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Institutional Adjustments For Coping With Prolonged And Severe Drought In The Rio Grande Basin

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New Mexico Water Resources Research Institute
in cooperation with the

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Texas Water Resources Research Institute

Colorado Agricultural Experiment Station
New Mexico Agricultural Experiment Station
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EXECUTIVE SUMMARY

The Rio Grande originates in the southern Colorado Rocky Mountains, flows through New Mexico, and forms the border between the U.S. and Mexico on its way to the Gulf of Mexico. Serving over one-million acres of irrigated land and the municipal and industrial needs of cities like Albuquerque and El Paso, the Rio Grande represents a significant resource in the arid southwest.

In 1938, Congress approved the Rio Grande Compact which divided the annual water flow among the three states of Colorado, New Mexico, and Texas. The U.S.-Mexico Treaty of 1906 divides the river flows between the U.S. and Mexico. The Compact acknowledges the Treaty in Articles IV and VI by stating that the Compact shall not diminish the allocation of water to Mexico and shall not degrade its quality.

Since that time, significant growth in the Rio Grande Basin's demand for water due to increasing populations, growing economies, and emerging policies toward fish and wildlife habitat emphasizing endangered species, has stressed the region's already scarce water supply. Although the inevitable severe drought would cause significant economic damage to the regional economy, present institutional arrangements have not had to confront such an event since the 1950s. The objective of this research is to test the hypothesis that new institutions for interstate coordination of surface water withdrawal and reservoir operations could reduce economic losses resulting from water shortfalls in periods of severe and sustained drought.

A three-state research team of economists, hydrologists and a lawyer was formed to perform the analysis to test this hypothesis. A fully-integrated hydrologic-economic model was developed which extends the basin optimization procedures developed by Vaux and Howitt for California and by Booker and Young for the Colorado River Basin. The geographic scope included the Rio Grande Basin, from

Colorado through New Mexico to Fort Quitman, Texas, downstream of El Paso. The objective was to identify hydrological and economic impacts of possible changes in institutional structure for coping with drought.

This study was an effort to examine options facing river basin managers when confronted with the extenuating circumstance of a major drought. It did not attempt a precise description of the current system as it is managed. The research team realizes that many considered institutional changes for managing water considered in this report would be difficult to do, costly, and in some cases fought bitterly. Nevertheless, like other analyses of proposed changes in water policy, there are several reasons for conducting these policy experiments. Estimating impacts of a proposed water policy change can be a cheap substitute for carrying it out, especially if carrying it out has potentially high but unknown political or economic costs or benefits. If a proposed policy change produces a low economic benefit and high cost for many water users, information on the size and distribution of those benefits and costs is important. This information is a valuable resource for formulating or executing this action should it be considered is a real possibility. If, however, there is a high benefit and low cost to most water users, this is also important information to get out, for it may influence the shape of future policies pursued.

The general approach used in this study reflected the random supplies and uncertain demands for water. They also reflect river and reservoir management rules resulting from economic growth and competing demands for water to meet future needs such as endangered species habitats. Water supplies, which included all major tributaries, interbasin transfers, and hydrologically connected groundwater, were represented in a yearly time-step over a forty-four year planning horizon.

Agricultural water uses, the major source of water demands, were split into major crops for four major demand areas. Municipal and Industrial (M&I) and recreational demands were also identified. Separate economic values were identified for each water use at each major location. Information on the economic value of each water use at each location provides important facts to decision makers who wish to know impacts of complex proposals whose implementation affects several uses at many locations.

A mathematical model was developed that kept track of economic benefits subject to hydrologic and institutional constraints, and was solved with GAMS optimization software (Appendix CD ROM). Each institutional innovation considered was tested against the baseline Law of the River, the current set of rules for storing, allocating, and using water in the basin. Each proposal was tested for its impact on reducing total economic damages under a future, long-run drought scenario defined by inflows produced by the drought of the 1950s. Results are presented as economic and hydrologic impacts of measures for coping with drought by state, economic sector, and institutional alternative.

One baseline and three alternative institutional innovations were selected for evaluation. The baseline Law of the River focused primarily on the Rio Grande Compact and related rules for allocating the total quantity of water entering the Rio Grande Basin and available for use. Total economic benefits were calculated for: (1) long run normal inflows, (2) a sequence of drought inflows, defined by historical inflows for the period 1942-1985. This period was chosen to represent the severe drought of the 1950s bound by the years leading up to and following that drought. The period was extended to 1942 and 1985 because spills occurred in these two years, wiping out accrued debits and credits under the Compact. For that period, average inflows summed over six headwater stream gages used for this study were 1.40 million acre-feet per year, about 11 percent below the long-run average of 1.57 million.

