accounted for over 93% of actual diversions from 1986 to 1995 in Water District 20. Simulating cropping activities that divert water from the Rio Grande is sufficient to account for most of the water diverted for irrigation in the Closed Basin.

Irrigation ditch/canal companies own the water rights in the San Luis Valley and producers own shares, each of which receives the same amount of water. Each ditch/canal company owns a suite of water rights with different priorities and decree amounts. Water right, decree amount, geographic location, and decree date were obtained from the Colorado Division of Water Resources. Five irrigation ditches/canals are included in the simulation - four actual irrigation ditches/canals and one to account for diversions to cropping activities outside the study area. Cropping activities are simulated only for representative agricultural areas along the four irrigation ditches/canals explicitly included in the model. Four of the 101 irrigation ditches on the Rio Grande account for over 60% of water rights within the study area. Explicitly included in the simulation model are the Rio Grande Canal, Farmer's Union Canal (now the San Luis Valley Irrigation District), Prairie Ditch, and the San Luis Valley Canal.

Table 3-16 identifies the number of acres serviced by each of the four irrigation ditches in 1995, the number of shares held by each ditch and the annual assessment for diverting water from the ditch. All other ditches are combined into a single diversion "ditch" with the priority and decree amount of individual diversions maintained.

**Table 3-16. Canals / Ditches Modeled in the Analysis, Acres Serviced by Canal/Ditch, Number of Shares Held by the Canal/Ditch, and Annual Assessment for Each Share, San Luis Valley Colorado.**

| Canal/Ditch | Acres | Number of shares | Assessment |
|---|---|---|---|
| Prairie Ditch | 13,196.40 | 250 | $300/share |
| Rio Grande Canal | 75,701.90 | 7152.825 | $60/share |
| San Luis Valley Canal | 10,051.50 | 13280 | $7.50/share |
| San Luis Valley Irrigation District | 7,933.10 | 388[a] | $1200/quarter-section |

[a] The ditch does not use shares, but services 388 quarter-sections. Landowners serviced by the ditch get an equal share of the water if they call for it.

The five canals/ditches represent the nodes addressed in the river flow model where water is diverted from the river. Figure 3-5 is a schematic of the Rio Grande with the irrigation ditches and canals included in the simulation model. Crop production is simulated for representative agricultural areas that divert irrigation water from the four irrigation ditches explicitly included in the simulation model.

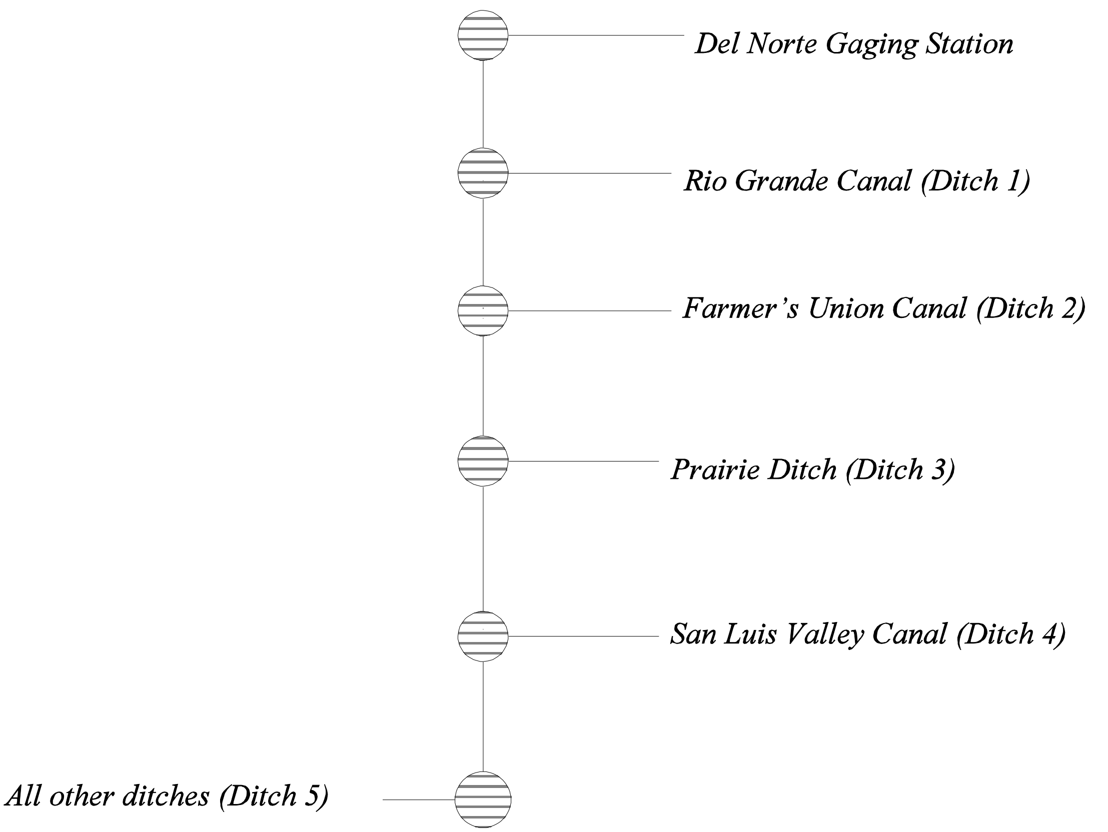



*Figure 3-5. Schematic of Irrigation Ditches/Canals and Ditch Number Identifier used in Simulation Model, San Luis Valley, CO.*

Groundwater in the study area is pumped from the unconfined aquifer that lies mostly below the north half of the Valley. Precise data for the amount of water in the aquifer are not available, but are estimated for this study. The depth to the blue clay series that separates the Unconfined from the Confined Aquifer represents the depth of the Unconfined Aquifer. This depth changes from north to south and west to east in the study area.

For analytical purposes, several assumptions were made.[5] The Unconfined Aquifer was divided into nine separate cells determined by the depth to the blue clay series, with each aquifer cell treated as a

---

[5]Many of these assumption necessarily simplifies reality. For example, water often moves more easily through the aquifer than these assumptions suggest. It would be highly desirable to develop a detailed hydrological model of the Valley that accounts for relevant interactions between aquifer size, shape, and characteristics, groundwater pumping, snowmelt, surface water supplies, surface water diversions, crop production, and crop return flows.

bowl containing an amount of groundwater dependent upon its volume. Water does not move between aquifer cells in the model during the cropping season. Recharge from drainage and recharge pits percolates only into the aquifer below where crop production is occurring. Aquifer recharge occurs from percolation from irrigation ditches and canals, watershed runoff, precipitation, and leakage from artesian wells. Two-thirds of aquifer recharge occurs during the cropping season and is allocated equally to each aquifer cell in the model. At the start of each simulation, a quantity of water is allocated to the nine aquifer cells in a way consistent with the movement of recharge water across the Valley. That is, each aquifer cell is allocated an amount of water equal to its share based upon the depth and holding capacity of the cell. Since water flows to the lowest point, the deepest aquifer cells receive water first and others receive water only if there is sufficient water.

The specific yield for most portions of the aquifer is approximately 0.20, which is used in this analysis (Emery 1970; Woodward-Clyde-Sherard and Associates 1967). In general, the aquifer locations cover areas from northwest to southeast with surface areas that range from 4,480 to 65,920 acres. The amount of water simulated in the nine aquifer cells (2.46 million acre-feet) compares well with other estimates of the Unconfined Aquifer (Woodward-Clyde-Sherard and Associates 1967).

Most producers in the study area do not apply surface water directly to their fields, but rather divert the water to holding ponds (known as recharge pits), which recharge the aquifer. Most water diverted to recharge pits percolates to the aquifer, but is not available for pumping until the next time period. The aquifer is also recharged through inefficient irrigation of applied water by crops. The amount of aquifer recharge from surface and groundwater sources is dependent upon the irrigation technology used. In the Closed Basin, all irrigation is done by relatively new center pivot equipment. Therefore, recharge rates are considered to be the same on each representative farm.

Thirty-three representative agricultural areas were used to simulate crop production along each of the irrigation ditches/canals included in the analysis. Representative agricultural areas were determined by the soil characteristics, source of surface water used for irrigation (ditch/canal), and groundwater source. The 47 primary soil types in the study area range from clay loam to gravelly sandy loam. These were partitioned into sand and sandy loam soils for the crop simulation model. These two soils account for a majority of the variation in soil characteristics. Representative agricultural areas were restricted to diverting surface water from a single irrigation ditch/canal and could pump groundwater from only the aquifer cell beneath the farm. Equipment and financial status of most farms in the Closed Basin are similar and were treated as such in the model. Farms within the study area were assumed to be price takers because the amount of production for any crop does not influence national prices. Even though Colorado is one of the leading producers of potatoes in the country, San Luis Valley production of this crop represents only 6% of national production. Alfalfa represents 4% of the national production and barley 2.7%.

Data were obtained on historic crop acreage for grain (primarily barley and spring wheat), potatoes, and alfalfa on each quarter section in the study area from 1983-1994, the primary crops produced. Malting barley is often grown with contracts from the Coors Brewing Company, but the higher prices received were not considered in the analysis. The seed variety most frequently grown (Moravian III) for both brewery contracts and feed is the same. Some vegetable crops, particularly carrots, lettuce and peas are gaining popularity, but are not considered primary crops so were not addressed in the analysis. Land around the periphery of the valley floor is used for grazing cattle, but cattle operations were not considered in the analysis.

The model was calibrated using river flow data for ten years for the Rio Grande at Del Norte, the headwater gage on the Rio Grande. The baseline model results for diversions and cropping patterns were compared to historic stream flows, diversions and cropping patterns to ensure that reasonable results were obtained.

Hydrology Model Development

A mass balance river flow model that diverts water by priority and decree amount was developed in GAMS (Brooke et. al. 1988). The model identifies diversions that maximize the total amount of water diverted while satisfying each decree by priority. When river flow is insufficient to satisfy all users, junior decrees are not provided water. Water available from each irrigation canal/ditch is used in the second stage of the model to simulate crop growth and estimate the value of crop production.

Five equations establish the constraints and water allocation amounts. First, diversions at each node must be less than or equal to the decreed water right held by the ditch at that node for each time period and must also be less than or equal to the amount of water in the river as shown in Eqs. 3.18a. and 3.18b. River flow is simulated for six time periods to account for the cropping season.

$$Divert_{i,t} \leq Water\ right_{i} \quad i = 1 - 123; \quad t = 1 - 6 \tag{3.18a}$$

$$Divert_{i,t} \leq Flow_{i,t} \quad \text{where i is the right (i = 1 - 123), and t is time (t = 1 - 6)} \tag{3.18b}$$

To simplify the analysis, water rights for ditches with consecutive priorities were grouped together and considered a single water right with a single priority, which reduced the total number of water rights from 337 to 123. That is, when a single irrigation ditch or canal owned priority numbers 1, 2 and 3, they were combined to priority 1 with a diversion right equal to the sum of decrees for the three rights.

Second, river flow at the first node is the same as the constant entered into the model as the flow for that time period. At the second and subsequent nodes, river flow is reduced by the amount of water diverted by upstream ditches (Eqs. 3.19a and 3.19b).

$$Flow_{i,t} = Inflow_t, \quad for \ i = 1 - 123; \ t = 1 - 6 \quad (3.19a)$$

$$Flow_{i,t} = Flow_{i,1t} - Divert_{i-1,t} \quad (3.19b)$$

Third, the highest priority ditches receive water before more junior priorities, even when the higher priority ditch is geographically located downstream from the junior priority. The objective of the first stage of the model is to maximize the total amount of water diverted to irrigation ditches constrained by the priority and decree amount of each irrigation ditch using Eq. 3.20. This weighted equation limits diversion of water at any upstream ditch to zero in each time period if there are downstream ditches with higher priorities and river flow is not sufficient to satisfy all rights.

$$\text{Objective} = \sum_{i=1}^{123} \sum_{t=1}^{6} 1 / \text{Priority}_i^2 * \text{Divert}_{i,t} \quad (3.20)$$

Equation 3.21 is used to identify the irrigation ditch receiving water and the amount of water diverted for each right.

$$\text{Ditch}_{l,t} = \sum_{I=1}^{123} \text{Divert}_{i,t} \quad \text{for each Owner}_i = \text{Ditch ID}_i \quad (3.21)$$

The volume of water in the aquifers is dependent upon the initial condition, quantity of water added from recharge pits, drainage of water not consumed by crops and the amount of water removed through pumping activities. Water added through recharge pits is positive when a representative farm diverts water from an irrigation ditch/canal. That is, to ensure all surface water is used in the analysis, to reflect operations in the San Luis Valley, all water diverted from an irrigation ditch/canal is used by the representative farm, either in recharge pits, or surface applied to a field by flood irrigation. Since all cropping activities in the study area use center pivot irrigation systems, a charge is assessed for flood irrigation activities to artificially force use of recharge pits. The amount of surface water available, water from irrigation ditches/canals less the amount of water surface applied, represents the amount of water applied to recharge pits.

Water not used by plants ("Drain") is calculated using Eq. 3.22.

$$\text{Drain}_{q,t} = \sum_{M=1}^{33} (1 - \text{ETA}_M) * \text{Wapplied}_{M,t} * \text{RtnFrac}_{M,q} \tag{3.22}$$

Where:

| | | |
|---|---|---|
| *Drain* | = | amount of water seeping into aquifer |
| *q* | = | aquifer identifier (1-9) |
| *t* | = | time periods (1-6) |
| *M* | = | farm (1-33) |
| *ETA* | = | irrigation efficiency by farm |
| *Wapplied* | = | amount of irrigation water applied to crops, and |
| *RtnFrac* | = | proportion of non consumption returning to aquifer. |

Pumping costs are included in the variable costs and are applied at a rate of $37.50 - $40.00/acre-foot for all representative agricultural areas while costs to apply surface water are much lower, estimated at $5/acre-foot.

Bredehoeft and Young (1983) found that the optimum capacity for wells in their study area (the Platte River Valley of Colorado) was about one-half the capacity of wells actually installed. Increased well capacity provided insurance against low-river flows, reduced the variance of expected income, and maximized expected income. Pumping rights are required to remove water from the aquifer in the study area of the San Luis Valley. Average well capacity in the region is 900-1000 gallons/minute. Estimated pumping capacities for some farms in the study area were higher than crop requirements, but groundwater rights are frequently less than pumping capacity. Representative agricultural areas were constrained to pumping no more than the minimum of the groundwater right plus the amount of recharge from recharge pits, the farm pumping capacity, or their proportion of the amount of water remaining in the aquifer. The farm proportion of aquifer water is based upon their proportion of total surface area above the aquifer.

Crop Growth Simulation Model

A crop growth simulation model was used to develop coefficients for the optimization model production functions (Cardon 1990). Second and third order polynomial equations, depending upon the crop, represent the results of the crop growth simulation model better than other functional forms. Equation 3.23 describes the general form of the crop growth function used for all crops to derive the relative yield variable:

$$Y = a + bX + cX^{2} + dX^{3} \qquad (3.23)$$

Where:
- $Y$ = relative yield
- $a$ = intercept coefficient
- $b$ = slope coefficient
- $X$ = amount of water applied (acre inches)
- $c$ = slope coefficient, and
- $d$ = slope coefficient.

Relative yield, Y, is constrained to be less than or equal to one in the model because production functions for all crops do not have a global maximum. Coefficients (Table 3-17) for crop growth functions were derived through regression analysis of data from the crop growth simulation model. The model employs a daily time-step to simulate the relationships between water and soil, water and plant growth and yield, and evapotranspiration to derive relative yield parameters based upon water available for plant growth. It simulates water movement through the soil profile and water uptake by the plant. Site specific input files were generated to reflect growing conditions and hydraulic properties of soils in the study area (Rawls 1992; U.S.D.A. 1988). Crop growth was simulated with the number of irrigation events varying from 0 to 24 for potatoes (fewer irrigations for alfalfa and barley) to generate production functions for each crop. All nutrients except water were assumed adequate for normal crop production and effective rainfall was included as a parameter.

**Table 3-17. Crop Growth Coefficients for Crop Production Functions (Eq. 3.23)**

| | a | b | c | d |
|---|---|---|---|---|
| Sandy Soils | | | | |
| Alfalfa | 0.06106 | 0.12290 | -0.00395 | 0.00000 |
| Barley | 0.24736 | -0.01420 | 0.00573 | -0.00016 |
| Potatoes | -0.01130 | 0.05690 | -0.00080 | 0.00000 |
| Sandy Loam Soils | | | | |
| Alfalfa | 0.48808 | 0.09000 | -0.00389 | 0.00000 |
| Barley | 0.38689 | 0.06960 | 0.02024 | -0.00245 |
| Potatoes | 0.40019 | 0.16650 | -0.01585 | 0.00052 |

Total water applied to crops is determined using Eq. 3.24 and is constrained to be less than the combined amount of surface water applied and pumped from the aquifer. Net irrigation is calculated using Eq. 3.21 where irrigation efficiency of the irrigation system is addressed.

$$\text{Wapplied}_{\text{M,t}} = \sum_{c=1}^{3} (\text{Wapprate}_{\text{M,c,t}} * \text{Cropacre}_{\text{M,c}}) \qquad (3.24)$$

Where: *Wapplied* = total amount of water applied to crops

*M* = farm (1-33)

*t* = time period (1-6)

*c* = crop (alfalfa, barley, potatoes)

*Wapprate* = a free variable determined by the model, and

*Cropacre* = number of acres planted to each crop.

$$\mathrm{Nir}_{M,c} = 12 * \sum_{t=1}^{6} \mathrm{Wapprate}_{M,c,t} * \mathrm{Eta}_{M} \quad (3.25)$$

where:

*Nir* = net irrigation amount

*M* = farm (1-33)

*t* = time period (1-6)

*c* = crop (alfalfa, barley, potatoes)

*W apprate* = a variable determined by the model, and

*Eta* = irrigation efficiency parameter

The objective of the second stage of the model is to maximize the sum of net returns from all crops and farms in the study area. Moore, Gollehon and Carey (1994) determined that the choice of acres on which to produce crops is the first decision made by producers and the cost of water was second. Therefore, the costs for shares of irrigation ditch water are not included in the optimization, but are subtracted from returns net of other variable costs. The coefficients for price and variable costs are included in Table 3-18.

**Table 3-18. Price and Variable Costs for Alfalfa, Barley and Potatoes**

| | Alfalfa | Barley | Potatoes |
|---|---|---|---|
| Price | $85.00/ton | $3.26/bu | $5.50/cwt |
| Variable Cost/Acre | $129.60 | $179.66 | $596.12 |
| Variable Cost/Yield | $24.25 | $0.34 | $0.12 |

Results and Discussion

The first stage of the model identifies river diversions to irrigation ditches consistent with actual diversions. Deliveries of 153,720 and 72,600 acre-feet are needed to satisfy Rio Grande Compact requirements for 100% and 50% flow levels, respectively. The amount of water available for diversion is

423,964 acre-feet when river flow is 100% and 211,982 acre-feet when river flow is at 50% of normal. The initial aquifer volume is 2,461,440 acre-feet, which declines to 1,230,720 acre-feet when the aquifer is at 50% of capacity.

The crop production portion of the model accounts for over 88% of crop acreage for the base year. Six of the seven representative agricultural areas lacking groundwater rights do not produce crops when 100% of river flows are unavailable, regardless of available aquifer water. These agricultural areas are included in the model to account for surface water diversions even though crop production does not always occur. The model accounts for 100% of crop production on farms holding both surface water and groundwater pumping rights.

The amount of water available from river flow for crop production, which is the amount of water diverted to irrigation ditches/canals, is included in Table 3-19 for 100% and 50% flows for each irrigation ditch/canal.

**Table 3-19. Water Diversions for Each Irrigation Ditch/Canal with 100% and 50% of River Flow Available**

| Ditch/Canal | Amount of River Diversions (Acre-feet) | |
|---|---|---|
| | 100% River Flow | 50% River Flow |
| 1 | 77,302.2 | 44,889.6 |
| 2 | 16,630.5 | 0.0 |
| 3 | 13,923.7 | 1,071.0 |
| 4 | 11,053.2 | 0.0 |
| 5 | 305,054.4 | 166,021.4 |

The amount of water used for crop production on each representative farm, the irrigation ditch from which water was diverted, total acres available for crop production, and the number of acres on which crop production occurred are included in Table 3-20. A 50% decline in river flow and available groundwater results in a reduction of 17,522 acres from full production of 144,973 acres when full water is available. Seven of the 33 representative agricultural areas reduce crop production in response to declining water supplies with 14,668 acre-feet less water applied to crops.

Acres producing alfalfa, barley and potatoes are included in Tables 3-21 through 3-23. Alfalfa production remains constant as river flow declines. A 50% reduction in both groundwater and surface water results in an 11% decline in alfalfa production. When there are no river flows and available water in the aquifer is at least 50%, alfalfa production is decreased by 17% compared to the results when full water is available from both groundwater and surface water sources.

**Table 3-20. Representative Farm, Irrigation Ditch/Canal from which Water is Diverted, Acres Available for Crop Production, Acres Cropped, and Amount of Water Applied when River Flow and Aquifer Volume are Full and Reduced by 50%**

| Farm | Ditch / Canal | Acres Available | Acres Cropped | | Water Applied to Crops (Acre-feet) | |
|---|---|---|---|---|---|---|
| | | | 100% Flow and Aquifer | 50% Flow and Aquifer | 100% Flow and Aquifer | 50% Flow and Aquifer |
| 1 | 1 | 14,268 | 14,268 | 14,268 | 38,005 | 38,005 |
| 2 | 1 | 11,316 | 11,316 | 11,316 | 28,693 | 28,693 |
| 3 | 1 | 12,792 | 12,792 | 12,792 | 33,109 | 33,109 |
| 4 | 1 | 13,776 | 13,776 | 13,776 | 36,439 | 36,439 |
| 5 | 1 | 3,936 | 3,936 | 3,936 | 10,831 | 10,831 |
| 6 | 1 | 3,444 | 3,444 | 3,444 | 2,811 | 2,811 |
| 7 | 1 | 3,936 | 0 | 0 | 0 | 0 |
| 8 | 1 | 3,444 | 0 | 0 | 0 | 0 |
| 9 | 1 | 5,412 | 0 | 0 | 0 | 0 |
| 10 | 2 | 7,380 | 7,380 | 7,380 | 20,682 | 20,682 |
| 11 | 2 | 2,952 | 2,952 | 2,952 | 7,082 | 7,082 |
| 12 | 2 | 1,968 | 0 | 0 | 0 | 0 |
| 13 | 2 | 12,792 | 12,792 | 12,792 | 10,353 | 10,353 |
| 14 | 2 | 2,952 | 2,952 | 0 | 2,416 | 0 |
| 15 | 2 | 3,444 | 3,443 | 3,443 | 2,794 | 2,794 |
| 16 | 2 | 1,968 | 1,967 | 0 | 1,593 | 0 |
| 17 | 2 | 1,476 | 0 | 0 | 0 | 0 |
| 18 | 2 | 2,460 | 2,460 | 2,460 | 2,124 | 2,124 |
| 19 | 2 | 2,460 | 2,460 | 0 | 2,161 | 0 |
| 20 | 2 | 1,968 | 1,968 | 1,968 | 5,083 | 2,284 |
| 21 | 2 | 984 | 490 | 0 | 1,432 | 0 |
| 22 | 2 | 4,428 | 4,428 | 4,428 | 3,861 | 3,861 |
| 23 | 2 | 3,444 | 3,444 | 3,444 | 2,602 | 2,602 |
| 24 | 2 | 1,476 | 0 | 0 | 0 | 0 |
| 25 | 3 | 984 | 330 | 25 | 738 | 57 |
| 26 | 3 | 984 | 984 | 984 | 2,893 | 2,893 |
| 27 | 3 | 8,856 | 8,855 | 8,855 | 7,232 | 7,232 |

| | | | | | | |
|---|---|---|---|---|---|---|
| 28 | 3 | 3,444 | 3,444 | 3,444 | 2,708 | 2,708 |
| 29 | 3 | 4,428 | 4,428 | 4,428 | 4,164 | 4,164 |
| 30 | 4 | 5,904 | 5,904 | 5,904 | 4,914 | 4,914 |
| 31 | 4 | 7,380 | 7,380 | 0 | 6,227 | 0 |
| 32 | 4 | 2,952 | 2,952 | 2,952 | 2,338 | 2,338 |
| 33 | 4 | 4,428 | 4,428 | 4,428 | 12,792 | 12,792 |

**Table 3-21. Acres of Alfalfa Produced with Different Quantities of Water Available**

| Proportion of | Proportion of River Flow (%) | | |
|---|---|---|---|
| Aquifer Available (%) | 100 | 50 | 0 |
| | ----------------- Acres -------------- | | |
| 100 | 24,425 | 24,425 | 24,425 |
| 50 | 21,751 | 21,751 | 20,331 |
| 0 | 5,306 | 4,444 | 0 |

Barley production requires less water than either alfalfa or potatoes, but the value of barley as a crop enterprise is less than either of the other two crops. To attain the highest net returns, production should be shifted away from lower value crops to higher value crops when water becomes scarce. The simulation model reflects the change in crop mix by reducing the amount of barley produced when water shortages occur. A 50% reduction in surface and groundwater causes a 9.8% reduction in barley production. Barley production is reduced by 33.3%, compared to production under full water availability conditions, when no river flow is available and 50% of the aquifer is available. This decline is larger than either the reduction in alfalfa or potato production, reflecting the shift away from lower value products and applying water to higher value products.

| Table 3-22. Acres of Barley Produced with Different Quantities of Water Available | | | |
|---|---|---|---|
| Proportion of | Proportion of River Flow (%) | | |
| Aquifer Available (%) | 100 | 50 | 0 |
| | -----------------Acres-------------- | | |
| 100 | 64,996 | 59,245 | 63,961 |
| 50 | 58,622 | 58,622 | 43,329 |
| 0 | 6,877 | 4,576 | 0 |

Potatoes are the highest value crop in the study area. As the highest value crop, irrigation of other crops should be reduced and the water applied to potatoes when river flows and available water in the aquifer decline. Potato production declines by 13.1% when river flow and available groundwater are reduced by 50%. When river flow is reduced to zero and 50% of aquifer water is available, potato production declines by 12.9% compared to production with full river flow and aquifer levels. The reduced potato acres is consistent with expectations when river flows are reduced to zero. Reduced acres of potato production in the face of reduced river flow are small, as most river shortages are allocated to grains and alfalfa, consistent with the high net income potential of potato production. However, the proportion of total acres for each crop produced remains relatively stable with 100% compared to 50% available surface and groundwater. Alfalfa production represents the same proportion (16.9%), barley production increases slightly (from 44.8% to 45.5%), and potato production declines slightly (from 38.3% to 37.5% of all production).

| Table 3-23. Acres of Potatoes Produced with Different Quantities of Water Available | | | |
|---|---|---|---|
| Proportion of | Proportion of River Flow (%) | | |
| Aquifer Available (%) | 100 | 50 | 0 |
| | -----------------Acres-------------- | | |
| 100 | 55,552 | 55,247 | 55,222 |
| 50 | 48,585 | 48,280 | 48,367 |
| 0 | 5,858 | 5,553 | 0 |

Total net returns from crop production with river flow and available groundwater varied from 100% to 0% are shown in Table 3-24. When available groundwater from the aquifer remains at 100%, reducing the river flow has only a minor impact on overall crop production. When river flow is reduced to zero, net returns show an increase because shares for irrigation ditch/canal water are not purchased, resulting in lower overall costs. Net returns are reduced $1.4 million when river flow is reduced by 50%, but available water from the aquifer remains at 100%. When river flow is 100% and available aquifer water is reduced by 50% net returns are reduced $10.7 million. When river flow and available aquifer water are reduced by 50%, net returns are reduced by nearly $11 million. A 50% reduction in available aquifer water is more costly than a 50% reduction in surface water, in the short run, by over $9.3 million.

**Table 3-24. Total Net Returns from Crop Production with River Flow and Aquifer Volume Declining from 100% to 0%**

| Proportion of | Proportion of River Flow (%) | | |
|---|---|---|---|
| Aquifer Available (%) | 100 | 50 | 0 |
| | ------- Net Economic Value of Returns ($) -------- | | |
| 100 | 83,866,156 | 82,511,569 | 84,405,297 |
| 50 | 73,187,984 | 72,927,298 | 70,0799,34 |
| 0 | 9,841,168 | 8,235,602 | 0 |

## Conclusions

The results of this analysis show the importance of the unconfined aquifer to crop production in the San Luis Valley and particularly in the study area. Net returns decline sharply when aquifer water is depleted, but are relatively unaffected by declining river flows.

Rio Grande flows are, however, important for crop production and recharging the Unconfined Aquifer. When river flow declines, irrigation diversions decline, and less water is available for aquifer recharge. As long as there is significant river flow, crop production is somewhat unaffected until very low flow levels occur. Net returns are $3.1 million higher when Rio Grande flows are 100% of normal with 50% of the aquifer, compared to returns when river flow and aquifer volume are both 50% lower.

These results should be interpreted with caution because cropping decisions in a static single-season simulation do not account for future events.

Recharge to the aquifer and allocation of water at the beginning of the simulation to each aquifer cell, based upon its volume and depth, were accounted for in the simulation model. However, recharge is allocated equally in each time period, and the movement of water between aquifer cells during the cropping season is not addressed. Additional research is required to refine the aquifer dynamics for both intra- and inter-year aquifer cells. Anecdotal evidence indicates that the aquifer cells should dry up from east to west, an artifact of aquifer dynamics that is not addressed in a static single-season model.

More robust findings would result from a dynamic model that accounted for declining aquifer levels in the cropping decisions by producers. The simulation model presented in this analysis can be used to provide input data for a discrete dynamic programming model. In the model presented, producers were free to deplete groundwater supplies because short-run decisions address only the current time period and do not consider future production possibilities.

## Documentation of Colorado Farm Drought Response Model

### Water Rights and Supplies

Agriculture is the primary industry in the San Luis Valley (SLV) of Colorado where natural precipitation is insufficient for producing most crops. Crop production in the SLV depends upon water flow in the Rio Grande and groundwater supplies during the cropping season in the basin area. Surface and groundwater are allocated by the doctrine of prior appropriation. A water right and priority are established by an individual or organization that applies water to a "beneficial use". The water right is maintained by continuing to use the water for the "beneficial use" for which the right was established and obtaining a decree from the water court, which legally establishes the priority date and decree amount of the water right. Irrigation ditch companies own surface rights for Rio Grande water. Producers own shares of the ditch and are allocated water based upon the number of shares they own and the amount of water diverted to the irrigation ditch from the river. Each ditch share receives an equal amount of water based upon the total number of shares issued by the ditch and the amount of water in the ditch, so when river flows are low, all shares are affected equally. Groundwater rights are property of the well owner. River diversions are controlled and monitored by the Division Engineer to ensure water is allocated accurately to water right holders.

Water supplies in the SLV are threatened from two different sources. First, increased demands for limited water supplies from metropolitan areas along the Colorado Front Range and nearby states are threatening to change the historical use of water in the SLV. Growing urban populations of New Mexico and Colorado are searching for additional sources of water for municipal and industrial uses. Over 97% of the water in the SLV is applied to agriculture. Agricultural cost and return budget analysis typically shows that on a per dollar per acre-foot basis, irrigated agriculture typically can afford to pay much less than cities will pay for the same water.[6]

Second, the amount of water flowing in the Rio Grande is dependent upon the amount of moisture accumulating as snow in the mountains over the winter. A sustained drought would impact river flow and water storage in the Unconfined Aquifer, thus affecting agricultural production. The purpose of this study is to provide decision makers, producers and water managers additional information about the value of water to agricultural production in the SLV, a topic which has not been analyzed.

The impact of exporting water out of the SLV or a sustained drought would have the same effect on agricultural production in the Valley - less water available for crop production. The analysis in the main text addresses the response to a sustained drought, which provides the same results as decreased water supplies from diversions to municipal and industrial uses outside the SLV.

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[6]Despite the low value of water in agriculture per acre-foot, many acre-feet of water are used in Colorado's Rio Grande Basin. In fact Colorado's use of water in the San Luis Valley has made many millionaires.

The response to sustained drought in the SLV is analyzed by simulating changes in cropping patterns and calculating the value of water by estimating the change in the value of crop production. A two-stage nonlinear optimization model is developed in GAMS (General Algebraic Modeling System) to allocate river water to irrigation ditches by priority and decree (Brooke, et al. 1988). The objective of the first stage is to maximize the amount of water allocated to ditches dependent upon the amount of water in the river. The first stage of the model allocates water to irrigation ditches based upon priority, decree and river flow for growing season months (April – September). A monthly time step is used in the GAMS model, so each simulation consists of six time periods.[7]

The objective of the second stage is to maximize the value of returns from crop production, determined by simulating irrigation and cropping decisions, constrained by available water, soil type, cropping history, and location. Cropping and irrigation decisions are based upon the amount of irrigation water available for crop production that is represented by the amount of water diverted to irrigation ditches from the river. The model identifies the changes in net returns from producing different crops when water shortages occur. Acres allocated to each crop on each farm were based upon the ten-year average of crops grown. Yields for each crop are derived from crop production functions generated by a crop growth simulation model.

The GAMS model is included in the Appendix with the input files used by the GAMS model. The remainder of this appendix includes a description of the optimization model that is not included in Chapter 3, the sources of data, and identifies the data manipulations required to obtain the correct format for successfully solving the model.

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[7]Important future research would examine water allocation on a daily basis. During the growing season, runoff experiences wide daily changes.

Selection of Water Source to Simulate

The Colorado Division of Water Resources has partitioned the state into seven water divisions organized around major drainage basins or series of rivers. The SLV study area is in the Rio Grande Basin designated as Water Division Three. Water divisions were historically subdivided into Water Districts, a classification that is no longer practiced, although data are maintained by these designations. The study area is in Water District 20, which contains 91 sources of water (rivers and streams) with 454 irrigation ditches and canals holding 861 water rights.

Simulating all the water sources and diversion nodes within the study area is too extensive to include in a river flow model. The Rio Grande accounts for 337 of the 861 water rights and 101 of the 454 irrigation ditches and canals in the study area. When decrees without a priority assignment and decrees for reservoir storage are not included, the Rio Grande accounts for 77.3% of all water decreed in Water District 20. Water rights for reservoir storage are junior and represent a very small proportion of total diversions from the Rio Grande. The most junior water rights are deleted from consideration because they cannot be simulated. Since the Rio Grande accounts for most of the decrees in study area, only irrigation ditches on the Rio Grande are simulated.

Six of the 101 irrigation ditches on the Rio Grande account for nearly 77% of diverted water from the Rio Grande. These irrigation canals and ditches (Rio Grande Canal, Farmers Union Canal, Monte Vista Canal, Prairie Ditch, San Luis Valley Canal, and the Empire Canal) account for a total of 56% of all diversions in Water District 20. The Rio Grande Canal, Farmers Union Canal, Prairie Ditch and San Luis Valley Canal account for over 60% of Rio Grande diversions, are in the study area, and are explicitly included in the model. The Monte Vista and Empire canals divert water from the Rio Grande, but apply it to acreage south of the river. All other ditches are combined into a single diversion "ditch" that maintains the priority and decree amount of individual diversions. The geographic location of the five ditches (specifically the upstream-downstream relationship) is not relevant because the priority and decree amount determine which ditches receive water. A downstream ditch with senior rights is allocated water by the model ahead of a junior upstream user.

Irrigation Ditch/Canal Data Analysis

The data were analyzed to determine if a limited number of ditches could adequately represent water diversions in the study area and to determine the proportion of diversions in Water District 20 provided by the Rio Grande. The methods used to determine which water sources and irrigation ditches to include in the model are identified in this section. The objective of the analysis is to identify the river source providing the majority of water for diversion to irrigation ditches and identify the irrigation ditches and canals that are likely to divert the majority of the water. The analysis in the remainder of this section addresses the relationship between the decrees for the six largest irrigation ditches and "all other" diversions to establish how representative the ditches included in the model are of all Rio Grande diversions. The proportion of decrees allocated to the four irrigation ditches explicitly included in the model can be derived from the tables.

Overall, Water District 20 contains 454 irrigation ditches with 17,707 cfs in decrees, based on numerous complex decrees. Associated with these ditches are 861 total water rights. The 12,418 cfs in decrees on the Rio Grande accounts for 70.1% of all decrees in Water District 20 (Table 3-25). Included in these data are many decrees without a priority assignment and decrees for reservoir storage. Decrees without a priority assignment are ignored because they cannot be simulated without arbitrarily assigning a priority and their dates of appropriation are recent. River flow would have to be above normal to satisfy these decrees. Above normal flows are not considered in this analysis.

| Table 3-25. Total Decrees from WD 20, Rio Grande and Six Ditches with Largest Decrees | | |
|---|---|---|
| **Location** | **Decrees (Cfs)** | **% of WD 20** |
| Water District 20 | 17,707 | 100.0 |
| Rio Grande | 12,418 | 70.1 |
| Top 6 Decrees | 10,119 | 57.0 |

The six ditches with the largest decrees in Water District 20 that divert water from the Rio Grande are included in Table 3-26 along with the decree amount. The six irrigation ditches and canals account for 57% of all decrees in Water District 20.

| Table 3-26. Irrigation Canals and Ditches with Largest Decrees in Water District 20 | |
|---|---|
| **Ditch Name** | **Decree (Cfs)** |
| Rio Grande Canal | 3,856 |
| Farmers Union Canal | 2,111 |
| Empire Canal | 1,526 |
| Prairie Ditch | 1,101 |
| Monte Vista Canal | 1,022 |
| San Luis Valley Canal | 500 |

Decrees for reservoir storage are not relevant to the economic analysis that addresses allocation of surface water to agricultural production. Six irrigation ditches contain decrees with no priority for diversion to reservoirs and the appropriation and adjudication dates are very recent. The six ditches are listed in Table 3-27 along with the amount of the decree, source of water, and appropriation/adjudication dates. According to Colorado water law, the appropriation date establishes the priority of the decree. These ditches are not considered in the analysis because they represent junior rights for reservoir storage with no priority assignments. These ditches represent 3,950 cfs that do not need to be addressed in the model. Removing the requirement to provide water to these ditches decreases the total decrees in Water District 20 to 13,757 cfs (Table 3-28). Total decrees allocated to the Rio Grande are 11,868 cfs, or 86.3%

of all decrees for Water District 20. According to these data, using the Rio Grande as a representative water source seems adequate because the Rio Grande accounts for nearly all the decrees in Water District 20.

**Table 3-27. Water District 20 Reservoir Decrees with No Priority and Late Appropriation/Adjudication Dates Not Included in the River Flow Model**

| Ditch Name | River Source | Decree Amount (Cfs) | Appropriation/ Adjudication Date |
|---|---|---|---|
| Continental Reservoir Rio Grande Exchange | San Antonio | 2,500 | 1968/1990 |
| Santa Maria Reservoir Rio Grande Exchange | San Antonio | 350 | 1968/1990 |
| Continental/Santa Maria Reservoir Exch. | San Antonio | 300 | 1981/1990 |
| Rio Grande/Santa Maria Reservoir Exch. | Rio Grande | 300 | 1981/1990 |
| Rio Grande/Continental Reservoir Exchange | Rio Grande | 250 | 1983/1990 |
| Santa Maria/Continental Reservoir Exchange | San Antonio | 250 | 1964/1990 |

**Table 3-28. Total Decrees from WD 20, Rio Grande and Six Ditches with Largest Decrees after Decrees Listed in Table A.2 Deleted**

| Location | Decrees (cfs) | % of WD 20 |
|---|---|---|
| Water District 20 | 13,757 | 100.0 |
| Rio Grande | 11,868 | 86.3 |
| Top 6 Decrees | 10,120 | 73.5 |

A number of the ditches on the Rio Grande have decrees with no priority, and are therefore not included in the model. Table 3-29 lists the ditches, canals, decree, and appropriation dates for the decrees with no priority that divert water from the Rio Grande.

| Table 3-29. Irrigation Ditches and Canals Diverting Water from the Rio Grande in Water District 20 with No Priority Number | | |
|---|---|---|
| Irrigation Ditch | Decree (Cfs) | Appropriation Date |
| Centennial Ditch | 164.80 | 11/01/1959 |
| Empire Canal | 1,021.00 | 11/01/1959 |
| Farmers Union Canal | 1,310.45 | 11/01/1959 |
| Monte Vista Canal | 681.54 | 11/01/1959 |
| Prairie Ditch | 734.04 | 11/01/1959 |
| Rio Grande Canal | 2,208.00 | 11/01/1959 |
| Rio Grande Res./Santa Maria Res. Exchange | 300.00 | 04/30/1981 |
| Rio Grande Res./Continental Res. Exchange | 250.00 | 07/31/1983 |
| Tres Rios No. 1 | 6.50 | 12/31/1991 |
| Tres Rios No. 2 | 6.50 | 12/31/1991 |
| Tres Rios No. 3 | 0.85 | 12/31/1991 |
| Tres Rios No. 3 | 2.00 | 12/31/1991 |
| Tres Rios No. 4 | 1.50 | 12/31/1991 |
| Tres Rios No. 4 | 2.00 | 12/31/1991 |

When all decrees for reservoir storage are deleted from the data for Water District 20, 774 of the original 861 decrees remain. This data refinement leaves 380 of the original 454 irrigation ditches and canals with a total of 7,415 cfs to address.

As shown in Table 3-30, after deleting diversions for reservoir storage and decrees with no priority, the total amount of decrees in Water District 20 declines to 7,415 cfs. The Rio Grande accounts for over 77% of the remaining decrees while the six largest ditches on the Rio Grande account for over 56% of all diversions in Water District 20. The Rio Grande's proportion of Water District 20 water rights declined because many of the water rights without a priority assignment represented Rio Grande diversions.

| Table 3-30. Total Decrees from Water District 20, Rio Grande and Six Ditches with Largest Decrees after Decrees with no Priority Number Deleted | | |
|---|---|---|
| Location | Decrees (Cfs) | % of WD 20 |
| Water District 20 | 7,415.183 | 100.0 |
| Rio Grande | 5,729.260 | 77.3 |
| Top 6 Decrees | 4,164.640 | 56.1 |

The six ditches diverting the largest amount of water account for over 72% of diversions from the Rio Grande (Table 3-31). There is a considerable drop between the sixth largest ditch (by decree amount) and the next largest, which is the Rio Grande Lariat Ditch with 106.8 cfs. This decree represents less than a third of the San Luis Valley Canal, which is the sixth largest and is less than two percent of all Rio Grande decrees.

**Table 3-31. Six Irrigation Canals and Ditches with Largest Decrees in Water District 20 After Deleting Decrees in Acre-feet and No Priority**

| Ditch Name | Decree (Cfs) |
|---|---|
| Rio Grande Canal | 1,648.5 |
| Farmers Union Canal | 801.45 |
| Empire Canal | 505.92 |
| Prairie Ditch | 500.98 |
| Monte Vista Canal | 367.02 |
| San Luis Valley Canal | 340.77 |

Not only is the amount of the decree critical in modeling producer response to a sustained drought, so too is the priority of the right. A severe and sustained drought means that not all priorities will be satisfied. The selection of irrigation ditches to include in the model is also based upon whether the simulated ditches have senior rights that will continue to receive water during periods of low river flow. The ditches that receive water during low river flows are determined by analyzing which ditches received water during average historic Rio Grande flows.

Decrees on the Rio Grande, excluding those deleted because they represented reservoir rights or were rights with no priority assignment, were ordered by the priority assigned by the Division of Water Resources to determine which irrigation ditches and canals receive water when river flows are below normal. These priorities are not sequential, so a new priority number was assigned that is sequential from 1-323. As shown in Table 3-32, of priorities higher than 75, the six largest irrigation ditches account for only 3.3% of decrees. However, the 75 decrees with the highest priorities account for only 8% of all water decreed from the Rio Grande. The top 100 priorities account for 1,038.2 cfs of river flow. When the river flow is 1,038 cfs, the six largest ditches would account for 44.8% of all water diverted for agricultural irrigation from the Rio Grande.

**Table 3-32. Comparing Priority and Decree of the Six Ditches with the Most Decrees and all Other Ditches with the Percent of Total Flow Required to Satisfy all Decrees**

| Priority | Decree of Others | Decree of 6 | All Others % of Required Flow | Top Six % of Required Flow | Required Flow |
|---|---|---|---|---|---|
| Priority <=25 | 111.44 | 3.00 | 97.4 | 2.6 | 114.44 |
| 25< Priority <=50 | 91.34 | 0.00 | 98.5 | 1.5 | 205.78 |
| 50< priority <=75 | 209.40 | 11.20 | 96.7 | 3.3 | 426.38 |
| 75< priority <=100 | 161.18 | 450.60 | 55.2 | 44.8 | 1,038.16 |
| 100< priority <=125 | 128.30 | 450.70 | 43.4 | 56.6 | 1,617.16 |
| 125< priority <=150 | 150.64 | 277.90 | 41.7 | 58.3 | 2,045.70 |
| 150< priority <=175 | 31.15 | 780.42 | 30.9 | 69.1 | 2,857.27 |
| 175< priority <=200 | 79.30 | 422.85 | 28.7 | 71.3 | 3,359.42 |
| 200< priority <=225 | 49.07 | 848.43 | 23.8 | 76.2 | 4,256.92 |
| 225< priority <=250 | 44.48 | 287.47 | 23.0 | 77.0 | 4,588.87 |
| 250< priority <=300 | 153.91 | 632.07 | 22.5 | 77.5 | 5,374.85 |
| Priority >300 | 354.41 | 0.00 | 27.3 | 72.7 | 5,729.26 |

The ten-year (1986-1995) daily average, minimum, and maximum monthly stream flow for the critical agricultural irrigation months for the Rio Grande as measured at the Del Norte gauging station are included in Table 3-33. These data indicate that, when river flows are average, the six ditches with the largest decrees would divert most of the water in May, June and July. However, during the remaining months, the decrees from all other ditches could divert the majority of the water from the Rio Grande. River flows at the maximum levels allow the six largest ditches to divert most of the water in all months. When flows are at minimum levels, however, the six ditches with the largest decrees would receive only minimal water.

| Table 3-33. Rio Grande Daily Average, Minimum and Maximum Flow for 1986-1995 at Del Norte During Critical Months for Agricultural Irrigation | | | |
|---|---|---|---|
| Month | Average Flow (cfs) | Minimum Flow (cfs) | Maximum Flow (cfs) |
| April | 738.3 | 227.0 | 3,580.0 |
| May | 2,547.4 | 561.0 | 6,920.0 |
| June | 3,321.4 | 1,020.0 | 7,150.0 |
| July | 1,488.2 | 260.0 | 6,120.0 |
| August | 715.4 | 189.0 | 2,450.0 |
| September | 530.2 | 207.0 | 1,240.0 |

All of the minimum river flows occurred in either 1990 or 1994. According to the priorities and decrees listed in Table 3-32, the six ditches with the most decrees would receive very little water during these years. However, from the data in Table 3-34, addressing actual diversions, the six ditches accounted for 50.1% and 57.0% of all diversions from the Rio Grande during these low flow years.

While the data in Table 3-33 provide an indication of the amount of water decreed for diversion, they provide no information on who actually is diverting water for irrigation. To gain a better understanding of which ditches are receiving water with various river flow levels, the actual diversion data are analyzed. Of the total diversions identified for Water District 20, the Rio Grande accounts for an average of 93.4% over the nine years of data analyzed. The six ditches with the largest decrees account for 63.8% of all Rio Grande diversions and 59.6% of all diversions in Water District 20.

Table 3-34 identifies total annual diversions for 1987-1995. During the lowest flow year, 1988, these six ditches and canals accounted for over 57% of all water diverted from the Rio Grande. In years with higher river flows, the six ditches account for most of the water diverted. In the year with the highest river flow (excluding 1987 which appears to be an anomaly), the six ditches with the most decrees accounted for over 72% of all water diverted from the Rio Grande.

| Table 3-34. Actual Rio Grande Diversions for the Six Ditches and Canals with the Most Decreed Water, all Other Ditches and Rio Grande Flow for 1987-1995 Del Norte Gauging Station | | | |
|---|---|---|---|
| Year | Diversions of Six Largest (cfs) | Diversions of All other Ditches (cfs) | Rio Grande Flow (cfs) |
| 1987 | 168,261 | 77,766 | 512,914 |
| 1988 | 106,362 | 78,872 | 219,240 |
| 1989 | 119,730 | 87,782 | 249,102 |
| 1990 | 132,844 | 92,819 | 265,165 |
| 1991 | 172,573 | 89,810 | 306,256 |
| 1992 | 140,434 | 86,126 | 245,601 |
| 1993 | 206,203 | 90,743 | 330,533 |
| 1994 | 155,188 | 93,208 | 272,279 |
| 1995 | 258,590 | 98,782 | 419,169 |

The results of this analysis indicate that the six ditches containing the most decrees adequately represent water diverted for agricultural irrigation from the Rio Grande.