Total drought damages were computed as the reduction in future economic benefits if future inflows to the basin averaged 1.40 million acre-feet per year compared to economic benefits if inflows averaged 1.57 million. Future economic activity is based on best available estimates for growth in M&I uses based on projected growth of the Albuquerque and El Paso areas.

Long-run annual average future drought damages, defined as the direct economic value of damages caused by the reduced streamflows to water users, were estimated at $5.8 million for the San

Luis Valley (Colorado), $3.37 million for New Mexico, and $8.0 million for west Texas, or about $101 per acre-foot of water supply reduction. Indirect economic impacts, resulting from interactions among drought-damaged water-users and the rest of the economy, were not measured.

The first institutional adjustment analyzed was increased carryover storage at Elephant Butte Reservoir. This carryover storage was based on reducing Rio Grande project deliveries downstream of Elephant Butte by 25,000 acre-feet per year in normal years, to be stored for use in drought years. The long- run average annual economic value of drought damages mitigated by this institutional change was zero for Colorado, minus $200,000 for New Mexico, and minus $433,000 for west Texas. This means that the current Law of the River produces less drought damage than the proposed institution of storing the added water at Elephant Butte.

The second institutional adjustment analyzed was a proposal to invest in technical measures to increase irrigation efficiency for the Middle Rio Grande Conservancy District, in which net stream depletions required for application to crops would be reduced by 18 percent. This institutional change produced virtually zero drought damage mitigation to each of the three states. Reduced water diverted from the Rio Grande brought about by greater irrigation efficiency would also considerably reduce irrigation return flows to the river. The result would be virtually zero water saved and essentially zero economic benefit. Zero drought damage mitigation benefits accrued to Colorado, $7,000 per year to New Mexico, and $15,000 to West Texas. This means that the cost of technologies needed to implement these increased irrigation efficiencies would have to be virtually zero to justify such investments economically.

The final institutional adjustment analyzed was to build 100,000 acre feet of new reservoir storage in northern New Mexico above Cochiti Lake. This action produced zero long-run average annual benefit to Colorado, $134,000 to New Mexico water users, and $685,000 to West Texas water users. The bulk of these benefits would result from reduced reservoir evaporation and reduced Rio Grande Compact over-deliveries by New Mexico to Texas.

Although the model developed for this study was comprehensive and detailed, it has several limitations in its current state. Overall, it does not precisely represent the behavior of the Rio Grande Basin system. One special area where further improvement is needed is to develop a better understanding and modeling of connections among economics, surface water movement, groundwater hydrology, and behavior of water users.

If improved models are to be used to support development, execution, and evaluation of proposed decisions, considerable resources need to be put into model development and use. The kind of integrated, basin-wide modeling described in this report is a new area of research. The integrations required between modeling the behavior of water users and underlying natural processes are quite complex, poorly understood, and will require much work and patience to bring to full fruition.

Nevertheless, this study succeeded in organizing a highly integrated interdisciplinary study dealing with water management in an important western river basin. Most western river basins are under stress, from natural factors like drought, institutional factors such as endangered species requirements, and external factors like economic growth. The use of interdisciplinary teams to build and apply models such as described in this report, helps prepare society for dealing with unexpected circumstances, such as drought, to cope with future stresses on river basins.

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CHAPTER 1 – INTRODUCTION, SCOPE, AND OBJECTIVES

The Water–Related Problem

The potential for the occurrence of drought and the associated adverse consequences for the economy, political system, and social institutions, is always an issue in dry places, like the southwestern United States (Young 1995). Numerous natural hazards, including earthquakes, floods, and drought, impose economic damages (Howe and Cochrane 1992). Adverse impacts of droughts are felt by both instream and offstream users of water, including reduced agricultural output, falling hydropower production, reduced water quality, damages to recreation users, groundwater overdraft, and damages to endangered species.

In the Rio Grande Basin, (Figure 1-1) each drought since the late nineteenth century has given rise to analysis of water problems, to questions regarding the adequacy of the water and institutional resources to meet the existing needs for water, and to actions intended to achieve a better balance between supply and demand for water in the future (Thomas 1963). For example the severe drought during 1951-57 was largely responsible for increased development of groundwater pumping and use of groundwater storage.

The quality of the water throughout the Rio Grande Basin is generally poorer in years of drought than in years of more abundant water supply. Because there is typically a progressive increase in total salt concentration of the river water from the upper to the lower end of the basin, the problem of quality is more critical to the downstream users than to those near the headwaters. In much of Texas, the major problem during drought conditions is elevated salinity in the river, thus making river water less suitable and/or more expensive for irrigation and municipal uses. Apportionment of water is also more important and also more difficult during drought when water supplies are lower than normal. Apportionment is a central objective of international treaties, interstate compacts, state water laws, and court decisions pertaining to water (Thomas 1963).