Eleven of the 35 ditches not included in the analysis hold priorities higher than 100 accounting for more than 130 cfs in decrees (Table 3-32). Removing these decrees from the analysis allows the six ditches with the most decrees to account for more of the water in a drought situation.

Water Rights

Four of the six irrigation ditches and canals that account for most diversions from the Rio Grande are within the Closed Basin portion of the SLV. Water diversions for the Rio Grande Canal, Farmers Union Canal (now called the San Luis Valley Irrigation District), Prairie Ditch and the San Luis Valley Canal are explicitly simulated in the model. The Empire Canal (now called Commonwealth) and Monte Vista Canal are included in the "all other" category for which water diversions are accounted for by the model, but crop production is not simulated. Diversions by all irrigation ditches or canals are accounted for to ensure available water for ditches explicitly addressed in the model is accurate.

## Defining Representative Agricultural Areas

Representative agricultural areas were derived based upon location of the irrigation ditches and canals in relationship to soil characteristics, and locations of the underlying aquifers developed as a proxy for the Unconfined Aquifer. The Director of the San Luis Valley Water Conservation District provided a detailed map of the SLV that identified the areas serviced by each irrigation ditch and canal. These locations were mapped into a spreadsheet according to the U.S. Bureau of Land Management system of land subdivision (Quadrant, Township, Range and Section). The study area lies between Townships 39 and 43 North within Ranges 7 and 12 East.

Forty-seven representative agricultural areas were initially identified. However, when nine years of crop data were analyzed, no crops included in the model (alfalfa, barley and potatoes) were grown on four of the farms. In addition, ten of the farms were located on acres that did not own rights to surface water. Therefore, only 33 representative agricultural areas are simulated with two different soil types (sandy loam and loamy sand) that withdraw groundwater from 9 separate aquifers and divert surface water from five irrigation ditches or canals. Not all representative agricultural areas have access to groundwater, but all receive a portion of the surface water available. The methods used to define the acres of each crop, farm size, aquifers, soil characteristics, and allocation of surface and groundwater for the representative agricultural areas are included in the following sections.

## Defining Crop Acres

Ten years of cropping data by quarter-section were obtained from the USGS for the study area. The data include the number of acres and location of each crop grown from 1983-1994. Spreadsheet maps were generated documenting the location of the primary crop grown on each quarter-section to gain an understanding where different crops are grown in the study area. By knowing the Township, Range and Quarter-section of each crop, it can be mapped to the location of each representative farm so that the exact number of acres of each crop grown during the ten years can be placed directly at the farm location.

The primary crops for the region are alfalfa, barley and potatoes. The model simulates crop production on 112,129 acres which include 16,124 acres of alfalfa, 51,451 acres of barley, and 44,554 acres of potatoes. These data represent the ten-year average production acres for each crop. Using the average acres allocated to each crop over a historical period accounts for crop rotation sequences. For example, barley and potatoes are generally grown on the same fields. A ten-year average accounts for the proportion of acres allocated to each crop and accounts for crop rotations and changing cropping patterns. Acreage allocated to each crop is constrained to the average maximum acres of the crop grown during the ten years. That is, a representative farm is constrained in the model to producing no more alfalfa than has been historically produced on the given acres of the farm.

The maximum size of each representative farm is the sum of the acres allocated to each crop. Representative farm sizes range from 154 to 12,847 acres as identified in the input file Farm Acre.txt.

## Defining Aquifers

The Unconfined Aquifer represents the sole source of groundwater for agricultural production within the study area. The depth to groundwater, depth to the bottom of the aquifer, and the dynamics of return flows from irrigation activities presented complications when trying to model the single large aquifer. The aquifer is simulated in the model by dividing the Unconfined Aquifer into nine separate smaller aquifers with similar characteristics that were defined through three steps.

First, the blue clay layer, which separates the Unconfined from the Confined Aquifer, represents the depth of the Unconfined Aquifer, which changes from north to south and west to east in the Closed Basin. The depth to the blue clay layer for all parts of the Unconfined Aquifer by Township, Range and

Section were obtained from the Colorado Division of Water Resources and incorporated into a spreadsheet. The standard deviation of the depth to the blue clay layer for all cells within a defined aquifer ranged from 5 to 9.3 feet or about 8%. Depths to the blue clay ranged from 50 to 130 feet.

Second, the elevation of each Section (cell) within the study area was derived from topographic maps of the region. Aquifers defined for the model were further divided by grouping areas of similar elevations. The elevation of the study area ranges from 7,545 in the northeast to 7,760 feet in the west. The standard deviations of the differences between elevations within an aquifer ranged from 5.6 to 8.9 feet.

Third, to prevent the height of the aquifer from being above the surface, the relative elevation of the blue clay layer was determined by subtracting the depth to blue clay from the elevation at the surface. Each aquifer was then defined by identifying those cells (Sections) with similar relative elevations of the blue clay layer and height to the surface. In general, the aquifer locations cover areas from northwest to southeast with surface areas that range from 4,480 to 65,920 acres.

Aquifer volume, representing the amount of water available for pumping, is addressed as a parameter for the first time period in the GAMS model as V(o). Water available from the aquifer changes during the cropping season. Withdrawals for irrigation, recharge from water placed in recharge pits, and drainage from irrigation due to sprinkler inefficiencies, and non-consumptive use by crops make the aquifer volume dynamic.

## Defining Areas with Similar Soil Characteristics

Colorado County Soil Surveys for Alamosa, Conejos, Costilla, and Rio Grande were used to identify the soil characteristics for the optimization model and for the crop growth simulation model used to derive the crop coefficients. The study area consists of 44 different soil types that represent more than 50% of the soil in a given section. Soil classifications for the primary soil in each section were identified to determine if the area could be represented by a few soils. The soils generally range from loamy sand to gravelly sandy loam. For the simulation model, soils were identified as either sandy or loamy sand to account for the most likely differences between the actual soils found in the area. The soil type associated with each representative farm, the ditch, and aquifer from which water is withdrawn are included in the model. The specific soil characteristics are not included explicitly in the model. Crop coefficients for each production function are determined by the soil type and assigned accordingly to each representative farm.

### Allocation of Surface Water to Representative Agricultural Areas

Ditch shares are used in the model to allocate water from irrigation ditches and canals to representative agricultural areas. Ditch shares are distributed differently in the study area, depending upon the irrigation ditch company. When the irrigation ditches were built, shares were distributed equally to producers diverting water from the ditch so that all farms of the same size were entitled to the same amount of water. Over time, ditch shares were sold or traded until today when shares are not owned in proportion to the size of farm. For example, quarter sections on the Rio Grande Canal hold from 5-35 shares with each share receiving the same amount of water. The number of shares owned by each quarter section within the model is not known.

The Farmer's Union Canal (San Luis Valley Irrigation District) is unique because it issues each farm on the ditch one share for each quarter-section of cropland, and water is then allocated equally to each share holder. Farm share of each ditch was determined by running the model with water allocated proportionate to farm size, then changing proportions until the historical cropping patterns for all farms were simulated.

Surface water is not typically applied directly to fields for crop production within the study area. Between 80-95% of the irrigated acreage in the study area use recharge pits where surface water is diverted to a reservoir from which water is pumped to the center pivot for irrigation or drains directly into the aquifer through infiltration. A small cost penalty that is higher than pumping costs is applied within the GAMS model to prevent irrigation activities that apply surface water diverted from irrigation ditches directly to the field. For simplicity, in this analysis all water applied to recharge pits adds to available water in the aquifer for the farm associated with that aquifer. Representative agricultural areas are constrained to pumping no more than their combined groundwater right and recharge amount that are tracked separately throughout the simulation. Groundwater rights are separate and distinct from surface water rights, so surface water used to recharge the aquifer may be pumped without infringing upon the groundwater right.

Allocation of Groundwater to Representative Agricultural Areas

Groundwater pumping is constrained by whether a farm owns a groundwater right, the pumping capacity of the farm, and available groundwater. Data for groundwater rights for the study area were obtained from the Colorado Division of Water Resources. Rights were correlated to the representative agricultural areas through Township, Range, and Section as identified in the data. Groundwater rights are defined in cfs, which were converted to acre-feet per month for inclusion in the model. Groundwater rights for each of the 33 representative agricultural areas are identified in the model.

Pumping capacities for each representative farm were determined by estimating the potential amount of water that could be applied to fields if center pivots were run continuously 24 hours/day for the length of the growing season. The number of center pivots on each farm is a function of total farm acres - one center pivot for each 130 acres of crop land.

The amount of groundwater in the aquifer may decline over time from decreased snow melt infiltration and if return flows from irrigation and recharge pits are not sufficient to maintain the aquifer at capacity. Representative agricultural areas are further restricted to pumping less than their aquifer share, which is based upon the size of the farm. That is, the farm's aquifer share is a function of the total acres that are above the aquifer. Aquifer share, as defined for the input file for the model, is included in the model.

The amount of applied water available for crop growth is determined by the irrigation efficiency of the irrigation systems. Center pivots in the study area are of similar age and efficiency and are therefore treated that way in the analysis. An efficiency rating of 0.80 is used for all systems in the analysis as defined in the model.

## Costs and Returns

Enterprise budgets were developed from budgets and a custom rate survey generated by Colorado State University (Dalsted et al. 1996), and locally available data. Crop budgets for each crop analyzed are included in the model. The crop budget identifies variable and fixed costs of all pre-harvest, harvest, and operating costs.

## Description of Crop Growth Simulation Model

Coefficients for crop production functions were developed for the crops considered in the GAMS model using the crop growth simulation model developed by Cardon (1990). The modified van Genuchten-Hanks model combines a FORTRAN model developed by van Genuchten that simulates transpiration and redistribution of water and the Hanks BASIC model that simulates irrigation/infiltration. The model employs a daily time-step to simulate the relationships between water and soil, water and plant growth, and yield and evapotranspiration (ET) to derive relative yield parameters based upon water available for plant growth. It simultaneously simulates water movement through the soil profile and water uptake by the plant through a series of equations from the two separate models. Site specific input files were generated to reflect growing conditions in the study area. The remaining paragraphs of this section describe the crop growth simulation model parameters used.

The crop growth simulation model requires data for the hydraulic properties of the simulation site, specifically the water content, matric potential, and hydraulic conductivity. Water contents varied from 0.02 to 0.50 $cm^3/cm^3$ in increments of .02, for both sandy loam and sandy soils, to calculate matric potential and hydraulic conductivity. Matric potential is calculated using Equation 3.26.

$$H=He\ (\Phi/\Phi_s)^{-b} \tag{3.26}$$

Where:
- $H$ = matric potential
- $He$ = air entry water potential constants, -15.98 for sandy soils and -30.20 for sandy loam soils ( Rawls et. al. 1992)
- $\Phi$ = soil water content
- $\Phi_s$ = soil water content at saturation
- $b$ = constant parameter equal to 2.87 for sandy soils (Ghosh 1977) and 3.5 for sandy loam soils (Campbell 1974).

The unsaturated hydraulic conductivity is estimated using a single hydraulic content measurement and a moisture retention function (Campbell 1974):

$$K = K_{sat}(\Phi/\Phi_s)^{B} \tag{3.27}$$

Where:
- $K$ = unsaturated hydraulic conductivity
- $K_{sat}$ = saturated hydraulic conductivity (468 cm/hr for sandy soils and 62.16 cm/hr for sandy loam soils) (Rawls et. al. 1992)
- $\Phi$ = soil water content
- $\Phi_s$ = soil water content at saturation
- $B$ = parameter equal to 4.48 for sandy soils (Ghosh 1977) and for sandy loam soils (Campbell 1974 ).

The data from these equations are included in input files to run the crop simulation model. Input files were used that included irrigation, rainfall, matric potential, and hydraulic conductivity parameters. To generate crop production functions the number of irrigation events was varied to simulate changing water availability. Alfalfa was provided up to 21, potatoes 24, and barley 16 irrigation events during the growing season with varying amounts of water. To limit the number of permutations required to generate an adequate production function, pair-wise combinations of possible irrigation strategies were simulated that required 2,047, 256, and 4,095 input files for each of the crops and for each soil type.

Planting, irrigation and rainfall dates for each of the crops simulated (alfalfa, barley, and potatoes) are included in the model. Rainfall is incorporated into the model the day after irrigation occurs because this is the standard practice for adding water to the simulation model and because rainfall in the study area is minimal during the growing season. Irrigation generally begins on 15 April for all crops and continues until just before harvest. Scheduling for irrigation events were derived from generally available local knowledge, including expert opinion at the Colorado State University Cooperative Extension at the San Luis Valley Research Center, and the consulting firm, Agro Engineering.

A second input file, Van.fmk, is in the FORTRAN portion of the model, which is generated once. Included in this file are the crop coefficients, potential ET, rooting depth, osmotic salt potential, and matric potential at which yield is reduced by half. The osmotic potential is not relevant for this study, but is included in the input file. In the row above these columns are additional soil property variables. The first variable, 468, represents the saturated hydraulic conductivity for sandy soils. Next is the total porosity followed by the matric potential at the inflection point defined by Hutson and Cass (1987), which is calculated as:

$$H_i = a(2b/(1+2b))^b \tag{3.28}$$

Where: $H_i$ = pressure potential inflection point

a = air entry water potential (a constant equal to -15.98 cm for sandy soils and -30.20 for sandy loam soils) (Rawls et. al. 1992)

b = constant parameter equal to 2.87 for sandy soils (Ghosh 1977) and 3.5 for sandy loam soils (Campbell 1974).

Relative yield parameters for each crop are derived by taking the ratio of model generated ET to potential ET (USDA) for the study area. Figures 3-6 – 3-11 provide the data points generated by the crop simulation model for each combination of irrigation strategies. Figures 3-12 -- 3-17 show the production functions resulting from fitting a line to the point of maximum relative yield for each irrigation combination (no irrigation, one irrigation, two irrigations, and so on, with each irrigation at a different time).

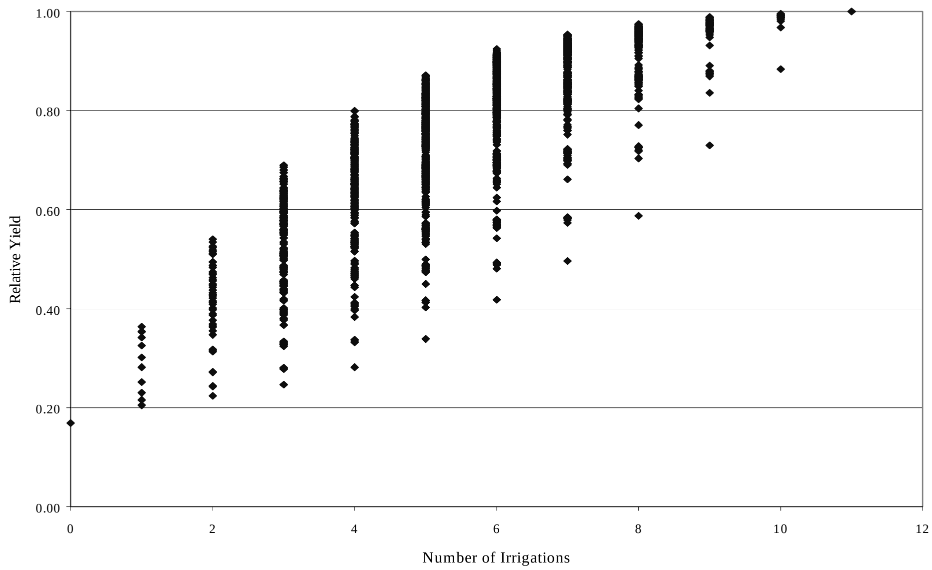


Figure 3-6. Relative Yield from Crop Growth Simulation Model with Each Possible Irrigation Combination for Alfalfa on Sandy Soil

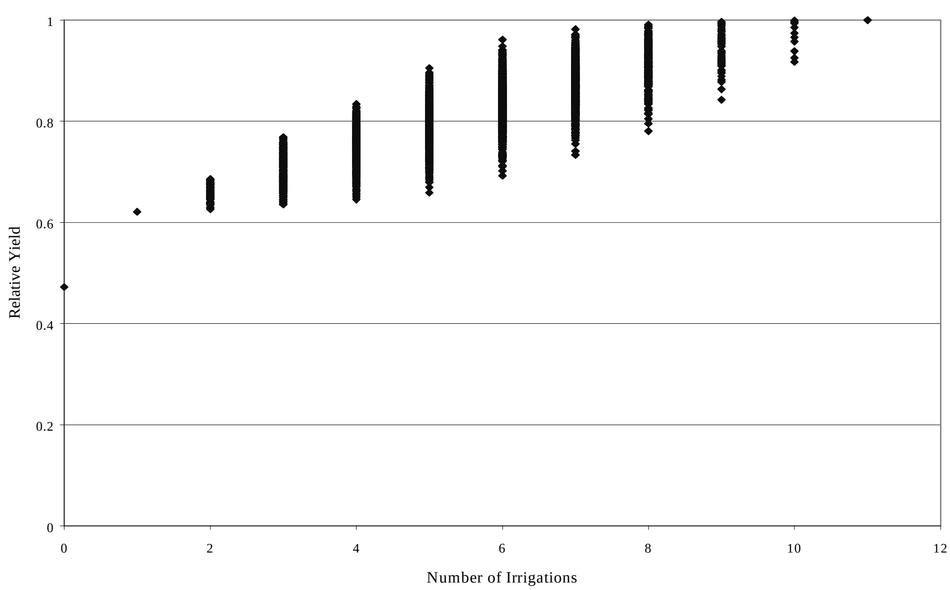


Figure 3-7. Relative Yield from Crop Growth Simulation Model with Each Possible Irrigation Combination for Alfalfa on Sandy Loam Soil

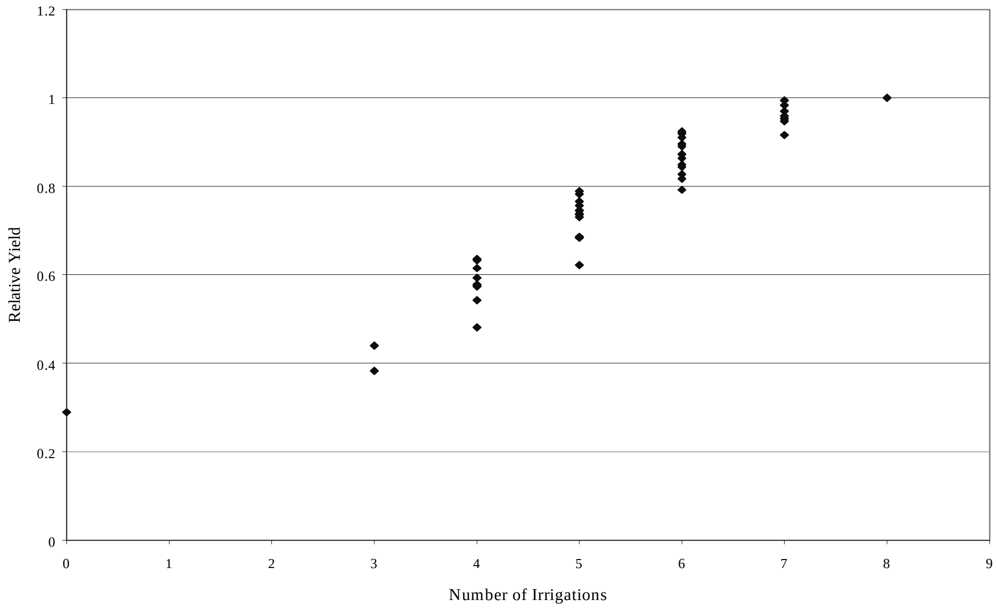


Figure 3-8. Relative Yield from Crop Growth Simulation Model with Each Possible Irrigation Combination for Barley on Sandy Soil

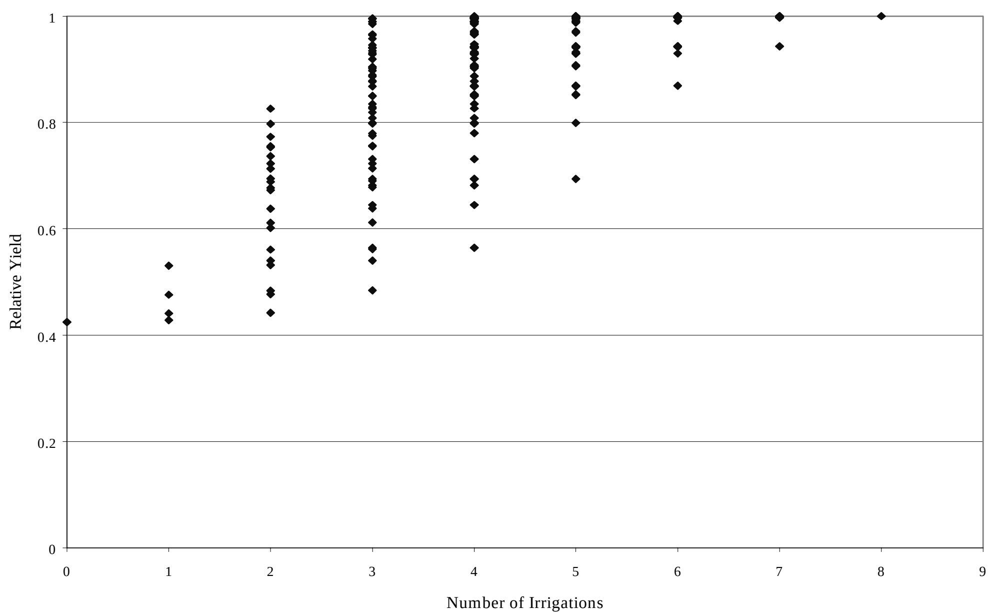


Figure 3-9. Relative Yield from Crop Growth Simulation Model with Each Possible Irrigation Combination for Barley on Sandy Loam Soil

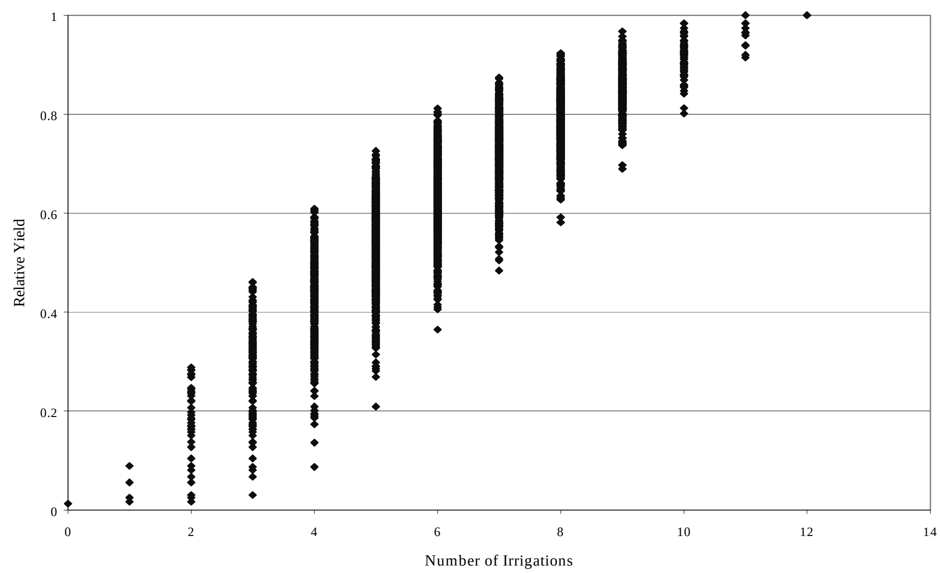


Figure 3-10. Relative Yield from Crop Growth Simulation Model with Each Possible Irrigation Combination for Potatoes on Sandy Soil