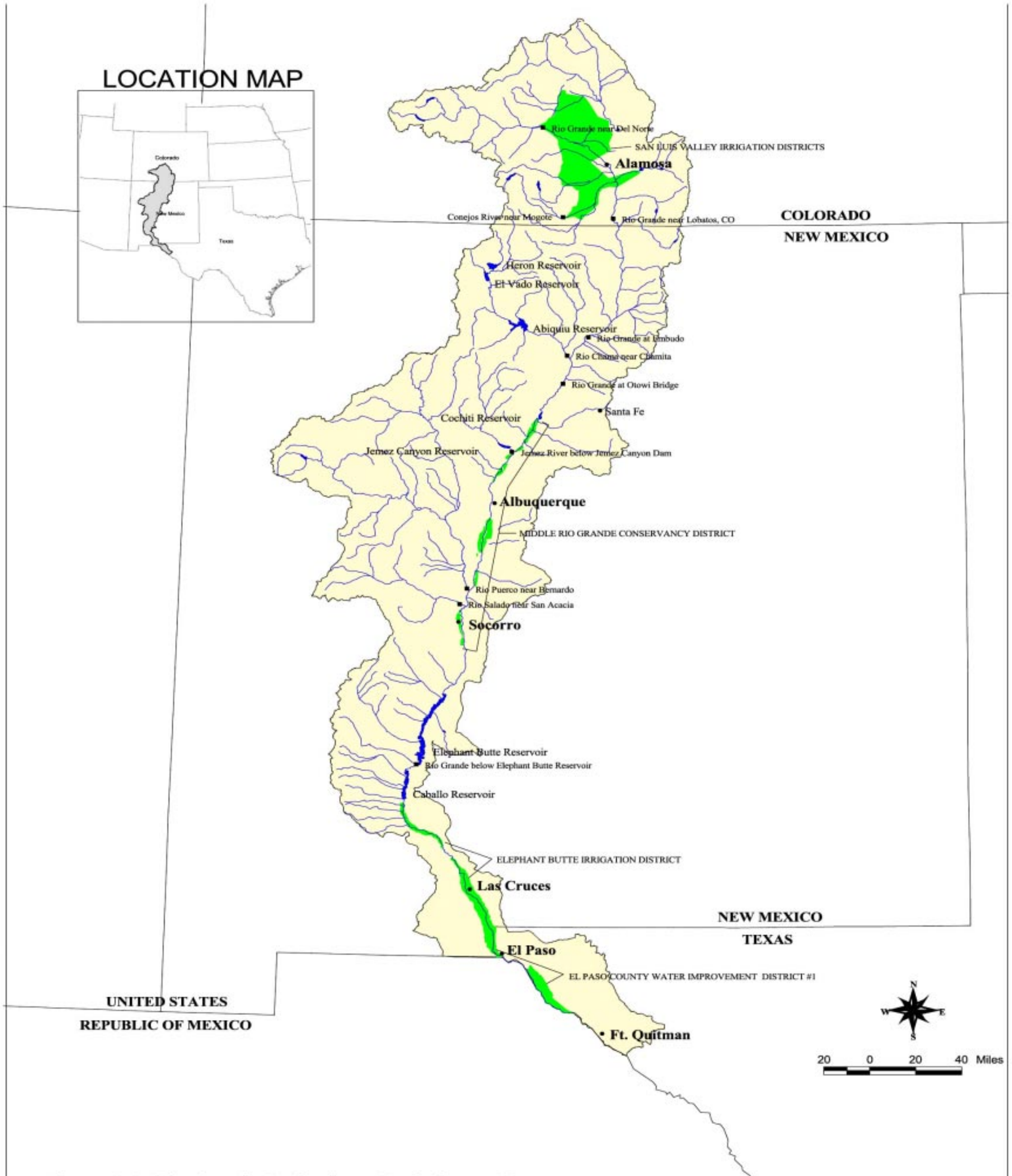
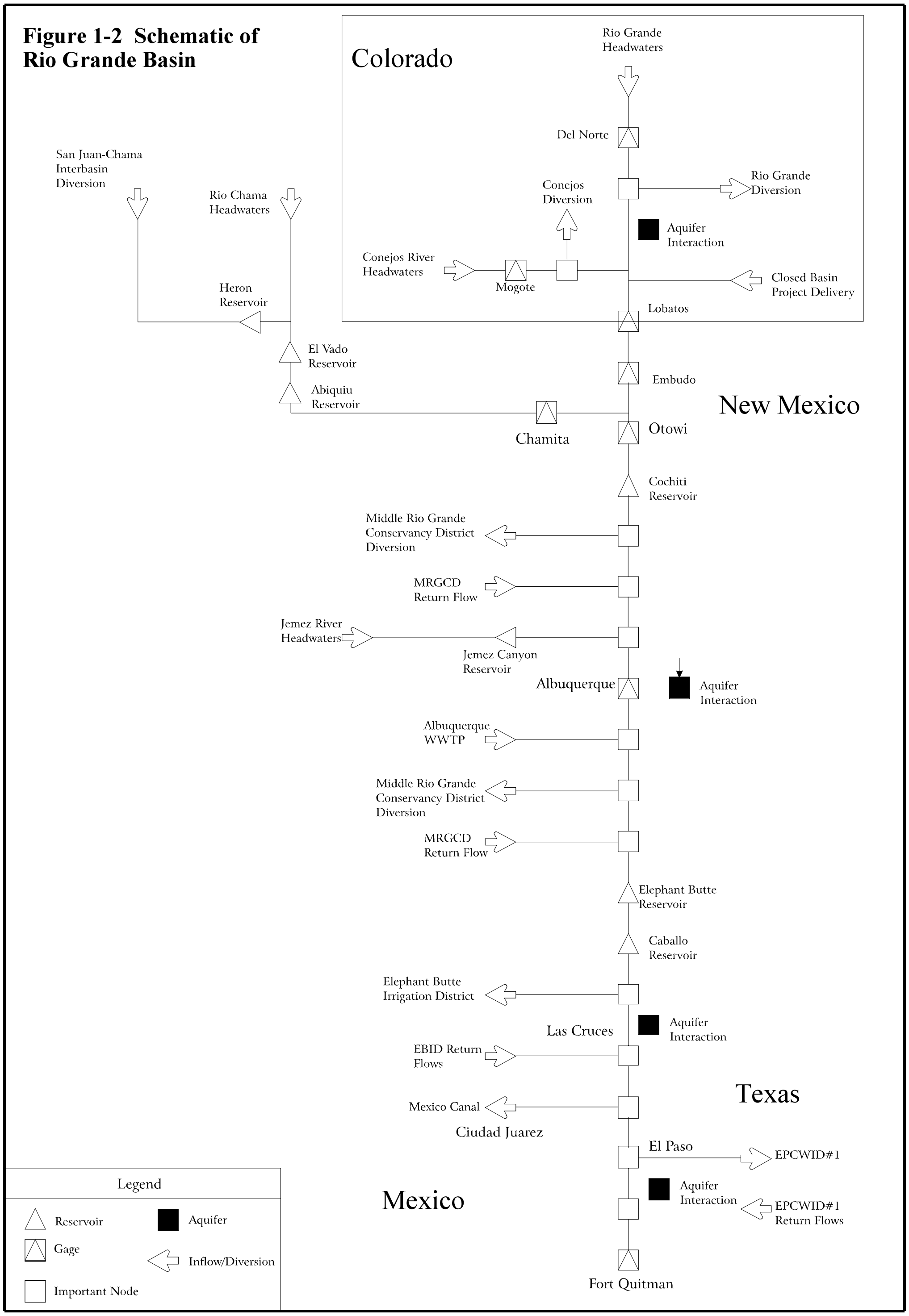


Figure 1-1. Rio Grande Basin above Ft. Quitman, Texas

Figure 1-2 Schematic of Rio Grande Basin



As of the year 2001, the physical and institutional systems serving the Rio Grande Basin (Figure 1-2) have a considerable capacity for coping with severe drought. Still, there has been no comprehensive analysis to date of information needed for drought planning for the basin. Moreover, increasing population and growing demands placed on land and related water, including demands for endangered species habitat, are increasing potential drought severity and magnifying probable economic losses incurred during a series of dry years.

This research aimed to identify economic and hydrologic impacts of policy measures for addressing severe and sustained drought in the Rio Grande Basin.

Objectives

The overriding objective was to evaluate various institutional adjustments for coping with severe drought in the Rio Grande Basin of Colorado, New Mexico, and Texas. Detailed objectives are as follows:

- (Hydrology) Formulate credible drought scenarios by assessing the probability of a prolonged and severe drought and develop drought scenarios for the major water resource systems of the study area.
- (Hydrology-Institutions) Develop a mass balance hydrologic model that accounts for sources and uses of water in the Rio Grande Basin under present water laws, policies, and management institutions. This model was the basis for evaluation of the hydrologic and economic impacts of droughts of various severities and durations.
- (Hydrology-Economics) Identify economic damages associated with selected drought scenarios by identifying the magnitude, location, and distribution of drought damages under present laws, policies, and management institutions.
- (Institutions-Economics) Incorporate institutional responses in the model for mitigating economic damages of drought by identifying available legal and institutional flexibility to limit drought damages.

- (Hydrologic-Economic-Legal Policy Analysis) Operate the model to assess hydrologic and economic impacts of alternative drought mitigation policies.