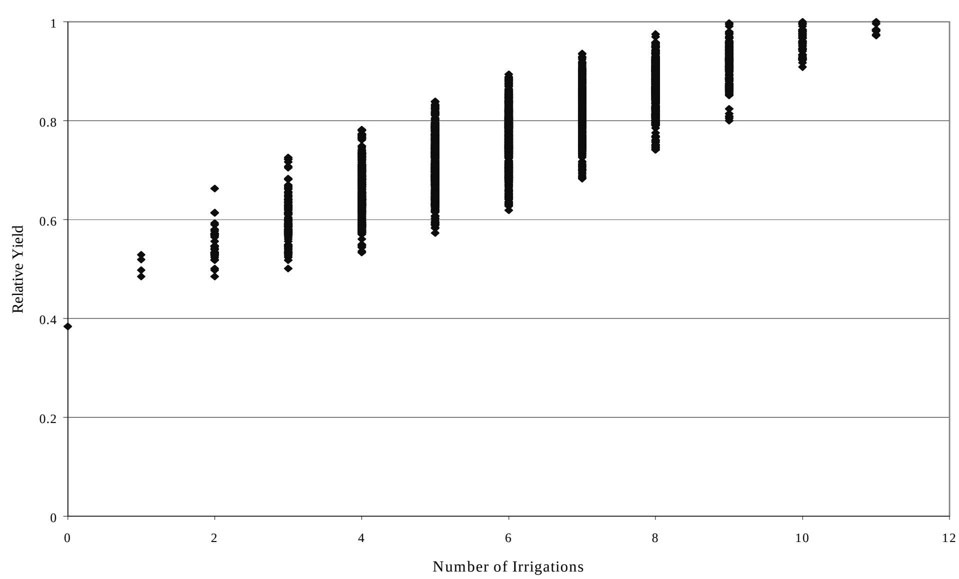


Figure 3-11. Relative Yield from Crop Growth Simulation Model with Each Possible Irrigation Combination for Potatoes on Sandy Loam Soil

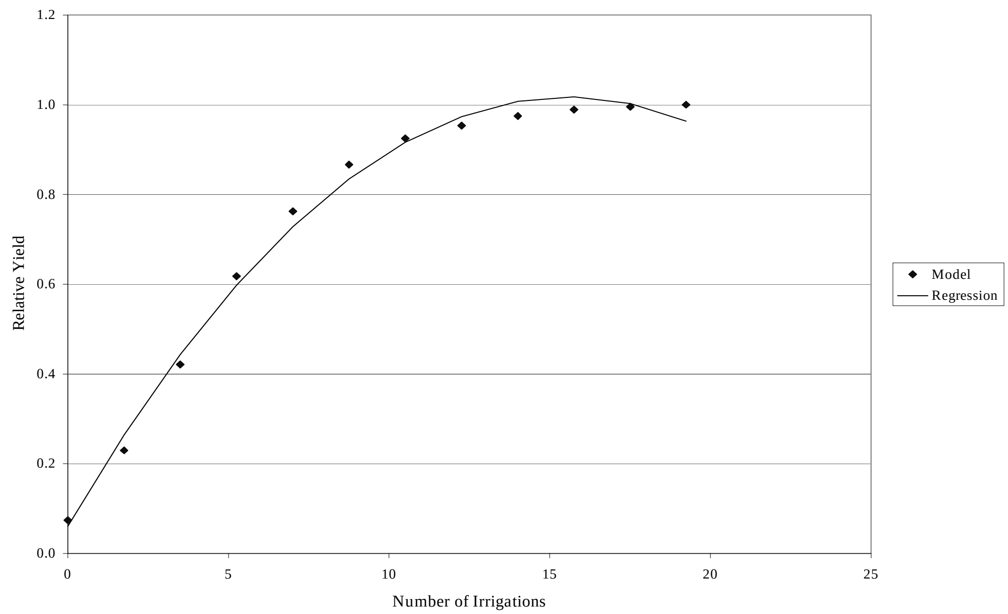


Figure 3-12. Regression Results to Derive Crop Growth Coefficients for Alfalfa on Sandy Soil

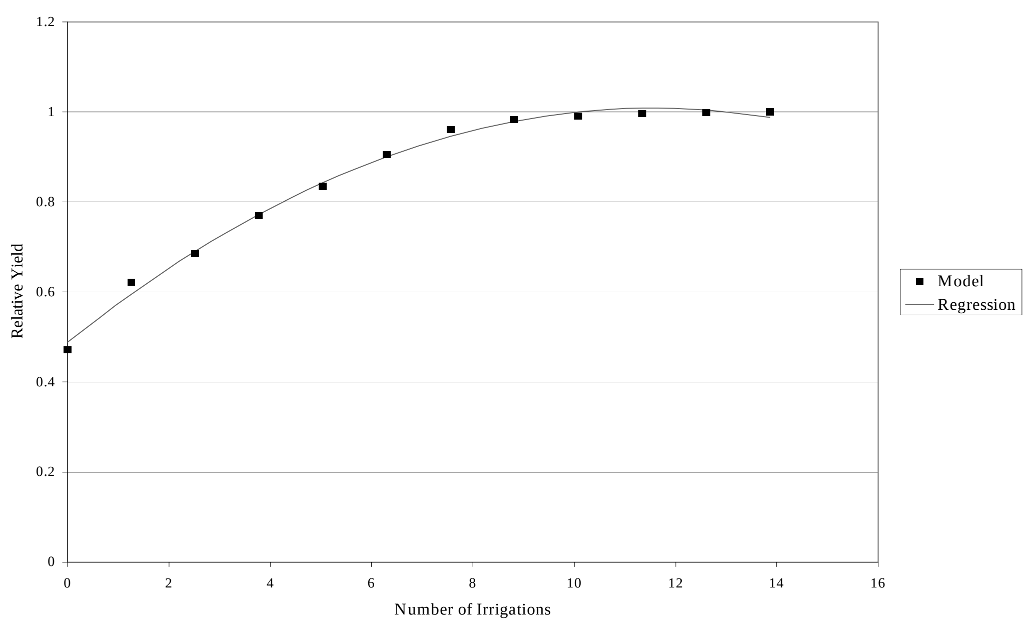


Figure
3-13. Regression Results to Derive Crop Growth Coefficients for Alfalfa on Sandy Loam Soil

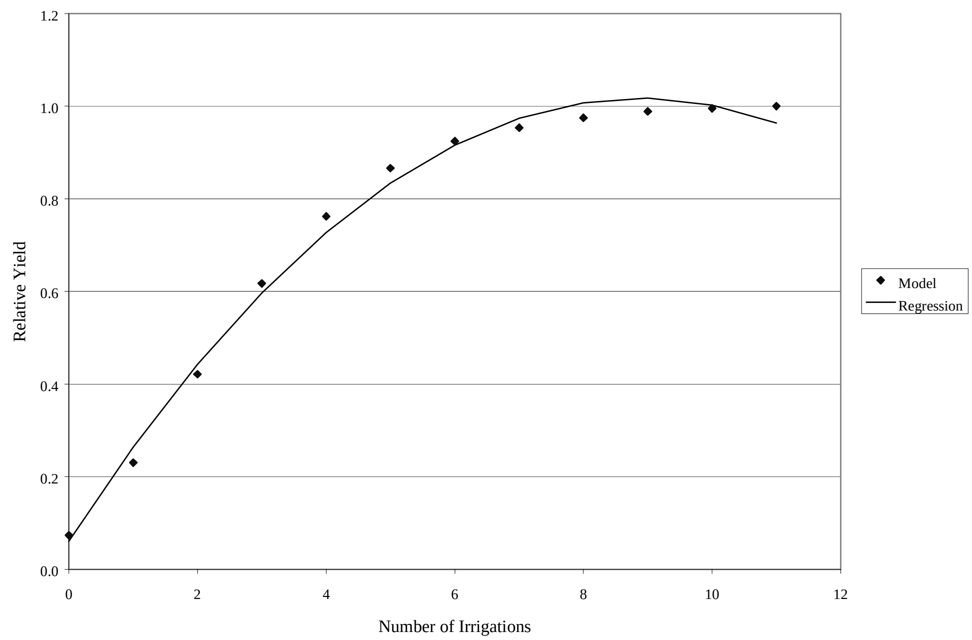


Figure 3-14. Regression Results to Derive Crop Growth Coefficients for Barley on Sandy Soil

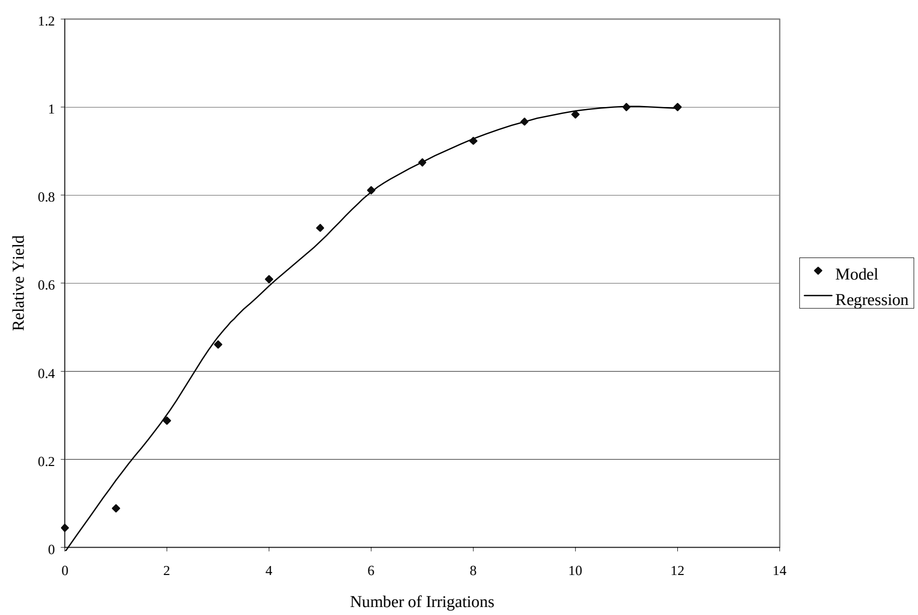


Figure 3-15. Regression Results to Derive Crop Growth Coefficients for Barley on Sandy Loam Soil

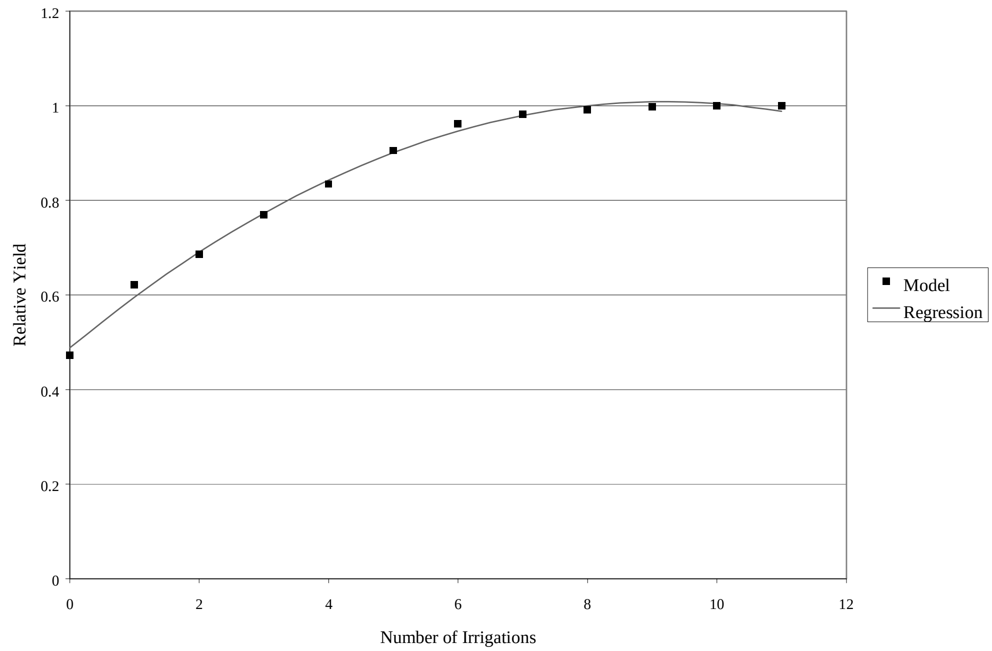


Figure 3-16. Regression Results to Derive Crop Growth Coefficients for Potatoes on Sandy Soil

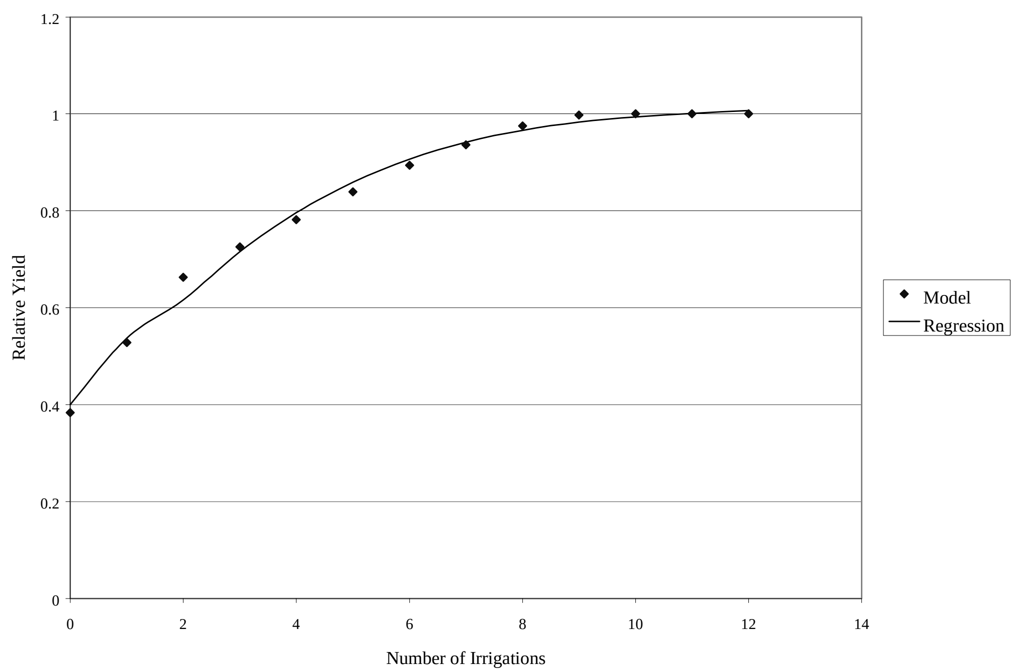


Figure 3-17. Regression Results to Derive Crop Growth Coefficients for Potatoes on Sandy Loam Soil

**Economic Analysis of Farm Response to Drought in New Mexico and West Texas**

Summary

This section of the report describes estimation of economic impacts of drought on irrigated agriculture for the Rio Grande Basin of New Mexico and West Texas. The analysis is based upon identifying cropping practices under full water supply conditions and estimating how those practices adapt to various degrees of drought severity. Agricultural prices, yields, and production costs are incorporated for 9 classes of crops, using New Mexico State University cost and return farm enterprise budgets, adapted to irrigated agriculture in the El Paso, Texas area, where complete Texas A&M farm budgets were not available. A linear programming model is used to represent behavior of commercial producers who maximize net returns. This farm behavior adjusts to 49 combinations of surface and groundwater shortages induced by drought, ranging from 3 to 0 acre-feet per acre of each water source.

Results indicate that for Elephant Butte Irrigation District, New Mexico income-maximizing net returns averaged $376 per acre with 82,680 acres planted under a full supply of surface and groundwater. Under the most severe drought, average net returns per acre rose to $538 on 19,950 acres of remaining pecan orchards produced from a deep aquifer. Returns from all remaining crops are zero. If additional water could be found, its economic value per acre-foot is $30 for surface water and $0 for groundwater when there is a full supply of both. In the face of increased drought severity, the value of additional water continues increasing to a maximum of $155 for the first acre-foot for surface water and $112 for the first acre-foot of groundwater when there is none of both.

Results for Middle Rio Grande Conservancy District, New Mexico showed income-maximizing net returns averaged $156 per acre with 54,000 acres planted under a full supply of surface water. This area has no significant groundwater development. Under the most extreme drought of zero available surface water for a year, net returns fall to zero with no production occurring. If added water were

available, its economic value per acre-foot is about $2 per acre-foot for surface water when there is a full supply. As drought becomes more severe, the value of added water continues increasing to a maximum of $44 per acre-foot for surface water when there is zero supply.

For El Paso area agriculture, results showed income-maximizing net returns averaged $409 per acre with 53,300 acres planted under a full supply of surface water. There is no significant groundwater development in this area. Under the most severe drought of zero available surface water annually, net returns fall to zero with no production occurring. If additional water were available, its economic value per acre-foot is zero when there is a full supply. As drought severity increases, the value of added water continues increasing to a maximum of $213 per acre-foot for surface water when there is zero supply.

## Analysis

Linear programming is a widely used method to determine the use of land, water, labor, and other resources and their associated net returns to a commercial farm. This method consists of expressing the farm producer's aim as a mathematical production program that aims to maximize net income. The decision maker is presumed to take actions that maximize net farm returns subject to a series of resource and marketing constraints. These constraints represent the farm's limited access to land and water resources and are typically written as linear equations.

## A Prototype Example

The following prototype example shows the general structure of the farm management problem. Suppose a commercial farm operator faces limited resources of land and irrigation water, including 500 acres of land and 20,000 acre-inches of water to use in the irrigation season, which amounts to 40 acre-inches per acre. This example shows an amount of water slightly above a full allocation water year for the Rio Grande Project, where the designed  full allotment is 3 acre-feet per acre. For this example, the operator is assumed to have three production choices: cotton, alfalfa, and lettuce. Each of these crops requires a certain amount of land and water, and also produces a known amount of net returns per acre. Suppose those values are as shown below in Table 3-35.

**Table 3-35. Water and Land Use in a Hypothetical Western Irrigated Farm**

| Crop | land use (acres) | water use (ac-inches/acre) | Net Returns/acre |
|---|---|---|---|
| cotton | 1 | 36 | $145 |
| alfalfa | 1 | 72 | $220 |
| lettuce | 1 | 45 | $450 |

Equations representing the economic decision environment for the producer are:

Maximize net income = 145 * Cotton + 220 * Alfalfa + 450*Lettuce (objective function)

in which the opportunity to increase net income is limited by the following three constraints on available resources:

1.0* Cotton + 1.0* Alfalfa + 1.0* Lettuce $\leq$ 500 (Land acreage constraint)

36 * Cotton + 72 * Alfalfa + 45 * Lettuce $\leq$ 20,000 (water constraint)

Cotton, Alfalfa, Lettuce $\geq$ 0 (Non-negativity constraints)

The three terms cotton, alfalfa, and lettuce are variables that represent decisions (decision variables), for which the value of each variable is unknown before solving the problem. They represent the number of acres of each crop that should be grown to maximize the producer's net income. This solution method is called linear programming because both the objective function and the constraints are algebraically linear. That is, none of the unknown terms have complicated exponents or other nonlinear terms. Because all terms are linear, there are many computer programs available to solve the problem.

The answer to the above farm management problem produces what is called an optimal solution. This optimal solution includes four important pieces of information for analysis of institutions for coping with drought in agriculture:

1. The maximum value of the objective function (in dollars)
2. The income-maximizing levels for each decision variable (# of acres)
3. The total amount of each resource used (land and water) including anything left over
4. The economic value (shadow price) of increasing the supply of each fully used resource by one unit; resources not fully used have a shadow price of zero. The shadow price is the economic value to the farm operator if one more unit of the scarce resource could be made available for use.

The above water and farm management problem has the following optimal solution, summarized in Table 3-36.

**Table 3-36. Solution to Hypothetical Farm Management Problem**

| **Item** | **Value** |
|---|---|
| Objective (net income) | $200,000 |
| Optimal Crop Mix (acres) | |
| Cotton | 0 acres |
| Alfalfa | 0 acres |
| Lettuce | 444 acres |
| Resource Use | |
| Land | 444 acres |
| Irrigation Water | 20,000 acre-inches |
| Economic value (shadow price) of one more unit ($/unit) | |
| Land | $ 0.00 |
| Water | $ 10.00 |

The income-maximizing plan for this example produce a net income of $200,000 with the crop mix shown. Only lettuce is grown in this example because its ratio of net income to water used per acre is the highest of the crops. The producer uses all available 20,000 acre-inches of water but only 444 acres of the 500 acres of land available. The shadow price measures what the producer can afford to pay for another unit of each resource. Water is fully used in the optimal solution, so the producer is willing to pay up to $10 for another acre-inch if he could find it. This is because one additional acre-inch produces $450 in net income divided by 45 acre-inches of added water per acre. Purchasing some from a neighbor or drilling a well are two possible sources of additional water. The shadow price for land, however, is zero dollars since not all existing 500 acres of land are used.

One can estimate the response of the producer, using linear programming, to a variety of conditions, including that of drought defined by water shortages. Impacts of drought can be estimated by solving the above numerous times with different quantities of water available, and observing the response of the producer's objective function, crop mix, and shadow prices as water supply is progressively reduced from a full supply to nothing.

Simulating a worsening drought, the availability of water is reduced systematically and the optimal response by the income-maximizing producer measured.

Extending this simple example, the general farm management problem can be stated as:

- decision variables are represented as $X_i$ for any given $i$th crop up to $n$ crops,
- net returns per acre as $NR_i$ for each $i$th crop,
- resource use $a_{ij}$ for each $i$th crop and the $j$ th resource, and
- resource availability $avail_j$ for up to $k$ resources.

Using this more general notation, the problem is written as:

$$\text{Maximize objective} = \sum_{i=1}^{n} NR_i \, X_i \qquad (3.29)$$

subject to: $\sum_{i=1}^{n} a_{ij} \, X_i \leq avail_j$ for available supply of all resources $j = 1, 2, ...$

$X_i \geq 0$ for $i = 1, 2, ...$

In practice, resource constraints may be enforced as inequalities ( $\leq$ or $\geq$) as well as equalities (=) depending on drought or other conditions facing farm producers.

New Mexico and West Texas Agriculture

Agricultural practices in New Mexico and West Texas consist of numerous supplies of resources, including both surface and groundwater constraints as well as other limiting resources such as land, labor and capital, technology constraints such as crop varieties, and weather conditions that influence crop yields such as temperature and rainfall. The three agricultural irrigation districts studied for this analysis include Middle Rio Grande Conservancy District (MRGCD), New Mexico, Elephant Butte Irrigation District (EBID), New Mexico, and El Paso Water Improvement District #1 (EPWID) near El Paso, Texas.

Each of the several hundred producers for this study in the three irrigation districts face their own resource constraints and preferences for crops and resources. Determining the unique conditions for each producer is impractical, which prompts use of the typical farm producer to represent the group.

Acreage Limits

Several parts of the previous simple model were expanded to more accurately show the regional response of each irrigation district. The presence of three major kinds of crops in this area of the Rio Grande Basin prompted the use of three land classes for the land constraints.

The first group, vegetable crops including lettuce, chiles, or onions, are often grown on contract. Such prearranged price and acreage agreements between producers and agricultural product buyers often results in a nearly constant amount of land devoted to those crops from one year to the next. Total demand within a given region typically changes little. Profitability is often high for such crops due to their specialty nature, but can vary widely if too many acres are planted within a region or the nation. Prices received in the study region can vary greatly in this situation, and for this reason vegetables are typically highly profitable but risky. When planting lettuce, for example producers may clear $600 per acre one year and lose $400 the next.

Row crops such as cotton or grain sorghum are generally less profitable but have somewhat more stable returns than the vegetables. In general such crops are not forward-contracted and acreage grown varies substantially as national prices vary.

Pecans are a major crop in southern New Mexico and West Texas and their large establishment costs prompted their inclusion as a separate land class. This crop is highly profitable and producers will likely go to great lengths to protect their large investment in orchards under times of drought. Several growers have drilled wells 500 feet deep or more to help insure dependable supplies of water for this valuable investment in the case of severe and sustained drought.

For these reasons, three separate land classes, one each for row crops, vegetables, and pecans were set up for the model. Total acreage within each land class were established based on historical information over the period 1988-1997, taking into account possible double cropping on some acreages as well.