Scope

The original plan of the study was limited to the geographic area of the Rio Grande Basin from the Colorado headwaters to the Gulf of Mexico. Subsequently, the scope was reduced to include only the basin above El Paso, Texas. The economic analysis is limited to impacts of drought on the direct economic effects on agricultural, municipal, hydroelectric, and recreation uses. The hydrologic scope was limited to the mainstem of the Rio Grande and associated groundwater aquifers connected to the mainstem. The time step of the hydrology model is annual.

Approach

A highly experienced and nationally recognized interdisciplinary team was assembled to define the existing engineering-institutional-economic system, to structure credible drought scenarios in light of occurrences during the period for which recorded data exist, to assess their hydrological and economic impacts, and to evaluate selected drought mitigation strategies for reducing economic damages when such droughts occur. Because of recent memories of water users and managers in the basin, the severe drought of the 1950s was examined closely to see what adjustments would be needed today to adapt to a drought of that severity, in comparison to a future period of normal water supply.

As part of the information transfer plan, we also established an advisory council. One objective in establishing an advisory council was to preserve productive interaction between the study and individuals in the private sector and government charged with water management responsibilities in the basin. Another objective was to maintain contact with the broad range of public opinion on water resources development and management in the study area. This continuing contact was particularly important in assessing political impacts of various proposed institutional adjustments for coping with drought.

CHAPTER 2 -- RELATED RESEARCH

Causes and Effects of Drought

Climate describes a normal condition. A climatic change alters that condition. In contrast, a drought is a temporary departure from the normal. However, this conceptual distinction blurs in application because one never knows at the time they occur whether a series of years is a short-term fluctuation or a change in the long-term condition.

While continued future efforts will add scientific understanding with long-term payoffs, the near-term need is to develop quantitative models for better drought evaluation. This will buy time in preparing for the drought and relax the more stringent and costly water use controls during and after serious drought periods. The result could provide sounder information for deciding which water management policies should be implemented, intensified, or discontinued.

Yevjevich (1967) described how drought losses grow out of the time and space processes of supply and demand for water. The severity of a drought depends on its duration intensity, and geographical extent. These physical factors define the supply side. On the demand side, drought is a deficit in water availability for human purposes, riparian vegetation, and endangered species. Where past research has emphasized hydrologic characteristics, this study extends to societal impacts by integrating demand with supply considerations.

A primary problem in studying the interface between water supply and demand is that the water shortages during drought years occur in different ways. Mixing these concepts often leads to management confusion on what action to take. A drought may be meteorologic (shortages in precipitation), agricultural (shortages in soil moisture), hydrologic (shortages in runoff, streamflow, and reservoir contents), or economic (losses determined by all three shortages). The four indicators are poorly correlated (Wilhite and Glantz 1987) because of complex but unknown relations in the divisions of rainfall between infiltration and runoff and infiltrated soil moisture between soil-water storage and percolation below the plant root zone. Quantitatively, agricultural and hydrologic drought are based on two different precipitation filters. Economic drought adds a third.

Systems Operations

The structural systems supplying water in the three Basin states of Colorado, New Mexico, and Texas, are distinct but interlinked (Figure 1.1). Their operating rules, governed largely by the Rio Grande Compact, are mostly coordinated on an ad hoc basis and are generally inflexible when adapting to extreme drought events. One major potential contribution of drought contingency planning in this case comes from a finding (Getches 1989) that people and institutions are largely willing to cooperate in emergencies. Having contingency plans should help them quickly reach sound policies so they do not have to rely on ad hoc consideration of rapidly changing events.

Each structural system is operated following rules that have largely been developed and tested over time and codified into law. These have been incorporated into the models used by the various agencies for their water management purposes. The U.S. Bureau of Reclamation, the Corps of Engineers, and Texas A&M University (Rosenthal, et. al. 1995; Srinivasan and Arnold 1994; Srinivasan and Engle 1994) have developed models that could have been adapted for the Rio Grande system.

Drought Response Planning

There is a need to complement state drought programs with regional and national plans that address trans-state water and land use management issues (Easterling 1988; Morton 1988). However, this is complicated by:

- The difficulty in measuring the long-term and cumulative effects of drought (Riebsame 1987).

- The fact that the magnitude and severity of drought is never known until the event is viewed in retrospect (Gleick 1988).
- The spatial and temporal scales affiliated with drought exceed those for which policies and programs have historically been developed (Ciborowski and Abrahamson 1987).

Political and Institutional Analysis

A series of papers published in the *Water Resources Bulletin* summarized findings from a comprehensive study on coping with severe and sustained drought in the Colorado River Basin. These papers included hydrologic aspects (Meko et. al. 1995; Tarboton 1995), economic issues (Booker and Colby 1995; Booker 1995) , and institutional (Kenney 1995) and policy (Henderson and Lord 1995) responses to drought.