Perennial crops such as alfalfa and improved pasture also require an establishment year in which no production takes place. Only variable costs of establishment are incurred in that year, yet scarce land is taken up by the establishment activity. Suppose that alfalfa fields take one year to establish and produce a crop in the following 4 years. A constraint reflecting this establishment requirement could read

$$ALFEST = 0.25 * ALF \tag{3.30}$$

where the variables are acres of alfalfa establishment and alfalfa, respectively. The constraint above means that if anything more than zero alfalfa acres (ALF) enters the optimal income-maximizing solution, then one quarter of its acreage amount must also be in the establishment activity. This equation requires that one quarter of the optimal alfalfa acres enters the solution, even though it contributes no positive return to the overall net income objective, other than to insure re-establishment of alfalfa acres over time. Similar constraints apply for irrigated pasture. Pecan acreage was assumed to be constant given the long useful life of those orchards and the uncertainty of when the next serious drought may occur.

Accounting for Risk

Another component of the model developed involves the notion of accounting for risk through the use of a concept known as flexibility constraints. Maximization of income in farm level linear programming models often results in overspecialization, that is, the maximization of net income under the conditions described might result in the model predicting that all available 500 acres should be planted with lettuce. The riskiness of vegetable production as well as the nature of forward contracts precludes the option of all acres being planted to one or more vegetables. Consequently, two sets of constraints were designed to allow a range of proportions for which the vegetable and row crops could vary.

The nature of these constraints is written as:

$$\sum_{k} VEG_{k} \leq \max propveg * TOTVEGACRE \qquad (3.31)$$

The above equation means that maximum proportions of vegetable acres are based on historical high and low proportions from area historical acreage. Note that many types of a given vegetable (i.e., sweet Spanish onions and midseason onions) can be included in order to make up the total amount of that vegetable type.

An additional constraint elsewhere in the program sums the total vegetable acres resulting in a known value of the term *TOTVEGACRE*, which is used by the equation above. Constraints similar to those shown above were also enforced for the row crops in the model. Inclusion of such flexibility constraints is often used in agricultural production models to add more realism to the model-predicted crop mix. The highly profitable crops will generally enter the solution at their maximum proportion and the less profitable crops at their lower bound proportion.

The situation becomes more complicated as resource availability of essential inputs such as irrigation water falls due to drought. Area-wide response by agriculture to drought typically shows that the more profitable crops per acre-foot of water, such as pecans and vegetables, stay in the solution, while less profitable row crops per unit water falls. For the EBID example, the program’s structure in which there are 3 land classes (pecans, vegetables, and row crops) deals with this fact.

Nevertheless, historically observed responses to previous droughts teach the lesson that the proportions of more profitable crops within a class (i.e., vegetables or row crops) sometimes increase as water supply conditions fall from full supply. As water supplies fall, producers can be expected to change to the more profitable crops within a classification, and that they will grow less, and sometimes none at all, of the less profitable crops within a class.

Accounting for Drought

For these reasons, a mechanism was added to the flexibility constraints described above which allows the range of producer responses to drought to widen as water supplies fall. Using the example of EBID, a full water supply is defined as 6 acre-feet/acre consisting in the model of 3 acre-feet of surface and 3 acre-feet of groundwater, reflecting the design of the Rio Grande Project and pumping permits established by the New Mexico State Engineer's Office.

For a given drought situation, the percent decline from this baseline was calculated. This decline was then applied to the midpoint of the historically observed high and low proportion for each crop. This calculation produced a percentage that could be added to the upper bound and subtracted from the lower bound proportion, thereby widening the flexibility constraints more and more as total water supplies dwindle. The example below illustrates this procedure in Table 3-37.

**Table 3-37. Sample methods and data, illustrated for onions, Elephant Butte Irrigation District, New Mexico**

| | | |
|---|---|---|
| 1. | Historically max proportion of crop<br>Historically min proportion<br>Midpoint of range | 0.3<br>0.1<br>(.1 + .3)/2 = .2 |
| 2. | Surface water supply in given drought<br>Ground water supply<br>Total water supply<br>Full water supply<br>Percent change | 2.0 ac ft/ac<br>1.0 ac ft/ac<br>3.0 ac ft/ac<br>6 ac ft/ac<br>(1.0 - 3.0/6.0) = 50% decline from full supply |
| 3. | Percent widening to be added/subtracted from full water supply crop proportions<br>= percent change calc. In step 2 * midpoint of range = 0.50 * 0.2 = 0.10 | |
| 4. | Modified upper bound proportion = original upper bound plus change<br>= 0.3 + 0.10 = 0.40<br><br>Modified lower bound proportion = original lower bound minus change<br>= 0.1 - 0.10 = 0.00 | |

For the example above, the original bounds of (0.1 and 0.3) are allowed to expand to (0.00 and 0.40) for the reduced water supply scenario with only 3 acre-feet per acre of total available water. Similar calculations were programmed for all water availability scenarios examined and the upper and lower bound proportions were allowed to widen as a function of reduced total water availability. An additional lower bound proportion of zero was also enforced.

One additional component was added to the flexibility constraints. In some cases the widening of the upper bound proportion can result in an absolute amount of acres well above historically observed highs for a crop. Such a situation makes little sense in a drought, so a second set of maximum acreage constraints for given crops were added. The program user may specify a maximum increase above the normal upper proportion for which the widening impact on proportions may apply. An example is be a 10% increase above the upper proportion. The program would then generate a second type of maximum acreage constraint for each crop type similar to the following:

$$\sum_k VEG_k \leq 1.1 * \max propveg * BASEVEGACRE \qquad (3.32)$$

In this case, *BASEVEGACRE* equals the normal total base vegetable acres. This constraint places a maximum upper bound on $VEG_k$ that is only 10 percent above historical highs. The optimization model will select the constraint most binding of this latter type of constraint and the maximum proportion constraints described earlier.

Crop-Water Production Technologies

Several crop-water production technologies were also incorporated. Farm producers can respond in several ways in times of drought. Including several crop water production options that vary the mix of surface water and groundwater producers use, reflects the range of drought response actions producers face.

These production technologies were included in two ways. The first consists of alternative production options based on water availability as summarized below. NMSU farm cost and return budgets for EBID (Doña Ana County), MRGCD (Socorro county), and EPWID#1 (adapted from Doña Ana County[8]) were used to represent water use by crops for a full water supply condition, referred to as the 'base' technology. Those budgets were adjusted to historical drought conditions to estimate water use, yields, and costs for two other crop-water use technologies. These included a 50 percent surface water 50 percent groundwater option, referred to as a 'mixed' technology, and as well as a 100 percent groundwater option, referred to as the 'all groundwater' technology. In fact, there is unlikely to be much groundwater pumping for either EPWID#1 or MRGCD according to their respective managers.

A fourth technology was also considered, namely crop production from a deep aquifer, which would only be used after all surface water and shallow aquifer groundwater is gone under the most severe drought. For this deep aquifer technology, yields, costs, and returns were calculated only for pecans as they are presumed the only crop capable of economically supporting the increased well drilling and deep aquifer pumping costs.

A second set of water conservation choices was also incorporated to allow producers the option of reducing their surface water use. These were applied to Upland and Pima cotton as well as alfalfa. Production options with reduced total water use, referred to as "water short" production options, were devised for each of the base, mixed, and all groundwater technologies described above. For EBID, water use was cut back from 36 to 24 acre-inches on both Pima and Upland cotton, with a corresponding reduction from 60 to 42 acre-inches on alfalfa. Yields and costs were reduced accordingly. An outline of the approach is shown in Table 3-38.

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[8]Texas A&M crop budgets were not available for El Paso area agriculture.

| Table 3-38. Crop Water use Technologies, Elephant Butte Irrigation District, New Mexico | | |
|---|---|---|
| **Production Technology** | **Description** | **Crops** |
| Base | NMSU cost and return farm budgets, typically based on 100 % surface water | all |
| Mix | Surface and groundwater mix includes 50% surface and 50% groundwater. Higher costs and/or lower crop yields occur. | all |
| All groundwater | 100% groundwater used for all crops. Higher costs and lower yields due to increased groundwater salinity. | all |
| Deep aquifer | Drilling of deep wells to maintain pecan production in extreme drought. | pecans |

Findings

Results of the income maximizing model, are presented in Table 3-39 for the case of EBID. Total economic returns, drought damages, net economic value per additional acre-foot of water (shadow price), and total acres planted, are shown for 49 combinations of ground and surface water available, reflecting various drought severity levels.

Similar kinds of results are shown in Table 3-40 and Table 3-41 for the remaining two districts, MRGCD and EPWID#1. For MRGCD, water applied varies from 6 to 0 acre-feet for surface water, with no significant groundwater. For EPWID#1 applications vary from 4 to 0 acre-feet, again with no groundwater. The same variables are shown for these two districts as for EBID.

## Table 3-39. Economic Damages from Selected Water Shortages, Elephant Butte Irrigation District, New Mexico

| Water supply | | Economic Returns | | Drought Damages | | Water's value | | Land |
|---|---|---|---|---|---|---|---|---|
| Surface Water (ac-ft/acre) | Ground-water (ac-ft/acre) | Net returns per acre ($/acre) | Total net returns all acres ($) | Economic losses/acre: compared to full supply ($/acre) | Total Economic Losses all acres: compared to full water allocation ($) | Added value + 1 a-f ($/ac-ft) | | Acres Planted (acres) |
| | | | | | | surface | ground | |
| 3.0 | 3.0 | 375.97 | 31,085,082 | 0.00 | 0 | 30.12 | 0.00 | 82,680 |
| 2.5 | 3.0 | 359.44 | 29,718,155 | 16.53 | 1,366,927 | 30.12 | 0.00 | 82,680 |
| 2.0 | 3.0 | 335.87 | 27,769,403 | 40.10 | 3,315,679 | 43.92 | 0.00 | 82,680 |
| 1.5 | 3.0 | 311.79 | 25,778,949 | 64.18 | 5,306,133 | 43.92 | 0.00 | 82,680 |
| 1.0 | 3.0 | 287.72 | 23,788,495 | 88.25 | 7,296,587 | 43.92 | 0.00 | 82,680 |
| 0.5 | 3.0 | 263.64 | 21,798,040 | 112.33 | 9,287,042 | 43.92 | 0.00 | 82,680 |
| 0.0 | 3.0 | 239.57 | 19,807,586 | 136.40 | 11,277,496 | 43.92 | 0.00 | 82,680 |
| 3.0 | 2.5 | 375.97 | 31,085,082 | 0.00 | 0 | 30.12 | 0.00 | 82,680 |
| 2.5 | 2.5 | 359.44 | 29,718,155 | 16.53 | 1,366,927 | 30.12 | 0.00 | 82,680 |
| 2.0 | 2.5 | 335.87 | 27,769,403 | 40.10 | 3,315,679 | 43.92 | 0.00 | 82,680 |
| 1.5 | 2.5 | 311.79 | 25,778,949 | 64.18 | 5,306,133 | 43.92 | 0.00 | 82,680 |
| 1.0 | 2.5 | 287.72 | 23,788,495 | 88.25 | 7,296,587 | 43.92 | 0.00 | 82,680 |
| 0.5 | 2.5 | 263.64 | 21,798,040 | 112.33 | 9,287,042 | 43.92 | 0.00 | 82,680 |
| 0.0 | 2.5 | 239.57 | 19,807,586 | 136.40 | 11,277,496 | 43.92 | 0.00 | 82,680 |

**Table 3-39 (cont.) Economic Damages from Selected Water Shortages, Elephant Butte Irrigation District, New Mexico**

| Water supply | | Economic Returns | | Drought Damages | | Water's value | | Land |
|---|---|---|---|---|---|---|---|---|
| Surface Water (ac-ft/acre) | Ground- water (ac-ft/acre) | Net returns per acre ($/acre) | Total net returns all acres ($) | Economic losses/acre: compared to full supply ($/acre) | Total Economic Losses all acres: compared to full water allocation ($) | Added value + 1 a-f ($/ac-ft) surface | ground | Acres Planted (acres) |
| 3.0 | 2.0 | 375.97 | 31,085,082 | 0.00 | 0 | 30.12 | 0.00 | 82,680 |
| 2.5 | 2.0 | 359.44 | 29,718,155 | 16.53 | 1,366,927 | 30.12 | 0.00 | 82,680 |
| 2.0 | 2.0 | 335.87 | 27,769,403 | 40.10 | 3,315,679 | 43.92 | 0.00 | 82,680 |
| 1.5 | 2.0 | 311.79 | 25,778,949 | 64.18 | 5,306,133 | 43.92 | 0.00 | 82,680 |
| 1.0 | 2.0 | 287.72 | 23,788,495 | 88.25 | 7,296,587 | 43.92 | 0.00 | 82,680 |
| 0.5 | 2.0 | 263.64 | 21,798,040 | 112.33 | 9,287,042 | 43.92 | 0.00 | 82,680 |
| 0.0 | 2.0 | 265.06 | 18,514,392 | 110.91 | 12,570,690 | 74.52 | 30.60 | 69,849 |
| 3.0 | 1.5 | 375.97 | 31,085,082 | 0.00 | 0 | 30.12 | 0.00 | 82,680 |
| 2.5 | 1.5 | 359.44 | 29,718,155 | 16.53 | 1,366,927 | 30.12 | 0.00 | 82,680 |
| 2.0 | 1.5 | 335.87 | 27,769,403 | 40.10 | 3,315,679 | 43.92 | 0.00 | 82,680 |
| 1.5 | 1.5 | 311.79 | 25,778,949 | 64.18 | 5,306,133 | 43.92 | 0.00 | 82,680 |
| 1.0 | 1.5 | 287.72 | 23,788,495 | 88.25 | 7,296,587 | 43.92 | 0.00 | 82,680 |
| 0.5 | 1.5 | 293.56 | 20,504,846 | 82.41 | 10,580,236 | 74.52 | 30.60 | 69,849 |
| 0.0 | 1.5 | 305.33 | 17,128,508 | 70.64 | 13,956,574 | 74.52 | 30.60 | 56,099 |

**Table 3-39 (cont.) Economic Damages from Selected Water Shortages, Elephant Butte Irrigation District, New Mexico**

| Water supply | | Economic Returns | | Drought Damages | | Water's value | | Land |
|---|---|---|---|---|---|---|---|---|
| Surface Water (ac-ft/acre) | Ground- water (ac-ft/acre) | Net returns per acre ($/acre) | Total net returns all acres ($) | Losses/acre: compared to full supply ($/acre) | Total Losses all acres: compared to full supply ($) | Added value +1 a-f ($/a-f) | | Acres Planted (acres) |
| | | | | | | surface | ground | |
| 3.0 | 1.0 | 375.97 | 31,085,082 | 0.00 | 0 | 30.12 | 0.00 | 82,680 |
| 2.5 | 1.0 | 359.44 | 29,718,155 | 16.53 | 1,366,927 | 30.12 | 0.00 | 82,680 |
| 2.0 | 1.0 | 335.87 | 27,769,403 | 40.10 | 3,315,679 | 43.92 | 0.00 | 82,680 |
| 1.5 | 1.0 | 311.79 | 25,778,949 | 64.18 | 5,306,133 | 43.92 | 0.00 | 82,680 |
| 1.0 | 1.0 | 322.05 | 22,495,301 | 53.92 | 8,589,781 | 74.52 | 30.60 | 69,849 |
| 0.5 | 1.0 | 340.81 | 19,118,962 | 35.16 | 11,966,120 | 74.52 | 30.60 | 56,099 |
| 0.0 | 1.0 | 375.97 | 31,085,082 | 0.00 | 0 | 30.12 | 0.00 | 82,680 |
| 3.0 | 0.5 | 359.44 | 29,718,155 | 16.53 | 1,366,927 | 30.12 | 0.00 | 82,680 |
| 2.5 | 0.5 | 335.87 | 27,769,403 | 40.10 | 3,315,679 | 43.92 | 0.00 | 82,680 |
| 2.0 | 0.5 | 350.55 | 24,485,755 | 25.42 | 6,599,327 | 74.52 | 30.60 | 69,849 |
| 1.5 | 0.5 | 376.29 | 21,109,417 | -0.32 | 9,975,665 | 74.52 | 30.60 | 56,099 |
| 1.0 | 0.5 | 418.74 | 17,733,078 | -42.77 | 13,352,004 | 74.52 | 30.60 | 42,349 |
| 0.5 | 0.5 | 458.43 | 13,747,857 | -82.46 | 17,337,225 | 110.40 | 66.48 | 29,989 |
| 0.0 | 0.5 | 458.43 | 13,747,857 | -82.46 | 17,337,225 | 110.40 | 66.48 | 29,989 |

**Table 3-39 (cont.) Economic Damages from Selected Water Shortages, Elephant Butte Irrigation District, New Mexico**

| Water supply | | Economic Returns | | Drought Damages | | Water's value | | Land |
|---|---|---|---|---|---|---|---|---|
| Surface Water (ac-ft/acre) | Ground- water (ac-ft/acre) | Net returns per acre ($/acre) | Total net returns all acres ($) | Economic losses/acre: compared to full supply ($/acre) | Total Economic Losses all acres: compared to full water allocation ($) | Added value of one more acre-foot | | Acres Planted (acres) |
| | | | | | | surface | ground | |
| 3.0 | 0.0 | 375.97 | 31,085,082 | 0.00 | 0 | 30.12 | 0.00 | 82,680 |
| 2.5 | 0.0 | 359.44 | 29,718,155 | 16.53 | 1,366,927 | 30.12 | 0.00 | 82,680 |
| 2.0 | 0.0 | 379.05 | 26,476,210 | -3.08 | 4,608,872 | 74.52 | 30.60 | 69,849 |
| 1.5 | 0.0 | 411.77 | 23,099,871 | -35.80 | 7,985,211 | 74.52 | 30.60 | 56,099 |
| 1.0 | 0.0 | 465.74 | 19,723,532 | -89.77 | 11,361,550 | 74.52 | 30.60 | 42,349 |
| 0.5 | 0.0 | 524.80 | 15,738,312 | -148.83 | 15,346,770 | 110.40 | 66.48 | 29,989 |
| 0.0 | 0.0 | 538.18 | 10,736,752 | -162.21 | 20,348,330 | 155.76 | 111.84 | 19,950 |

**Table 3-40. Economic Damages from Selected Water Shortages, Middle Rio Grande Conservancy District, New Mexico**

| Water supply | | Economic Returns | | Drought Damages | | Water's value | Land |
|---|---|---|---|---|---|---|---|
| Surface Water (ac-ft/acre) | Groundwater (ac-ft/acre) | Net returns per acre ($/acre) | Total net returns all acres ($) | Losses/acre: compared to full supply ($/acre) | Total losses all acres: compared to full supply ($) | Added value +1 a-f ($/a-f) | Acres Planted (acres) |
| 6.0 | 0.0 | 156.18 | 8,433,934 | 4.01 | 0 | 2.28 | 54,000 |
| 5.5 | 0.0 | 155.04 | 8,372,320 | 5.15 | 61,614 | 2.28 | 54,000 |
| 5.0 | 0.0 | 153.90 | 8,310,705 | 6.29 | 123,229 | 2.28 | 54,000 |
| 4.5 | 0.0 | 152.76 | 8,249,090 | 7.43 | 184,844 | 2.28 | 54,000 |
| 4.0 | 0.0 | 151.62 | 8,187,476 | 8.57 | 246,458 | 2.28 | 54,000 |
| 3.5 | 0.0 | 147.32 | 7,493,366 | 12.87 | 940,568 | 44.28 | 50,863 |
| 3.0 | 0.0 | 144.53 | 6,299,033 | 15.66 | 2,134,901 | 44.28 | 43,582 |
| 2.5 | 0.0 | 140.63 | 5,104,699 | 19.56 | 3,329,235 | 44.28 | 36,300 |
| 2.0 | 0.0 | 134.75 | 3,910,366 | 25.44 | 4,523,568 | 44.28 | 29,019 |
| 1.5 | 0.0 | 124.95 | 2,716,033 | 35.24 | 5,717,901 | 44.28 | 21,737 |
| 1.0 | 0.0 | 105.26 | 1,521,699 | 54.93 | 6,912,235 | 44.28 | 14,456 |
| 0.5 | 0.0 | 45.63 | 327,366 | 114.56 | 8,106,568 | 44.28 | 7,175 |
| 0.0 | 0.0 | 0.00 | 0 | 160.19 | 8,433,934 | 44.28 | 0 |

**Table 3-41. Economic Damages from Selected Water Shortages, El Paso Area Irrigation, Texas**

| Water supply | | Economic Returns | | Drought Damages | | Water's value | Land |
|---|---|---|---|---|---|---|---|
| Surface Water (ac-ft/acre) | Groundwater (ac-ft/acre) | Net returns per acre ($/acre) | Total net returns all acres ($) | Losses/acre: compared to full supply ($/acre) | Total losses all acres: compared to full supply ($) | Added value +1 a-f ($/a-f) | Acres Planted (acres) |
| 4.0 | 0 | 409.03 | 21,812,956 | 0.00 | 0 | 0.00 | 53,328 |
| 3.5 | 0 | 409.03 | 21,812,956 | 0.00 | 0 | 0.00 | 53,328 |
| 3.0 | 0 | 408.96 | 20,775,756 | 0.07 | 1,037,200 | 0.00 | 50,801 |
| 2.5 | 0 | 428.43 | 17,885,502 | -19.40 | 3,927,454 | 0.00 | 41,747 |
| 2.0 | 0 | 458.72 | 14,994,561 | -49.69 | 6,818,395 | 132.12 | 32,688 |
| 1.5 | 0 | 512.24 | 12,103,620 | -103.21 | 9,709,336 | 136.56 | 23,629 |
| 1.0 | 0 | 632.32 | 9,212,679 | -223.29 | 12,600,277 | 140.88 | 14,570 |
| 0.5 | 0 | 825.41 | 5,365,165 | -416.38 | 16,447,791 | 213.84 | 6,500 |
| 0.0 | 0 | 0.00 | 0 | 409.03 | 21,812,956 | 213.84 | 0 |

**Economic Analysis of Recreation Response to Drought in the Rio Grande Basin**

Summary

A significant barrier to the design of drought-coping institutions in the Rio Grande Basin historically has been a lack of reliable economic information about how recreational values change with reservoir levels or total annual streamflow production, or institutional adjustments to either. This section presents findings on economic values of water for reservoir-based recreation at six major Basin reservoirs.

Monthly telephone survey data were collected on fishing and other water-based recreational visitors by origin and destination in 1988 and 1989 for a study conducted for the New Mexico Department of Game and Fish (Ward et. al. 1997). Because lake levels fluctuated widely during the telephone sample period, it was possible to isolate water's effects from price and other visit predictors. An estimated regional travel cost model containing reservoir levels as a visit predictor provided information to compute economic values of water in recreation. These findings are limited to use values of visitors who travel to the reservoirs and do not reflect passive use values to people who value the reservoirs but never visit them.

Background

Multiple-use management of reservoir systems occurs throughout the Rio Grande Basin and elsewhere around the world. In the Rio Grande Basin, both single reservoir management programs and larger comprehensive basin-wide plans include multiple-use management. Within a river basin, many uses of water complement and compete with each other, especially during periods of severe drought. These uses include irrigation, hydropower, water quality, flood control, municipal water supply, streamflow regulation, fish and wildlife enhancement, and recreation.

While various congressional acts and state and regional policies emphasize the importance of designing institutions to increase the total economic value of water, several barriers have historically made it difficult to manage these systems for their highest net economic benefit. One barrier is the lack of reliable economic information about system gains or losses produced by altered storage and release patterns at a series of reservoirs. Even less information is available about how recreational values change with reservoir levels. Throughout the Rio Grande Basin, much of the reduced water levels in the late summer and early fall reduce the reservoirs' values for many recreational activities including boating, sailing, waterskiing, swimming, and fishing.

Information on recreation economic water values permits recreation to be traded off with flood control, irrigation, fish and wildlife, and other water uses for which methods are more widely available to estimate benefits. Without a method to estimate recreational values, water managers cannot economically justify holding water for recreational purposes. The Rio Grande Basin contains several alternative uses for water; any one use may affect others through any or all of the quantity, quality, time, and location dimensions (Young and Haveman 1985, p. 479). For example, one reason for low water levels in this basin is prolonged drought periods and/or high summer demands for water in irrigation. Designing institutions that operate in the interest of society requires that increase in recreation benefits from holding water at reservoirs be compared to the benefits produced by the added agricultural and municipal uses of water.

There have been several studies about water's recreational value. Boyle and others (1993) used contingent valuation methods to estimate effects of changes in river flows in the Colorado River on recreational boating benefits. Young and Gray (1972) estimated recreation values of $3 - 5 per acre-foot of water. Creel and Loomis (1992) estimated that an acre-foot of water in San Joaquin Valley wetlands is worth about $300 for waterfowl hunting, fishing, and wildlife viewing. Their travel cost model included a variable for water flow levels into the wetlands. Ward (1987) also used travel cost analysis to estimate values from $20 to $30 per acre-foot of water released into the Chama River in New Mexico for anglers and rafters. Hansen and Hallam (1990) estimated marginal values of water as a recreational fishery resource. Cordell and Bergstrom (1993) used contingent valuation methods to estimate the impact of lake level fluctuations on recreation benefits for four North Carolina reservoirs.

Despite these studies, our literature search found little evidence about how recreational values of water vary over a wide range of drought-coping institutions or reservoir management plans. Basin-wide management plans center on the timing, location, and duration of reservoir drawdowns over several reservoirs in the system. Evidence about recreational values gained and lost from institutional change or reservoir drawdowns is especially important for managers. However, not only is evidence about these incremental values scarce, but factors that influence the water's recreational value have seldom been examined. One such study was conducted by Ward and others (1996), using methods similar to the ones developed for this drought study.

This section presents an analysis of water's economic value for reservoir-based recreation at the six major Basin reservoirs: Heron, El Vado, Abiquiu, Cochiti, Elephant Butte, and Caballo. An estimated regional travel cost model provides information to compute economic values of selected drought-coping institutions that would alter reservoir levels. During the 1988-1989 period in which telephone visitor use data were collected, most of the study reservoirs experienced considerable water-level fluctuations due to normal reservoir operations. Although this was a fairly wet period, reservoir fluctuations were rather large due to agricultural demands, so it was possible to observe recreational use over a wide range of reservoir levels.

These water fluctuations let us estimate a travel cost model (TCM) with enough variation in water level to isolate water effects from price and visitor demographic effects. Moreover, water level changes during the drought were pronounced enough to allow an estimation of incremental water values over the complete range of the six major basin reservoir capacities and reservoir water levels.

Methods of Analysis

Lake recreational benefit is an empirical function of reservoir surface area based on the principle that a greater number of visitors are attracted to reservoirs with larger accessible areas and longer shorelines.

Benefit equations for both lake and instream recreation are based on observing how visitor travel expenditures to lakes change in the face of lake level changes. Benefits are measured as visitor willingness to pay for the recreation experience, using the travel cost method, described in detail in Ward and Beal (2000). Regression methods are used to write equations that summarize visitor benefits under a wide range of reservoir levels. Similar methods were used to develop the New Mexico Game and Fish Department's RIOFISH model, completed in 1991 (Cole et al. 1987; Cole et al. 1990).

RIOFISH is a simulation of 132 reservoir, river, and stream fisheries in New Mexico used for comprehensive planning of sport fishery management. The RIOFISH model is based in part on the telephone monthly survey data described earlier that was collected in 1988-89. It estimates statewide benefits based on a regional travel cost demand model. The model is a function of travel cost, travel time, catch rates, stocking rates, and site characteristics, and examines the effects of changes specified by the user in reservoir volume, stream discharge, or other management activities on angler use and angler benefits (Cole et al. 1986, 1987, 1990; Ward et al. 1997). Changes in water reservoir volumes, stream discharges, or other management decisions are translated into changes in the willingness of anglers to pay for the increased quality of the fishing experience brought about by the management decision, based on changes in consumer surplus. To derive the partial benefit functions for the basin optimization model described in this paper, multiple RIOFISH simulations were run by varying streamflows and reservoir volumes and holding all other variables constant.

Visitation

Visitation at all six Rio Grande Basin reservoirs is expressed as separate mathematical equations for each reservoir. Each equation expresses total annual visits, in thousands of visitor days, as these days vary according to the reservoir's average annual volume, measured in acre-feet. Reduced volume reduces visitor days for each reservoirs as shown in the equation below:

$$\text{Visits} = \beta_0 \ (\text{Reservoir Volume})^{\beta 1} \qquad (3.33)$$

In order to express a separate equation for each of the six reservoirs, each of the six has its own $\beta_0$ and $\beta_1$ , as shown in Table 3-42. Using the example of Heron Reservoir, this table shows that visits are affected by reservoir volume, and is expressed as:

$$\text{Annual Visits at Heron} = 51.93 \ (\text{Reservoir Volume})^{0.27} \qquad (3.34)$$

which is interpreted as saying annual visitation at Heron Reservoir is 51.93 times that year's average reservoir volume raised to the power 0.27. If, for example, average annual volume at Heron is 200 (thousand) acre-feet, annual visits are predicted to be (51.93 x (200) raised to the 0.27 power)) = 217 (thousand) visits per year.

Benefits

Benefits at all six reservoirs are similarly expressed as mathematical equations. Greater annual average volume, in acre-feet increases recreation benefits, measured in thousands of dollars per year. The benefits equation is of the form:

$$\text{Benefits} = \lambda_0 \ (\text{Reservoir Volume})^{\lambda 1} \qquad (3.35)$$

in which benefits are expressed in thousands of dollars per year and volume is again measured in thousands of acre-feet per year. Using the numbers for Heron Reservoir in Table 3-42, applying Equation 3.20 results in the following predicted benefits:

$$\text{Annual economic benefits at Heron} = 1096.63\ (\text{Reservoir Volume})^{0.32} \qquad (3.36)$$

This means that annual visitation at Heron Reservoir is 1096.63 times that year's average reservoir volume raised to the power 0.32 as shown in Table 3-42. If, for example, average annual volume at Heron is 200 (thousand) acre-feet, annual visits are predicted to be (1096.63 x (200) raised to the 0.32 power) = 5976 (thousand) dollars in benefits per year, which is $5,976,000. Similar values can be calculated for any reservoir level desired.

**Table 3-42. Recreational Use and Benefit, Rio Grande Basin Reservoirs**

| Reservoir | Visits Predictor (1000s days/year) | | Benefits Predictor (1000s $/yr) | |
|---|---|---|---|---|
| | $\beta_0$ | $\beta_1$ | $\lambda_0$ | $\lambda_1$ |
| Heron | 51.93 | 0.27 | 1,096.63 | 0.32 |
| El Vado | 8.93 | 0.47 | 78.26 | 0.60 |
| Abiquiu | 7.02 | 0.27 | 104.58 | 0.34 |
| Cochiti | 8.16 | 0.33 | 105.64 | 0.43 |
| El Butte | 16.78 | 0.41 | 172.43 | 0.51 |
| Caballo | 2.72 | 0.58 | 18.36 | 0.76 |

Conclusions

For the range of the lake levels observed in the Rio Grande Basin, annual recreational values per acre-foot of water vary widely, and depend on the reservoir's average volume in a given year. Our estimated values of reservoir water are comparable with values reported in previous work. They are a plausible updating of Young and Gray's (1972) findings. However, they are generally lower than those reported by Creel and Loomis (1992).

Findings in this section have important implications for water managers, legislators, and other policymakers who wish to design better drought-coping institutions in which recreational values of water are traded with those used by agriculture, power production, and cities. In droughts or in times when demands for competing water uses are high, economically efficient basin management will draw down reservoirs that have lowest incremental values for recreation, other things being equal. Reservoir drawdowns produce the smallest losses in regional recreation benefits when reservoirs are isolated, large, and have steep bank slopes.

By contrast, drawing down reservoirs with high recreational values per acre-foot impose considerable economic losses to the region's visitors; these reservoirs typically have few substitutes, are located near population centers, or have shallow slopes at the waterline. In drought periods or times of high water demand, maintaining high lake levels at these sites will increase regional economic efficiency, other things being equal. In this way, trade-offs between recreation benefits and the benefits of competing water users can be identified for water managers and other decision makers.

## Economic Analysis of Hydropower Response to Drought in the Rio Grande Basin

Overview

Hydropower facilities have been one of the Rio Grande Basin's fastest growing renewable energy technologies. Construction was completed in 1991 on the last of three large new hydropower projects, which increases the basin's hydroelectric generating capacity from 24.6 megawatts in 1987 to 78.4 megawatts in 1991. This represents a 219 percent increase. No new facilities have been constructed in the Basin since 1991.

Construction of a 12-megawatt hydro unit at Abiquiu Dam on the Rio Chama was completed in 1991. The $27.4 million project initiated by Los Alamos joins two other large new hydropower projects recently completed: (1) the 30-megawatt hydro system at Navajo Reservoir on the San Juan River, completed by the City of Farmington at a cost of $30 million in 1988, and (2) the 8.8-megawatt hydro system at El Vado Dam on the Rio Chama completed by Los Alamos County at a cost of $13 million in 1990. Considering that the total capacity of the region's electrical generation facilities in 1987 was 5,132 megawatts, hydroelectric's share is small.

The movement of water flowing from a higher to a lower elevation has long been recognized for its energy value. The capacity of this water to create energy is considerably reduced in drought periods, where reservoirs typically experience large drawdowns to meet other demands, including irrigation, municipal and industrial, recreation, and fish and wildlife. To the extent that drought-coping institutions are able to maintain reservoir levels at reservoirs in the basin with generation facilities, economic damages from hydropower production loss will be reduced.

Hydropower is derived by converting the potential energy of water to electrical energy, using a hydraulic turbine connected to a generator. The energy potential from available resources in the Rio Grande Basin makes hydropower one of the most significant renewable energy resources in the region.

Analysis

Reservoir volume in any time period determines its surface elevation and surface area. Area, elevation, and volume are physical relationships linked to each other by the unique topography of the surrounding area. Tables that tie a reservoir's area, elevation, and capacity are used to determine the surface area and volume of reservoirs based on the elevation of its water. One area-capacity and one elevation-capacity mathematical function for each reservoir needed to be approximated. Ordinary least squares polynomial regression was used to estimate these functions. The percentage of explained variance ($R^2$) for estimates of all relationships was greater than 0.99.

The economic benefit of hydroelectricity is defined as the value of power generated compared to the cost of competing resources. The price of power is a function of the demand for electricity during any period of time. Power plants in the Rio Grande Basin, especially during severe and sustained drought, will be operated as run-of-the river. That is, the operation of the power plants in this basin, is not dispatchable; the utilities manager can not control releases to meet changes in peak demand.

Electricity can be produced only when managers from agencies that control the reservoirs release water. Electric utilities in the Rio Grande Basin must forecast their requirements for electricity in any period before the start of its fiscal year without control over releases. They typically are able to generate power from alternate sources or purchase it on the market to meet its requirements. Since reservoir releases for power generate electricity in excess of the utility's forecasted requirements, the value of nondispatchable hydroelectricity is equal to the market price of nonfirm energy, presently \$0.02 per kwh. If the releases were timed to meet peak power demands, hydroelectric benefits in the Rio Grande Basin would typically be about \$0.05 per kwh.

Hydroelectric benefits are a function of the effective head, defined as the arithmetic mean of the difference between reservoir surface elevation and the receiving stream channel elevation in the current and the subsequent time periods, and the release. However the difference between inflows and releases over time affects a reservoir's head and its surface area, which influences future lake recreation benefits. More generally, any given release in any time period affects the economic value of all uses. It affects current instream flows, and current and future downstream volumes and surface areas. Table 3-43 below shows rated capacity in kilowatts for each of the six basin reservoirs at which there are hydroelectric facilities. More details are in Ward and Lynch (1996).

**Table 3-43. Hydropower Capacity, Rio Grande Basin**

| Reservoir | Stream | Rated Capacity (KW) |
|---:|---:|---:|
| Heron | Willow Creek | none |
| El Vado | Rio Chama | 8,800 |
| Abiquiu | Rio Chama | 13,600 |
| Cochiti | Rio Grande | none |
| Elephant Butte | Rio Grande | 27,945 |
| Caballo | Rio Grande | none |

Sources: New Mexico Energy Conservation and Management Division, with web address: http://www.emnrd.state.nm.us/ecmd/html/Programs/Renewables/hydropower.html

Mathematical Documentation

This section documents the variables, parameters, and equations needed to measure the economic benefits of hydroelectric power and the benefits of various drought-coping institutions for dealing with water supply shortfalls.

| **Table 3-44. Indices for Hydropower Model** | |
|---|---|
| r | Reservoirs: El Vado, Abiquiu, Elephant Butte |
| g | Hydroelectric generators installed at the reservoir: #s 1 and 2 |
| m | Month of operation, beginning at the start of the water year (October) |

| **Table 3-45. Parameters for Hydropower Model** | |
|---|---|
| a | Converts streamflow cfs to million acre-feet per hour: $8.26 \times 10^{-8}$ |
| y | Hours per year: 8760 |
| p | Price of electricity per kwh = $0.02 |
| w | Weight per cubic foot water: 62.5 pounds |
| f | Thermodynamic efficiency of power plant: estimated at 90%. |
| l | Factor to convert foot-pounds to kilowatts: 737 foot - pounds / kw |
| c | Operating capacity for generator: 110% of rated capacity |
| k | Kilowatts produced per each cfs released: k = wf/l |

Columns listed below for the r index are illustrated by application to El Vado and Abiquiu Reservoirs respectively. Similar computations were made possible for the Elephant Butte Reservoir.

| | | |
|---|---|---|
| $\psi_r$ | Initial volume in million acre-feet for a representative water year (1990) | |
| | 0.106 | 0.134 |
| $\kappa_r$ | Maximum volume in million acre-feet | |
| | 0.186 | 1.2 |
| $\gamma_{r\,g}$ | Elevation of tailrace (stream channel) | |
| | 6735 | 6040 |
| $\chi_{r\,g}$ | Rated capacity of generator g (kw) | |
| | 8000<br>---- | 6800<br>6800 |
| $\delta_r$ | Minimum useable water volume of reservoir r in maf | |
| | 0.025 | 0.025 |

| | |
|---|---|
| $\iota_m$ | Inflow to El Vado (cfs) |
| $\mu_m$ | Lower bound on outflow from Abiquiu Reservoir |
| $\eta_m$ | Number of hours in month m |
| $\rho_{m\,r}$ | Streamflow into El Vado Reservoir in month m |
| $\nu_{r\,g\,m}$ | Maximum amount of electricity that can be produced at reservoir r, by generator g, in month m |
| | $\nu_{rgm} = \chi_{rg}\, c\, \eta_m$ |

Hydroelectricity production depends on reservoir surface elevation. Using the area-capacity-elevation data for the El Vado and Abiquiu reservoirs, 1st through 6th power polynomial functions were estimated to relate elevation to volume. The intercept and parameters are listed below for each of the two illustrative reservoirs, with applicable t-statistics in parentheses in Table 3-46.

**Table 3-46. Area Capacity Relations**

| | | |
|---|---|---|
| $\epsilon_{0\,r}$ | $6.77 \times 10^{3}$ (9842.285) | $6.16 \times 10^{3}$ (18153.795) |
| $\epsilon_{1\,r}$ | $3.44 \times 10^{3}$ (21.586) | $4.21 \times 10^{2}$ (89.373) |
| $\epsilon_{2\,r}$ | $-9.21 \times 10^{4}$ (-9.932) | $-6.57 \times 10^{2}$ (-28.855) |
| $\epsilon_{3\,r}$ | $1.54 \times 10^{6}$ (7.274) | $8.22 \times 10^{2}$ (16.251) |
| $\epsilon_{4\,r}$ | $-1.34 \times 10^{7}$ (-6.013) | $-6.20 \times 10^{2}$ (-11.138) |
| $\epsilon_{5\,r}$ | $5.76 \times 10^{7}$ (5.238) | $2.49 \times 10^{2}$ (8.453) |
| $\epsilon_{6\,r}$ | $-9.58 \times 10^{7}$ (-4.698) | $-4.08 \times 10^{1}$ (-6.847) |

Variables used for the hydropower model are shown in Table 3-47.

| **Table 3-47. Variables for Hydropower Model** | |
|---|---|
| $V_{r\,m}$ | Volume of reservoir r in month m (maf) |
| $S_{r\,m}$ | Surface area of reservoir r in month m (acres) |
| $R_{r\,g\,m}$ | Release from reservoir r that produces electricity in month m (cfs) |
| $BK_{r\,g\,m}$ | Economic benefits of hydroelectricity produced at reservoir r, by generator g, in month m ($/month) |
| $K_{r\,g\,m}$ | Quantity of electricity produced at reservoir r, by generator g, in month m (kwh) |
| $F_{r\,m}$ | Streamflow into reservoir r in month m (cfs) |
| $H_{r\,g\,m}$ | Head in reservoir r, at generator g, in month m (ft) |
| $E_{r\,g\,m}$ | Effective head in reservoir r, at generator g, in month m (ft) |
| $W_r$ | Flow out of reservoir r not used to generate electricity (cfs) |

Equations

The economic benefit of hydropower is the price of the power times the amount of power produced:

$$BK_{rgm} = pK_{rgm} \tag{3.37}$$

Power production is a function of the effective head; the flow released through the generators; a constant (k) based on the weight of water (w), the efficiency of the generator (f), and the number of foot-pounds per kilowatt (l); and the hours the generator runs:

$$K_{RGM} = E_{RGM} R_{RGM} K \eta_M \tag{3.38}$$

The quantity of electricity produced is a function of the effective head and the release; but the head is a function of the volume, which is a function of the release. To minimize the effect of large releases on the change in the head, the effective head is defined as the average of the heads in periods m and m+1.

$$E_{RGM} = \frac{H_{RGM} + H_{RGM+1}}{2} \tag{3.39}$$

The head is the elevation of the water surface minus the elevation of the tailrace:

$$H_{RGM} = \epsilon_{0R} + \epsilon_{1R} V_{RM} + \epsilon_{2R} V_{RM}^{2} + \epsilon_{3R} V_{RM}^{3} + \epsilon_{4R} V_{RM}^{4} + \epsilon_{5R} V_{RM}^{5} + \epsilon_{6R} V_{RM}^{6} - \gamma_{RG} \tag{3.40}$$

Reservoir volume is based on a simple mass-balance equation:

$$V_{RM} = V_{R(M-1)} + (F_{R(M-1)} - W_{R(M-1)} - \Sigma_G R_{RG(M-1)}) A \eta_{(M-1)} \tag{3.41}$$

The volume in month m is the volume in the previous month plus the inflows minus the outflows, the release through the generators and the flow that does not produce electricity. For this study, benefits of hydropower production are computed on an annual time step, which means that total monthly benefits are summed over the 12-month year.

Application to Drought Study

The simple economics and hydrology model of basin hydropower provides a sound basis for evaluating impacts of drought coping policies on hydropower benefits. Still, it was not possible to get the hydropower benefits equation into the final model satisfactorily. Issues dealing with the law of the river occupied most of our time, and hydropower appeared a small contributor to the Basin’s economy.

## Economic Analysis of M&I Response to Drought in the Rio Grande Basin

### Summary

The use of water produces considerable economic value in a modern household. Besides cooking, washing, cleaning, and sanitation, the typical American household uses water to maintain a domestic environment in landscapes and lawns. While not all these uses of water are essential for survival, they are still desired. Beyond the basic human requirements it satisfy water it has been extensively analyzed as an economic resource for which there is a considerable urban demand, particularly in the desert southwest. The willingness of people to pay for and use water in every day activities is what gives water an economic value. Similarly, water shortages resulting from drought or other interruption of services cause economic damages, for which people are willing to pay considerable amounts to avoid. One overriding purpose of this study is to analyze the potential of innovative institutional adjustments for coping with severe and sustained drought to reduce the size of those economic damages.

### Analysis

The economic value of water to the residential household is based on the idea of demand. People express this demand as a quantity of water they choose to use at various possible prices. For all household uses except the most basic essential purposes, quantity of water used is reduced in the face of higher prices and it increases as the price falls. The scarcity of water increases considerably as a drought becomes more extreme.

### Significance of Municipal Uses

Water is essential to life, and municipal suppliers provide this water. People can survive only a matter of a few days without water. Nevertheless, the daily per capita requirement of drinkable water necessary for survival is so small that water is no longer priceless after a few quarts have been made available. Daily per capita domestic water use in the Rio Grande Basin and elsewhere in industrialized countries is many times that the level of consumption required for survival.  The quantity actually used for municipal use, depends on consumption patterns and habits as well as relative availability and cost of water. A wide range of per capita rates of consumption is possible.

Special Problems of Municipal Water Valuation

The value of municipal water is defined by consumers' demand for it, and is measured by the amount consumers would be willing to pay for it. Consumption of municipal water is influenced by price, consumer income, population, by the configuration of commercial and civic uses of water, and by climate, especially rainfall during the season when home landscapes need water.

Most evidence indicates that water consumption is not greatly responsive to either price or income, at least within the range of observed variability. This can be explained by the fact of the small proportion of expenditures on water of total national consumption expenditures. This means that price could increase significantly and water consumption would only be reduced slightly.

However, water consumption studies have shown that users do respond some to changes in price. Where water is metered, consumers have been found to use significantly less water than those who are on a flat rate.  In cases when water is not metered, consumers pay a price of zero for additional water use. By contrast, metering means consumers pay a price for additional use larger than zero. Lawn and other outdoor landscape use of water is particularly sensitive to price changes.

Water pricing policies in many cities is complex enough so that it is difficult to infer much about consumers' willingness-to-pay, since they are not able to consume all they want at a constant price. Where water is sold on a flat-rate basis, the marginal price to the consumer is effectively zero. A number of published studies of the price elasticity of demand for municipal water[9] are available. Price elasticities tend to be relatively low, and differ between the two major components of use, domestic (indoor) use and outdoor use, such as lawn watering. The elasticities also vary among the different regions of the country.

Demand functions for water are the place to start when measuring people's willingness-to-pay for municipal water. Because the demand for indoor and outdoor uses typically respond to different factors and meet different needs, these two demands are best considered as two separate schedules. The willingness-to-pay concept can be applied to both uses.[10]

If one can derive a relationship on the amount of water people use at different water prices (a demand schedule) from observations of water use in the face of varying prices, this relationship can be used to estimate the total benefits of water as a mathematical function of supply. The same relationship can be used to estimate economic damages associated with water supply shortages caused by drought.

Seven study areas were selected for that study, and with the cooperation of water utilities in three southwestern states, information on residential water use, rate structures, revenues from water sold and non-price conservation programs covering the period from 1980 through mid-1995 was collected. The study area cities are: Los Angeles and San Diego, California; Broomfield and Denver, Colorado; and Albuquerque, Las Cruces and Santa Fe, New Mexico. Similarities and differences in residential water use, prices and rate structures, climatic conditions and demographic characteristics of people who live in the study areas

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[9]Price elasticity of demand is defined as the percentage change in quantity of a commodity consumed given a 1 per cent change in price. The sign on the elasticity coefficient is generally negative. The coefficient provides a convenient way of summarizing the price responsiveness of demand.

[10]Young and Gray (1972) emphasize that in assessing the value of municipal water, it is not the value of raw water that is reflected by the demand curve for residential water, but the value of treated water which has been given the added attributes of time and place utility. Because treated water delivered to peoples' homes have been given this utility, the costs of treatment, storage, and distribution must be subtracted from the higher values above to derive values of raw water in watercourses, which will be comparable with values derived in other uses for raw water.

provide an excellent cross-section of factual data for cities in the southwestern United States. These cities also exhibit a wide range of non-price conservation programs, from cities that have numerous ongoing water conservation programs to cities that have yet to implement any at all.

## Findings

The general findings of this study show that water price has a significant and negative impact on water use. However, despite the significance of price in influencing use, water demand is insensitive to price changes alone. Economists sometimes express this by saying water demand is very price inelastic, which means that large percentage increases in price are required to induce small percentage decreases in water use. The price elasticity of demand for water is measured as the percentage reduction in use from a one percent increase in price. The highest price elasticity estimate was for summer use (approximately -0.20). At this degree of consumer responsiveness, water utilities could double their water rates (increase them by 100 percent) and expect only a 20 percent decrease in water use during the peak season. Similarly, if a drought reduced supplies by 20 percent, demands would exceed supply unless prices increased by 100 percent. Overall, water utilities in the region can expect a water price elasticity of -0.10 on an annual basis; a 100 percent increase in rates will reduce use by 10 percent.