Institutional innovation may well be the most important present challenge in water resources planning (Ingram 1986; Allee et al. 1982). It offers potential solutions to many water resource problems, such as the use of water markets in managing water supply (Livingston 1985; Lord 1984). Several sets of criteria for evaluating water resource institutions have been proposed (Ostrom and Ostrom 1972; Dworsky and Francis 1973; Minton et al. 1980; and Blomquist and Ostrom 1985). These criteria cover the jurisdiction and authorities of an agency; the accountability, equity, and public acceptance of an agency's programs; and the technical capabilities of an institution. The evaluation criteria used for the current study were developed to identify economic damages of drought from the perspectives of each water-use sector (e.g., instream, agricultural, municipal, industrial), each drought scenario considered, and each of the three states.

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.

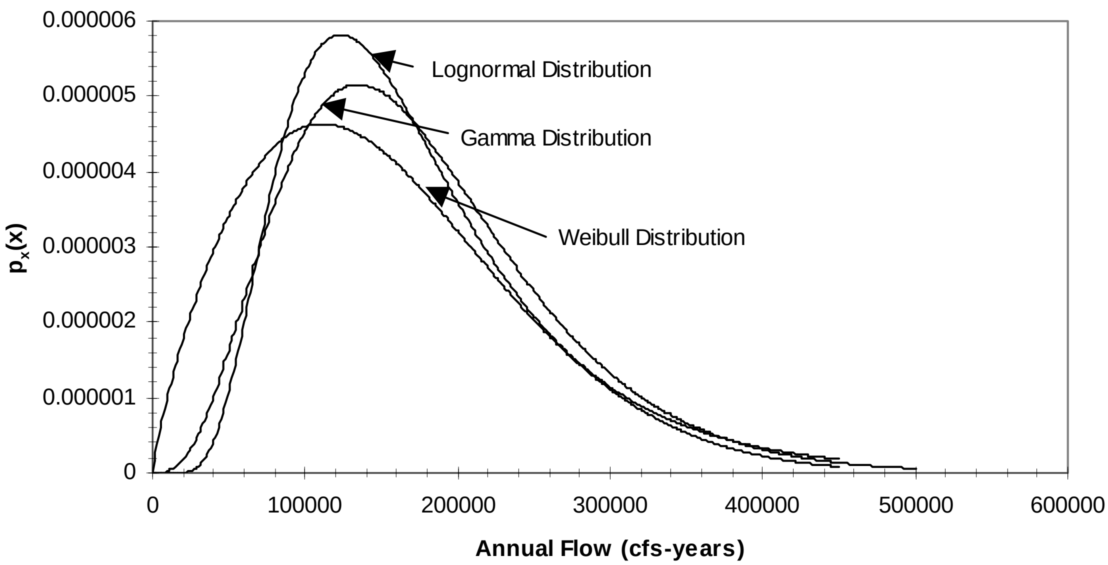
Frequency Distributions for Streamflow at Unimpaired Gaging Points

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

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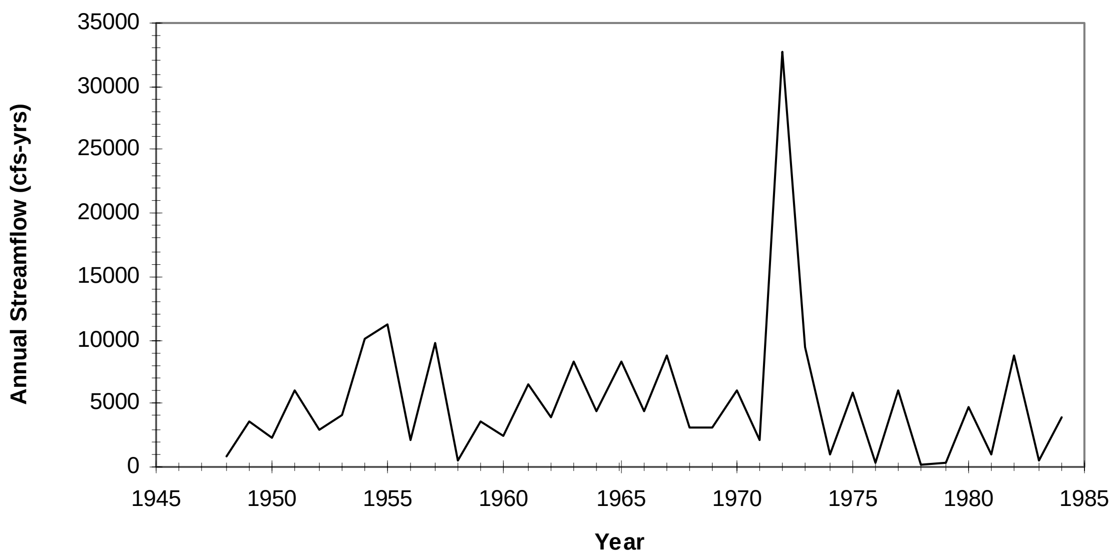
[2] In this section of the report dealing with developing drought scenarios for the Rio Grande Basin, streamflow is typically measured in the USGS format of cubic feet per second over a one-year period (cfs-years), except where otherwise noted. To translate cfs-years into acre-feet per year, multiply 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, λ and η 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 η in which $1.0 \leq \eta \leq 2.0$. For other values of the parameter η, 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, λ and η, 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:

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

$$\eta_{est} = [\, 1 + (1 + 1.333y)^{½} \,] \;/\; 4y \tag{3.3}$$

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

where x is total annual streamflow in cfs-years.