Nonprice conservation programs appear to be most effective only after a water utility achieves a critical mass of conservation programs. For Los Angeles, San Diego and Denver, the large number of non-price programs have had the desired effect of reducing demands. For cities with fewer programs or relatively new experience with conservation programs, non-price programs show no observable effect on reducing demand. Conservation programs appear to work independently of a drought environment, such as California’s severe drought in the late 1980s and early 1990s. Their conservation programs have continued to work after the drought conditions have ceased. Conservation programs may be ultimately necessary simply to counteract increases in residential use of water brought about by factors outside the control of water utilities, such as population growth and increased demands for swimming pools and lawns.

Climate effects residential use in predictable ways. Water use is strongly influenced by average monthly temperature and seasonal changes in temperature. However, surprisingly, precipitation was consistently found to be an insignificantly factor in affecting use, in all analyses performed. All cities in this analysis are semi-arid to arid in climate, so the ratio of water use by plants (evapotranspiration) to precipitation is much greater than one. Landscape watering is necessary to maintain residential lawns and trees. Random and infrequent rains do not change residential watering patterns to a significant degree. Other factors, beyond the control of a water utility, such as residential income and city population, also vary but their influence is estimated to have a relative minor impact on per capita residential use.

In summary, both price and non-price conservation programs are effective, but require a major commitment to implement. Consumers are unresponsive to price increases under current typical rate structures, requiring large increases in price to achieve small reductions in demand. Nonprice conservation programs appear to be most effective when there are a substantial number of programs conducted over longer periods of time. Because information regarding nonprice programs is incomplete, we are unable to distinguish the effectiveness of individual types or specific programs nor the residual or lasting effects of nonprice programs. Small changes in water rates or implementation of haphazard conservation programs will most likely not produce discernable results in reducing per capita water use.

We use the empirical demand schedule findings over all these cities from the Michelson study by applying the results to the climatic and demographic conditions of Albuquerque and El Paso. The demand model is remarkably good in predicting water use in the two cities. For example, predicted residential monthly consumption was computed for actual use in El Paso for 1988 - 1996. This is an out-of-sample comparison. With the El Paso water price structure, the model estimates that residential demand has a -0.115 demand elasticity.

Tables 3-48 and 3-49 show the application of the estimated demand functions for Albuquerque and El Paso. Formulas used for total benefits of added water as a function of water use are shown in the table footnotes. The functions are used to predict the market-clearing prices of water (price that reduces shortages to zero) if residential water is curtailed by various percentages due to drought. To illustrate use of the formulas, we show the impacts of percentage reductions from current (1998) usage of 5%, 10%, 15%, and 20% due to various severity of drought.

Drought Damages

As water use is cut back due to drought, the market-clearing price increases considerably due to the very low price elasticity of demand. Another way of stating this finding is that water users are willing to pay a higher price per unit in the face of more severe shortages. In Albuquerque, for example, the market-clearing price for water increases from $1.29 to $4.12 per 1000 g per month. The average of the with and without-drought market clearing price times the amount of curtailment is a good estimate of the economic loss produced by the drought.

Continuing with the Albuquerque example, consider the curtailment due to drought from 14.7 to 13.4 thousand gallons per month per household. This curtailment produces a $3.52 economic loss for the household. The loss is computed as (14.7 – 13.4) x ($1.29 + $4.12)/2 = $3.52. Note the initial and final market-clearing prices are averaged. The total loss for the city due to this water supply curtailment on an annual basis is estimated $ 376,640. This loss is computed as $3.52 x 107,000 = $376,640, based on 1998 actual water use levels.

| Table 3-48. Economic losses for selected water use curtailments due to drought: Albuquerque | | | | | |
|---|---|---|---|---|---|
| | Full Supply | Curtailment Percentage | | | |
| | | 5% | 10% | 15% | 20% |
| | | | | | |
| Number of households (numbers) | 107,000 | 107,000 | 107,000 | 107,000 | 107,000 |
| Total Use (acre-feet per / year) | 100,000 | 95,000 | 90,000 | 85,000 | 80,000 |
| Residential | 58,000 | 53,000 | 48,000 | 43,000 | 38,000 |
| Other | 42,000 | 42,000 | 42,000 | 42,000 | 42,000 |
| | | | | | |
| Residential Use (1000 gal / mo) | 14.7 | 13.4 | 12.2 | 10.9 | 9.6 |
| Price ($ / 1000 gal) | 1.29 | 4.12 | 6.73 | 9.56 | 12.39 |
| | | | | | |
| **Slope:** increase in price ($/1000 gal) per unit increase in water use (1000 gal / mo). | - 2.18 | | | | |
| **Intercept:** Price at which utility-supplied water use per household falls to zero | 33.29 | | | | |
| **Formula used for demand:** linear function of use, Figure 3.7a | Price = Intercept + Slope * Use<br>= 33.29 - 2.18 * Use | | | | |
| **Formula for total benefits of water use:** quadratic function of use, Figure 3.7b | Total benefits = Intercept * Use + 0.5 * [ Slope * Use $^2$ ]<br>= 33.29 * Use - 0.5 * [ 2.18 * Use $^2$ ] | | | | |

| Table 3-49. Economic losses for selected water use curtailments due to drought: El Paso | | | | | |
|---|---|---|---|---|---|
| | **Full Supply** | Curtailment Percentage | | | |
| | | 5% | 10% | 15% | 20% |
| | | | | | |
| Number of households | 120,553 | 120,553 | 120,553 | 120,553 | 120,553 |
| Total (1998) Use (acre-feet/year) | 107,000 | 101,650 | 101,650 | 101,650 | 101,650 |
| Residential | 58,850 | 53,500 | 53,500 | 53,500 | 53,500 |
| Other | 48,150 | 48,150 | 48,150 | 48,150 | 48,150 |
| | | | | | |
| Residential Use (1000 gal/mo) | 13.3 | 12.0 | 10.7 | 9.4 | 8.1 |
| Price ( $ / 1000 gallons) | 0.94 | 3.70 | 6.46 | 9.22 | 11.98 |
| | | | | | |
| **Slope:** increase in price ($/1000 gal) per unit increase in water use (1000 gal / mo). | - 2.12 | | | | |
| **Intercept:** Price at which utility-supplied water use per household falls to zero | 29.18 | | | | |
| **Formula used for demand:** linear function of use, Figure 3.7c | Price = Intercept + Slope * Use<br>= 29.18 - 2.12 * Use | | | | |
| **Formula for total benefits of water use:** quadratic function of use, Figure 3.7d | Total benefits = Intercept * Use + 0.5 * [ Slope * Use $^2$ ]<br>= 29.18 * Use - 0.5 * [ 2.12 * Use $^2$ ] | | | | |

**Figure 3-18a. Residential Demand for Water Per Household, Albuquerque**

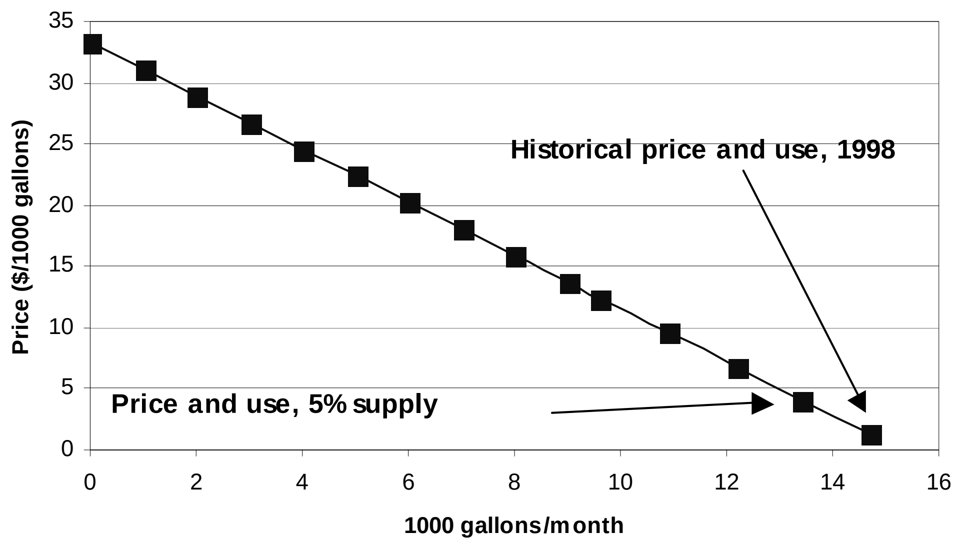
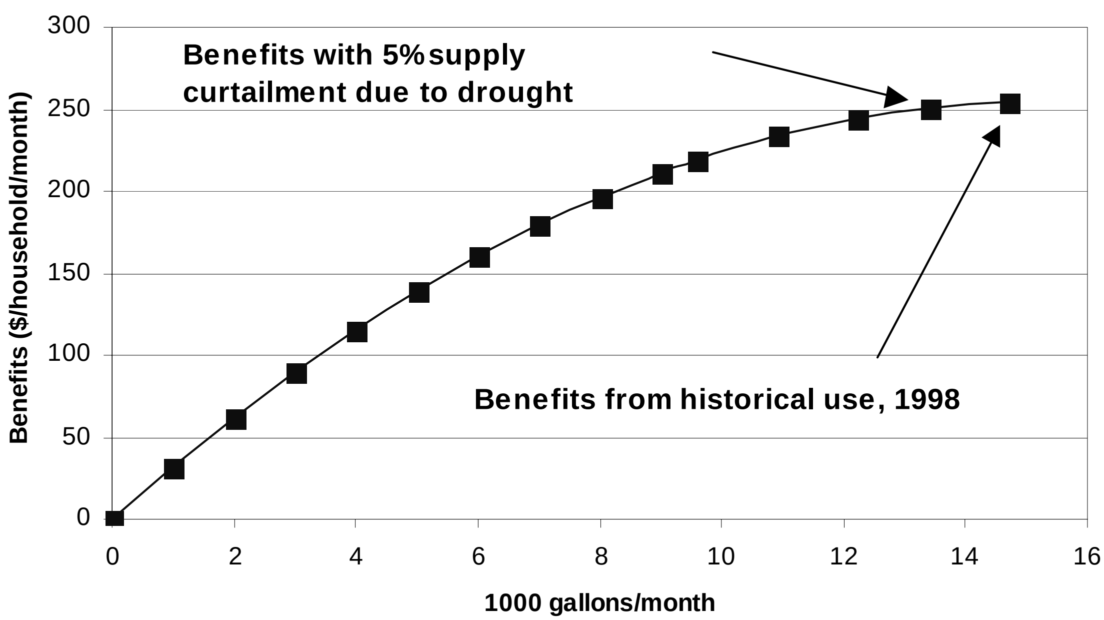



**Figure 3-18b. Economic Value of a Range of Water Uses-Per Household, Albuquerque**



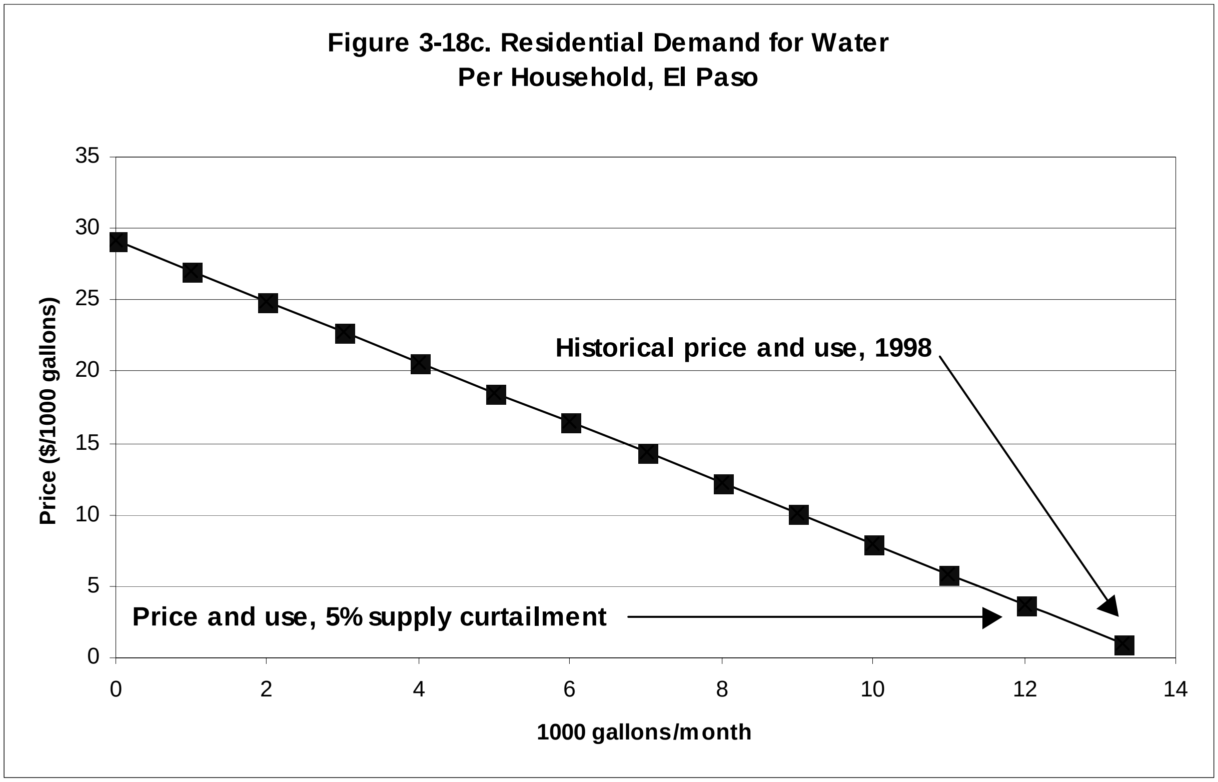


Figure 3-18c. Residential Demand for Water
Per Household, El Paso
Price ($/1000 gallons)
35
30
25
20
15
10
5
0
Historical price and use, 1998
Price and use, 5% supply curtailment
0
2
4
6
8
10
12
14
1000 gallons/month

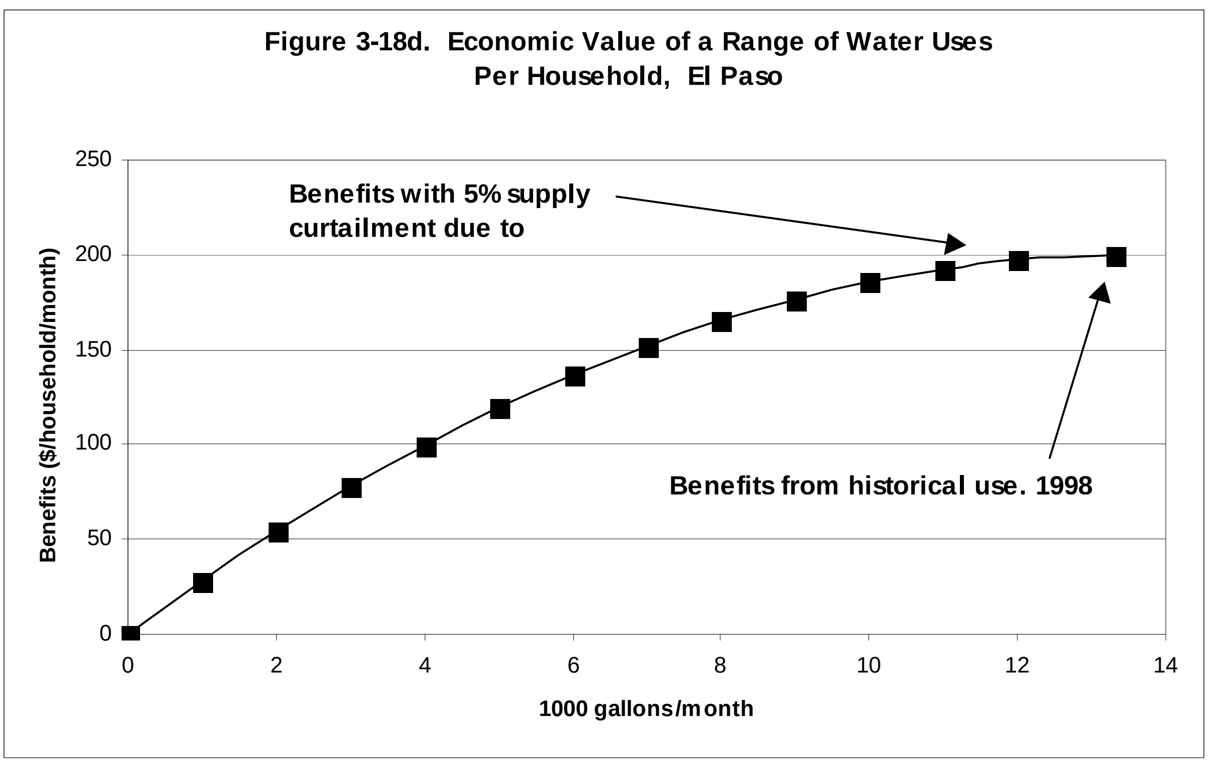


Figure 3-18d. Economic Value of a Range of Water Uses
Per Household, El Paso
Benefits ($/household/month)
250
200
150
100
50
0
Benefits with 5% supply
curtailment due to
Benefits from historical use. 1998
0
2
4
6
8
10
12
14
1000 gallons/month

## System Operation under Law of the River

### Overview

Rio Grande water resources are allocated under a complex set of institutions. These include the Rio Grande Compact, federal laws, court decisions, administrative rules, and a treaty between the United States and Mexico, which are described collectively as the "Law of the River." The Law of the River determines the water allocations under which use of Basin water resources are made. The method for characterizing the Law of the River for allocating future water shortages in periods of drought is described below. For each drought scenario considered, the current Law of the River is described, which is the baseline institution for allocating water, and for which a forecast is made of the resulting water use patterns. Compared to that baseline, a forecast is made for water use patterns and changes in economic benefits under all other institutional options considered. The difference in water use patterns and economic benefits between the Law of the River and each other institutional option for coping with drought are presented to show the relative effectiveness of each institutional option considered. How the Law of the River was modeled for allocating flows in the Basin also is described in this section.

### Rio Grande Compact

The Rio Grande Compact is the overriding mechanism for allocating water under the Law of the River. The following section describes implementation of the model to reflect the way it is written in the Compact. The discussion captures the essence of how the model allocates water under the Compact.

Water Colorado delivers to New Mexico at the Lobatos gage is a function of headwater flows in Colorado. These headwater flows, called Index flows for the Rio Grande Compact include three Conejos River Index gages plus the Rio Grande gage near Del Norte. Any water not delivered to New Mexico is available for use by Colorado. Equations are written in the model to summarize annual flows at the Lobatos gage, and therefore water available for use by Colorado, as a function of the Index flows described above.

Water New Mexico delivers to Texas at Elephant Butte, and measured at the gaging station below Elephant Butte, is a function of annual flows at the Otowi gage, not including San Juan Chama flows, which are available for use entirely in New Mexico. Equations are used in the model to deliver water to the Elephant Butte gage based on native flows at the Otowi gage (total flows minus imported San Juan Chama flows).

In very wet years, when New Mexico does not have the capacity to use its full Compact allocation, New Mexico may receive an annual credit of up to 200,000 acre-feet for its overdelivery to Texas. In dry years, New Mexico may underdeliver to Texas by an amount not to exceed 150,000 acre-feet, and an annual debit is incurred in such cases. New Mexico, under the Compact, may accrue total debits, offset by wet year credits, of up to a total of 200,000 acre-feet. Accrued debits and credits are subject to system losses, including evaporation that would have occurred had the debit or credit not been incurred. No attempt is made to calculate such losses precisely, but they are estimated at 15% annually.

Water Allocation Below Elephant Butte Reservoir[11]

The Compact does not apportion the water released from Elephant Butte-Caballo Reservoir system[12] between New Mexico and Texas. Historical contracts between the irrigation districts in the two states and the Bureau of Reclamation resulted in a constant ratio of irrigated land of approximately 57% in New Mexico and 43% in Texas, described more fully below. Based on this historical ratio, and the

[11]The authors are indebted to Mr. Wayne Treers, US Bureau of Reclamation, El Paso, Texas for explaining the complexities of Reclamation's operation of the Rio Grande Project.

[12]We refer to this system in the remainder of this report as Elephant Butte only. However the Bureau of Reclamation manages the two reservoirs as a single system.

Bureau's "DII" operating rule, the model allocates diversions from Project releases (after accounting for conveyance losses and the delivery to Mexico) in the ratio of approximately 57% to New Mexico and 43% to Texas. The New Mexico allocation goes entirely to irrigated agriculture, while the Texas allocation is proportionally distributed between City of El Paso M&I use and use by Texas irrigated agriculture. This proportional allocation occurs in the model, because the Texas water allocation goes to El Paso County Water Improvement District #1, and the City of El Paso is a contractor like any other farmer in the District.

### Water Delivery to Mexico

Based on the U.S. Mexico Treaty of 1906, 60,000 acre-feet of water per year is allocated to Mexico by the model.[13] For model simplicity, and because of the potential issues raised with any future delivery reductions to Mexico (despite such provisions under "extraordinary drought" in the Treaty), a constant 60,000 acre-feet annual delivery is assumed.

### Summary of Mechanics

This outline summarizes the model's forecast water use patterns under the Law of the River for three areas: water allocations below Elephant Butte Reservoir, water allocations within New Mexico above Elephant Butte, and water allocations in Colorado.

[13]While the 1906 Treaty states that Mexico will receive 60,000 acre-feet annually, they have not received the full 60,000 acre-feet in drought conditions. Article 2 of the Treaty states that Mexico will receive its amount of water in the same proportion as the water supplied to the lands within the Rio Grande Project (U. S. irrigated lands). Since 1951, IBWC and the Bureau of Reclamation have agreed on the Rio Grande Project allocation procedure such that Mexico will share in the same shortage as the U. S. irrigation districts. When total Project storage falls below approximately 1,000,000 acre-feet by Dec. 1 in any year, then less than full supply allocations are issued to the Districts and Mexico, and the allocations can be increased if subsequent inflow to Elephant Butte/Caballo reservoirs increases during the irrigation season. The authors are indebted to Wayne Treer for this insight.

Below Elephant Butte Reservoir

Storage-Release Rules for Elephant Butte. A full release from Project storage (water stored at Elephant Butte and Caballo) is defined as 790,000 acre-feet. However in drought periods, as Project storage falls below 1 million acre-feet, the water districts have historically released much less than the 790,000, holding water project storage as a savings account for the future. An examination of annual Project releases over the last 20 years was performed. Results of several regression analyses showed that Project releases were higher in years when Project storage was higher, and lower in years with lower levels of tributary inflows into Project storage. The historical relationship of best fit between Project releases, Project storage, and tributary inflows into Project storage of best fit was found to be: Project release = 672,000 + (0.14 * Project storage) - (1.55 * Estimated flow at the Rio Salado gage),[14] where all three units are measured in acre-feet per year. This historical relationship was used to characterize the Law of the River that governs future Project releases from Project storage.

Water Use Patterns from Elephant Butte Releases. The ratio of Elephant Butte Irrigation District (EBID) to Texas diversions is 0.567742 to 0.432258, taken from flows below Elephant Butte minus conveyance losses and the Mexican delivery. New Mexico diversions are used entirely for irrigated agriculture. Groundwater pumping supplements surface supplies. Texas water is used by El Paso area agriculture and El Paso M&I. The ratio of agricultural to M&I diversions decreases with time due to increasing M&I demand, and corresponding water purchases from agricultural uses. M&I also utilizes pumped groundwater, while El Paso agriculture has no significant groundwater backup. Mexico

[14]The Bureau of Reclamation has a method for calculating the yearly allocation to the U. S. Districts and to Mexico. It first looks at existing total storage in both reservoirs on December 1 each year. Then the total storage figure is adjusted for: estimated evaporation losses for both reservoirs for an entire irrigation season; Rio Grande Compact credit waters existing in Project storage; and, any non-Project water (such as San Juan-Chama water) existing in Project storage. These adjustments are subtracted from the total storage amount, and the net figure is the amount of storage allotted toward the yearly allocation at the diversion headings. If the net storage amount is less than 790,000 acre-feet, then a less-than-full supply allocation is given to the U. S. Districts and Mexico based on the historic ratio of irrigated lands of the U. S. Districts and Mexico's delivery to the Acequia Madre heading and the release from Project storage.

deliveries = 60,000 acre-feet per year (simplified interpretation of 1906 US Mexico treaty). Volume next year at Elephant Butte = Volume this year + inflow minus (release + evaporation).[15]

New Mexico above Elephant Butte Reservoir

Inflows into Elephant Butte. Flows into Elephant Butte are a function of flows at the Otowi gage not including San Juan Chama flows; the quadratic function summarizes the Rio Grande Compact tables that states New Mexico's delivery requirements to Elephant Butte as a function of Otowi gage flows.[16]

Albuquerque Area M&I: Albuquerque pumping depletes river flows by an amount estimated as a function of lagged past pumping over the past four decades (Cook and Balleau 1998). Given past and project demand patterns, this results in river depletions of about 60% of current pumping levels. Albuquerque currently returns 60,000 acre-feet per year to the river from wastewater treatment plant. In future years, Albuquerque will continue to return an amount to the river in acre-feet per year equal to the current ratio of return flow to total supply of 0.41. Albuquerque's M&I use will be supplied totally from groundwater pumping for the next 10 years. Albuquerque's total diversion of surface water will be 97,000 acre-feet after it fully develops its surface treatment facilities, assumed to occur by 2010. These diversions include a senior right to a net water use (diversions plus pumping induced groundwater use, minus return flow) of 48,200 acre-feet of San Juan Chama rights, with additional diversions having equal priority to New Mexico (MRGCD) diversions for irrigated agriculture.

[15]Reclamation calculates a mass balance analysis to account for reservoir storage for Elephant Butte and Caballo Reservoirs. While the basic engineering formula above holds true: INFLOW = OUTFLOW + CHANGE IN STORAGE, as we have indicated above, evaporation is not the only reservoir loss that is individually accounted for in change in storage. In order to account for unexplained losses in the mass balance analysis, Reclamation considers evaporation and other losses as two separate losses items. The other losses include bank storage effect and groundwater seepage, particularly through the dam embankment.

[16]As Otowi flows increase, New Mexico owes an increasing percentage of these flows to Elephant Butte. For example, when Otowi flows are 1.1 million acre-feet per year, NM delivers 0.839 million acre-feet per year to Elephant Butte. When Otowi flows increase by 0.1 million to 1.2 maf, NM deliveries increase by 0.1 million to 0.939 maf to Elephant Butte. As Otowi flows increase above 0.939, NM owes more than 100 percent of the increase to Elephant Butte. For example, when Otowi flows are 2.300 maf, NM owes 2.239 maf to Elephant Butte.

Rio Grande Bosque. Riparian use at the Bosque averages 255,000 acre-feet per year, with 195,000 acre-feet per year above San Acacia, and 60,000 acre-feet per year between San Acacia and Elephant Butte Reservoir. Bosque use, or riparian depletions, are represented as an increasing function of lagged river flows. The function captures Bosque use of shallow, river-flow-dependent groundwater, which reduces use in low flow years, while increasing use in high flow years.

Middle Rio Grande Conservancy District (MRGCD). MRGCD is the dominant water diverter in New Mexico above Elephant Butte Reservoir. Future Albuquerque area population growth and its planned surface water treatment development will increase net river depletions at the expense of some current MRGCD's surface water use. We would expect that Albuquerque will enter the water rights or water purchase or rental market as a buyer of MRGCD water. MRGCD currently has essentially zero groundwater pumping capacity.

Colorado

Deliveries to New Mexico. Water Colorado delivers to New Mexico at the Lobatos gage is a function of headwater flows in Colorado. These headwater flows, called Index flows for the Rio Grande Compact include three Conejos River Index gages plus the Rio Grande gage near Del Norte.

Use for Colorado Agriculture. Any water not delivered to New Mexico is available for use by Colorado agriculture.

San Luis Valley Closed Basin Project. Deliveries to the Lobatos gage can occur from pumping from the San Luis Valley Closed Basin project.

Relation Between Aquifer and Surface Water Use. When the aquifer level in the San Luis Valley is low, Colorado's water is used partly for crops and partly for aquifer recharge. When its aquifer is full, Colorado's water is entirely used for crops. Equations are written in the model to summarize annual flows at the Lobatos gage and water available for use by Colorado agriculture as a function of the Index flows described above.

**Integrated Model for Institutional Response to Drought in the Rio Grande Basin**

Summary

An integrated model of the Rio Grande Basin (RGB) was developed to bring the work on hydrology, economics, and institutions within a single framework. The RGB model is used to estimate hydrologic, economic, and ecological impacts of a prolonged basin drought. Proposed alternative water management institutions for minimizing drought damages are simulated using the RGB model. The model is then further utilized to explore the sensitivity of assumed parameters of critical physical linkages (e.g., surface-groundwater interactions) to the estimates of drought damages.

The integrated framework provides a flexible environment for representing alternative drought-coping institutions. At the same time, the framework plausibly accounts for a set of physical interactions between uses (e.g., agricultural, municipal, instream, and environmental), storage (including groundwater), flows (including diversions, pumping from groundwater, and return flows), and various losses (including field, canal, and conveyance losses). Because of the importance of interstate and international water policy issues, relevant compacts and decrees, uses, storage, and flows must be represented.

Existing models were not available to meet this need. Given the inability to examine the effectiveness of alternatives institutions with existing tools, a fully integrated RGB model capable of representing interactions between uses, storage, and flows within a flexible institutional environment was developed.

Background

The basin-wide RGB model structure builds upon similar integrated models previously used to evaluate basin-wide water policies (e.g., Oamek 1990). Such approaches have also been used to integrate instream uses, and water quality impacts (e.g., Ward and Lynch 1997; Lee et al. 1993). Water budgets define the geographical structure in these models, while optimization of an objective function serves as the driver. Objective functions may be chosen to replicate existing institutions, or may represent alternative water allocation rules. Certain allocation rules such as minimum required instream flows can be added as constraints. The model is written using GAMS 2.50, utilizing its integrated development environment. Model solutions are estimated using the MINOS nonlinear solver.

Hydrology

The RGB model is a water accounting model with mass balance of surface and groundwater at its core. Mass balance is developed for each node in the basin. Any given node may represent a river reach, a consumptive use location, or a storage location such as a reservoir or aquifer.

Approach

All nodes are measured in net flows of water per unit time, or consumptive use per unit time, or storage volume in a given time.

Mass balance requires that for any node i,

$$\Delta Y_i\,(t) \;=\; \sum_j \; y_{ij}(t) - x_i(t) \qquad (3.42)$$

where $\Delta Y_i\,(t)$ is change of storage volume $Y_i$ ; $\sum_j y_{ij}(t)$ is net inflow to node i from all nodes j,

and $x_i(t)$ is consumptive use at node i.

In the Rio Grande Basin, considerable time lags can occur in water transport between nodes. For example, aquifer return flows to the river critically impact minimum flows, particularly in winter, but occur over a time period longer than the anticipated time-step for implementation of this modeling framework. Inflows to node i are thus defined by

$$y_{ij}(t) = \sum_{t} d_{ji}\ y_{ji} \tag{3.43}$$

where $d_{ji}$ summarizes the lags in outflow delivery $y_{ji}$ from node j to i. For the special case where there is no lag in flows at all, $d_{ji} = 1$ where s = 0, and $\gamma_{ji} = 0$ for all s > 0, which means $y_{ji}(t)=y_{ji}(t)$. The approach is described by Fredericks, and others (1998) in their use of time-lagged depletion and return flows.

Detailed Implementation

Several important surface and groundwater interactions are represented in the model. Each are discussed below.

Surface Diversions for Consumptive Use. Diversions immediately reduce surface flow and are used to produce economic and/or ecological benefits. Through seepage losses both in conveyance to a downstream node and at the point of use, diversions typically increase storage in and availability of groundwater resources. Unrecoverable losses to evaporation or saline aquifers may also occur. Surface diversions are limited both by physical availability, and by institutional constraints such as the Rio Grande Compact or surface water diversions established by water rights under state laws.

Groundwater Pumping for Consumptive Use. Groundwater may be directly used to produce economic and/or environmental benefits. As with surface diversions, both recoverable and unrecoverable losses may occur. Groundwater pumping is limited by physical availability and by groundwater pumping permits established under state law.

Groundwater pumping limits reflect both available infrastructure, and the short-term possibility of substantial drawdown or depletion of shallow aquifers during drought. The latter effect is captured through a pumping limit that is a decreasing function of lagged river flows. The purpose of the functional form is to capture decreasing ability to pump from shallow, river flow dependent, groundwater.

Pumping Limits. Pumping limits are set to determine the degree to which pumping would be scaled back under sustained low-flow conditions. The parameter gamma is used, in conjunction with modeled river flows, to determine the maximum level of pumping in any given time period. Coefficients are used with modeled river flows to determine this pumping limit.

Water Use by Albuquerque. Albuquerque area surface diversions of its San Juan-Chama rights of just under 50,000 acre-feet per year are limited in the model to those diversions leading to a net river depletion by Albuquerque equal to these rights. Return flows accruing to the river increase diversion rights, while the estimated depletions to the river resulting from pumping reduce the diversion right.

Groundwater Pumping by the City of El Paso. El Paso uses both surface and groundwater to meet its M&I demands. In the model, El Paso is constrained to maintain a base level of groundwater pumping no lower than the absolute level of 1999 pumping. Increasing future water demands are satisfied largely from increased use of surface water.

Surface Water Use by El Paso. Surface water used by El Paso is provided out of the allocation of the EPWID #1. Water users within the district are subject to the same allocation, and hence El Paso municipal use of surface water is reduced proportionally to remaining agricultural uses in times of less than full allocations.

Mexican Surface Water Deliveries. A constant 60,000 acre-feet annual delivery is assumed. Historically, in times of severe drought, Mexican deliveries have in fact been reduced considerably below 60,000 acre-feet. Inspection of the data on Mexican deliveries show that a fairly simple regression relationship could be estimated showing Mexican deliveries as a function of Rio Grande project releases in periods of less than full supply.

Surface-Groundwater Interactions. Ground and surface water interactions are common throughout the Rio Grande Basin. Groundwater may either contribute to surface flows producing a gaining river, or, under other conditions, may remove water from river reaches resulting in a losing river. Past groundwater levels are determined in part by past water use and river conditions. These groundwater levels are modeled to determine the direction and magnitude of flows for a given reach and a given time period. These interactions, including time lags, are represented in the RGB model using Equation 3.38.

Net gains or losses from groundwater return flows are a function of the lagged seepage from, or depletion to, shallow tributary aquifers. Net seepage, the difference between percolation associated with water use, and pumping depletions in the same aquifer, is used together with the lag structure to calculate the net effect on river flows in any given time period. The lag is a simple linearly declining function of net seepage. The lag time may vary from just the current year (no lag) to the full number of model time-steps (years). The proportion of net seepage impacting river flows over the full lag ranges from zero to one. For lags longer than the number of time steps to the first modeled period (e.g., a five-year lag in model year 3), the net seepage in period one is used as a proxy for the missing periods.

Reservoirs. Reservoir accounting is used to determine reservoir storage, and direct economic benefits of reservoir use. Accounting components are limited to inflows, outflows, and evaporation. Equations based on reservoir levels characterize reservoir areas and hydropower head, allowing estimation of direct economic benefits from recreation and hydropower, respectively.

Consumption by the Bosque. Consumptive use of water by the Bosque near Socorro New Mexico is estimated using a simple physical model of local groundwater availability. The model uses a lagged response function. The model represents consumptive use by phreatophytes whenever water is present in the root zone. Bosque use, or riparian depletions, are represented as an increasing function of lagged river flows. The purpose of the functional form is to capture Bosque use of shallow, river flow dependent groundwater.

Inflows. The model reads a set of headwater inflows at six basin locations including water imports to the basin from the San Juan-Chama interbasin transfer project. For the 50 and 100-year drought scenarios, these inflows represent flows associated with the kind of drought expected to occur once in 50 years or once in 100 years, respectively.

Consumptive Use of Water. Consumptive use is defined as the difference between surface diversions plus pumped groundwater, and surface return flows plus deep percolation. The consumptive (use defines the quantity of flows that are lost (through evapotranspiration, or simple evaporation) to any future use by the system.

Mass Balance. Mass balance of all inflows and outflows occurs at each model node. Possible flows present at a model node include inflows, diversions, surface return flows, groundwater return flows and losses, bosque (riparian vegetation) depletions, reservoir evaporation losses, changes to reservoir storage levels not including evaporation, and other uncategorized conveyance gains or losses supported by historical relationships between pairs of nodes.

Compact Constraints. For purposes of this analysis, Colorado's obligation to New Mexico under the Rio Grande Compact, as described in the Compact delivery schedules, is captured by quadratic functions defining the obligation given the Rio Grande and Conejos supply indices, respectively.[17] Departures from the schedule result in debits or credits charged to Colorado. For this report, Colorado debits and credits

[17]The quadratic mathematical function approximates the lookup tables defined in the Compact, which relate upstream index flows (supplies) to downstream delivery requirements.

are set at zero in all years.[18] New Mexico's obligation to water users below Elephant Butte Reservoir is approximated by a quadratic function defining required flows to Texas based on the Otowi supply index. Departures from the schedule results in debits or credits, respectively, charged to New Mexico. Any flows in excess of those that accrue as credits under the Compact are accounted for when New Mexico cannot fully use its flows.

Water Distribution within New Mexico. Water use within MRGCD is assumed to be reduced proportionally when necessary to meet Compact obligations. While this neglects the reality of senior Native and acequia rights, it captures the reality that the dominant uses (by quantity) within the irrigation district are likely to be treated similarly in times of water shortage.

Institutions

Maximizing Beneficial Use

Institutions that allocate limited water based on economic value for each use, are frequently proposed. Examples of institutions which are intended to increase the total economic benefits from all water uses include water banking, dry-year options, and market transfers of water. In general, allocations that maximize economic value at any time t can be found by maximizing the economic benefits function

$$V(t) = \sum_k \pi_i(k,t) \tag{3.44}$$

where $\Pi_i\,(k,t)$ is the partial economic benefit produced by the k-th water use at time t.

A number of proposed institutions for operating the system, which vary from the status quo (Law of the River) to a wide range of alternative institutions, can be accommodated with this approach. For

[18] Colorado has chosen to incur virtually zero credits and debits, but is not required to do so under the Compact. Under it, both Colorado and New Mexico are permitted annual and accumulated debits and credits. Article VI permits Colorado up to 100,000 acre-feet of annual or accrued debit and up to 150,000 acre-feet of annual or accrued credits. It permits New Mexico up to 150,000 acre-feet of annual debit and 200,000 acre feet of accrued debit and up to 150,000 acre-feet of annual or accrued credits.

example, a regulated water bank with a set price can be modeled by adding a constraint on the price of water in the solution to Equation (3.44). In practice water transfers or markets occur over a short period of time. However Equation (3.44) can be modified to include the discounted sum of future benefits over any desired time period, thus becoming a multi-period dynamic model.

Benefits from Consumption. Total benefits of water use are represented as quadratic functions of total consumptive use, minus the net added cost per unit of consumptive use derived from pumped groundwater rather than surface water. This is applied to both agricultural and M&I uses.

Benefits from Recreation. Recreation benefits are not derived from the consumption of water in the same sense as agriculture or M&I users. These benefits are estimated as a quadratic function of reservoir volume. The benefits function is based on the dependence of benefits on reservoir volume, which depends of surface area.

Total benefits. Total benefits are the sum of benefits from consumption and benefits from recreation. These benefits are summed over the 44-year time period of analysis.

The Rio Grande Compact

The 1938 Rio Grande Compact provides detailed use rights and delivery obligations for water by Colorado, New Mexico, and Texas.[19] The Compact specifies total annual flows to be delivered downstream of major use points in Colorado and New Mexico, indexed to total annual flows upstream of these points. The Compact divides annual flows among the three states at two points.

First, Colorado must deliver to New Mexico a minimum water volume based on the headwater flows on the Rio Grande mainstream and the Conejos River. Colorado may use from 40% to 80% of

[19]Colorado and New Mexico have delivery obligations, Texas has none.

those total annual headwater flows, depending on those two rivers' total annual production. Colorado's delivery requirements to New Mexico are measured at the USGS Lobatos stream gage on the mainstem of the Rio Grande near the Colorado-New Mexico border.

Second, New Mexico must deliver annual flow to Texas at Elephant Butte Reservoir, defined as a percent of annual flow on the Rio Grande mainstream at the Otowi gauge in northern New Mexico downstream of the Rio Chama confluence. New Mexico may deplete between about 20% and 43% of the Otowi flow, depending on total supply available. For Compact purposes, Texas is defined at the outflow point of Elephant Butte Reservoir in southern New Mexico. Allocations downstream of Elephant Butte are divided in fixed proportions between Elephant Butte Irrigation District in New Mexico (57%) and El Paso Water Improvement District #1 Texas (43%). Table 3-50 describes allowed consumption of water by state according to the Rio Grande Compact. Inflows originating in Colorado are in the first column. These flows determine the use permitted by Colorado, and hence total flows that must enter New Mexico. Currently most of the flow entering New Mexico is used for irrigation in the Middle Rio Grande Conservancy District, and for uses downstream of Elephant Butte, (defined as Texas under the Compact), including agriculture, and municipal and industrial uses.

| **Table 3-50. Water use apportioned by state under Rio Grande Compact, in 1,000 acre-feet per year, exclusive of tributary flows produced in New Mexico and Texas.** | | | |
|---|---|---|---|
| **Total Inflow**<br><br>(Rio Grande at Del Norte, plus Conejos River near Mogote) | **Colorado Use**<br><br>(Based on total Compact obligation at Lobados) | **New Mexico Use**<br><br>(Between Otowi and Elephant Butte, from water delivered at Lobados) | **Texas Use**<br><br>(Total delivery below Elephant Butte Reservoir; includes uses in southern NM) |
| 300 | 240 | 26 | 34 |
| 400 | 315 | 37 | 48 |
| 500 | 380 | 52 | 68 |
| 600 | 439 | 69 | 92 |
| 700 | 493 | 89 | 118 |
| 800 | 541 | 111 | 148 |
| 900 | 585 | 135 | 180 |
| 1000 | 624 | 162 | 214 |
| 1100 | 660 | 189 | 251 |
| 1200 | 692 | 217 | 291 |
| 1300 | 720 | 248 | 332 |
| 1400 | 745 | 278 | 377 |
| 1500 | 767 | 308 | 425 |
| 1550 | 782 | 323 | 445 |
| 1600 | 789 | 334 | 477 |
| 1650 | 794 | 352 | 504 |
| 1700 | 794 | 360 | 546 |
| 1800 | 784 | 385 | 631 |
| 1900 | 784 | 399 | 717 |
| 2000 | 784 | 405 | 811 |

Water Rights

We treat water rights as having the characteristics of a water production function. In particular, for any given water right holder, the production function relates the actual water delivery over a given period (wet water) to the sum of river basin inflows. While the sum of all off-stream deliveries will increase roughly linearly with basin inflows (ignoring return flows and system losses), it is unlikely that a given water right holder will experience constant returns to basin inflows. Rather, the user (e.g., a state or nation) may be allowed decreasing (junior right) or increasing (senior right) marginal returns to basin inflows. The case of constant marginal returns is that of a proportional right. This concept of linking the seniority of a water right to the nature of the incremental flows reserved with increased total flows offers insights into characterizing water rights implicit in compacts and treaties. This concept is particularly helpful where, as is the case with the Rio Grande Compact, the text of the agreement provides little intuition as to the nature of the respective state water rights.

Compact Delivery Requirements

Allocations under the Compact[20] can be represented using a deterministic model. Central to the Compact are a set of supply indices specifying the proportion of inflows to one sub-basin that are to be passed to the downstream sub-basin. First, Colorado must deliver to New Mexico a minimum water volume based on the headwater inflows. Let $\alpha_i(Z_i)$ and $Z_i$ represent the supply indices and the headwater flows, respectively, for Colorado, and let $X_{Col}$ represent the implicit consumptive use allocated for Colorado of 40% to 80% of the total annual flows. Then

$$X_{Col} = \sum_i (1 - \alpha_i(Z_i))\ Z_i. \qquad (3.45)$$

This equation says that Colorado's consumptive use of water is one minus the proportion of headwater flows that Colorado delivers to New Mexico under the Compact times that headwater flow. If, for example, the headwater flow is 1,000,000 acre-feet and Colorado must deliver 0.376 of that flow to New Mexico, then Colorado is allowed to consume, through its agricultural water use, (1 - 0.376) times 1,000,000, which is (0.624) times 1,000,000, or 624,000 acre-feet.

[20]For discussion here the The Mexican Water Treaty of 1906 (the "Treaty") is included. The Treaty regulates the flow of the Rio Grande between the United States and the Republic of Mexico, requiring delivery of 60,000 acre-feet per year to Mexico.

Next, New Mexico must deliver annual flows at Elephant Butte Reservoir for water users in southern New Mexico, Texas, and Mexico. For New Mexico above Elephant Butte Reservoir ($NM_1$), its right to consume water under the Compact, $X_{NM1}$, is defined by the supply index applied to Otowi gage flows, labeled $\beta_i$. This supply index $\beta_i$ can be applied to original headwater flows, $Z_i$. Finally, New Mexico can consume water from tributaries that enter downstream of the Otowi gage, and also imported water. This means that

$$X_{NM1} = (1 - \beta(\alpha_i(Z_i)(Z_i)))(\textstyle\sum_i \alpha_i(Z_i) Z_i) + Z_{exempt} \quad (3.46)$$

where $Z_{exempt}$ are tributary inflows including San-Juan Chama imports that can be fully consumed in New Mexico above Elephant Butte. The river reach of greatest concern for the endangered silvery minnow lies downstream of (most of) these uses. The factor $1-\beta$ indicates the proportion of Otowi gage flows that New Mexico above Elephant Butte can use, and ranges from about 20% at high flow levels to a maximum of 43% at low flows.

Downstream of Elephant Butte, water deliveries to Mexico ($X_{Mexico}$) of 60,000 acre-feet per year must be made from the deliveries below Elephant Butte. With a fixed amount of water available, the remaining allocation available for use in Texas ($X_{Texas}$) and in southern New Mexico ($X_{NM2}$) is

$$X_{Texas} = \gamma\, \beta(\alpha_i(Z_i), Z_i) \textstyle\sum_i \alpha_i(Z_i) Z_i - X_{Mexico} \quad (3.47a)$$

$$X_{NM2} = (1 - \gamma)\, \beta(\alpha_i(Z_i), Z_i) \textstyle\sum_i \alpha_i(Z_i) Z_i - X_{Mexico} \quad (3.47b)$$

respectively. The proportion of Rio Grande Project water allocated to Texas, $\gamma$ =43%, and to New Mexico, $(1-\gamma)$= 57%, is independent of total flow, which means these two proportions are the same in wet or dry years.

## Institutions Selected

Several alternative institutions for managing basin water resources were modeled, described more fully in the subsequent Policy Analysis section. These are used to introduce the range of adaptations to drought in the basin and the resulting economic benefits or losses of various of alternation adaptations. Institutions range from "business as usual," current basin water resource management, through increasingly significant changes to existing regional water allocation institutions. To better understand the potential benefits of within-state management changes, an "unconstrained" institution allocating water to its highest economic use across all states and users, independent of the Rio Grande Compact or other institutional requirements, was selected.

## Reporting

Calculated hydrologic, economic, and ecological impacts of alternative management institutions under drought are reported by the model.

Impacts are presented for each modeled time-step, river reach, and economic and ecological sector. Reservoir conditions are also reported. Aggregated reports are presented for state and sector (e.g., agriculture) levels of water use and the resulting economic impacts. Aggregated reports provide both annual impact estimates, and total (present value) impacts calculated across all drought years.

## Discussion

A modeling framework, the Rio Grande Basin model, for investigating alternative approaches to drought mitigation in a three-state river basin is presented. The model provides a basis for understanding drought impacts, identifying hydrologic and economic impacts of alternative water allocation institutions. The Rio Grande Basin model provides a structure in which to investigate critical groundwater and surface water linkages in the basin. The model characterizes the Law of the River by assuming compliance with the Rio Grande Compact. Water reallocations under a number of alternative institutions are modeled as the institutional adaptations for reducing the cost of drought impacts.