For the second stage these values of λ and η 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
η = 4.40
λ = 2.49E-05
Stage 2
$E(\eta_{est}-\eta) = 3\ \eta_{est} / n$ = 0.22001
η_{cor} = 4.18 (3.4b)
λ_{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:

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

where x is annual streamflow, in cfs-years, and y = ln(x) is the natural logarithm of annual streamflow; μ_y and σ_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
			μ_y = 11.65			σ_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:

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

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

$$E(x) = \beta\, \Gamma(1 + 1/\alpha) \tag{3.7}$$

$$\mathrm{Var}(x) = \beta^2 \left[\Gamma(1 + 2/\alpha) - \Gamma^2(1 + 1/\alpha) \right]$$

The parameters, α and β, 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 α and β. 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)

μ =	331,868 (cfs-yrs)		μ_{gen} = 268,647 (cfs-yrs)	Δ =4.00 E+09
σ^2 =	1.21E+10		σ^2_{gen} = 1.21E+10	Δ = 2.93E+09
α =	2.6074		SSR =	6.93E+09
β =	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 α an β.

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: $D = \max \left| P_X(x) - S(x) \right|$.

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:

$$D_{crit} = \frac{1.22}{\sqrt{n}} \qquad (3.8)$$

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):

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

where x is annual streamflow, and λ and η are gamma distribution parameters defined previously.

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

where x is annual streamflow, and μ_y and σ_y^2 are the mean and variance of y, respectively, with y = ln(t).

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

where x is annual streamflow, and α and β 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.

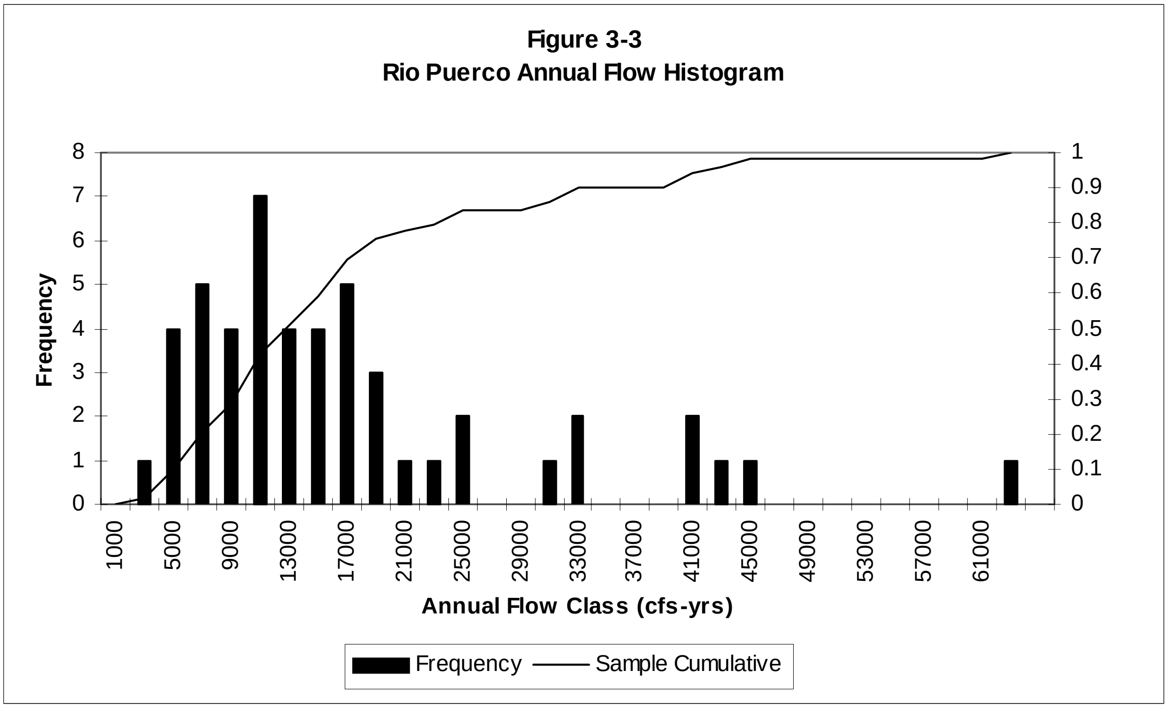


Figure 3-3
Rio Puerco Annual Flow Histogram
Frequency
Annual Flow Class (cfs-yrs)
0
1
2
3
4
5
6
7
8
0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0.9
1
1000
5000
9000
13000
17000
21000
25000
29000
33000
37000
41000
45000
49000
53000
57000
61000
Frequency
Sample Cumulative

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 η and scale parameter λ. 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, η, can be constructed by adding a gamma variable with an integer value of η and one with η 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, η =1.02. Therefore, η-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:

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

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:

$$\text{deficit}_{i} = \text{deficit}_{i-1} + (\text{streamflow}_{crit} - \text{streamflow}_{obs}) \qquad (3.15)$$

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 75% Average Annual flow = 249,380					
Year	Annual Flow (cfs-yrs)	75% ave annual flow (cfs-yrs)	Storage Deficit (cfs-yrs)	Cumulative Deficit (cfs-yrs)	Drought Deficit (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, λ, 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 λ 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 λ 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)
	λ =	0.17
GAMMA PARAMETERS:		
	avg (ln x) =	1.10
	ln (avg x) =	1.75
	y =	0.65
	η =	0.91
	λ =	0.158
Correcting for bias:		
	E (η_{est}-η) =	0.0021
	η_{cor} =	0.91
	λ_{cor} =	0.158
LOGNORMAL PARAMETERS		
	avg(ln x) =	1.1
	stdev (ln x)=	1.04
WEIBULL PARAMETERS		
	α=	0.73
	β=	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.

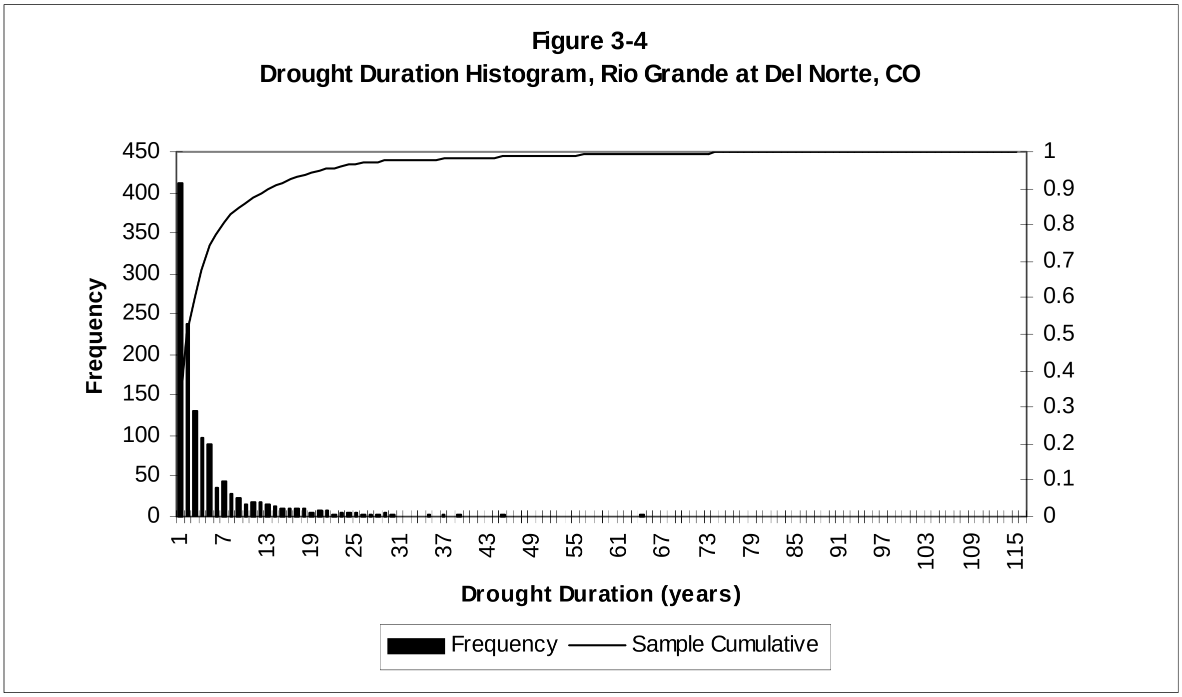


Table 3-9. Distribution of Drought Durations, 10,000 years of synthetic streamflow, Rio Grande Del Norte, CO headwater flows with 50 and 100-year drought events indicated in bold font

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
λ	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
η	0.9600	1.0209	0.9100	1.0333	1.1391	0.9351
λ	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
η_{corr}	0.9600	1.0187	0.9079	1.0311	1.1369	0.9330
λ_{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						
α	0.7900	0.8000	0.7326	0.7634	0.9950	0.5051
β	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

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[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.

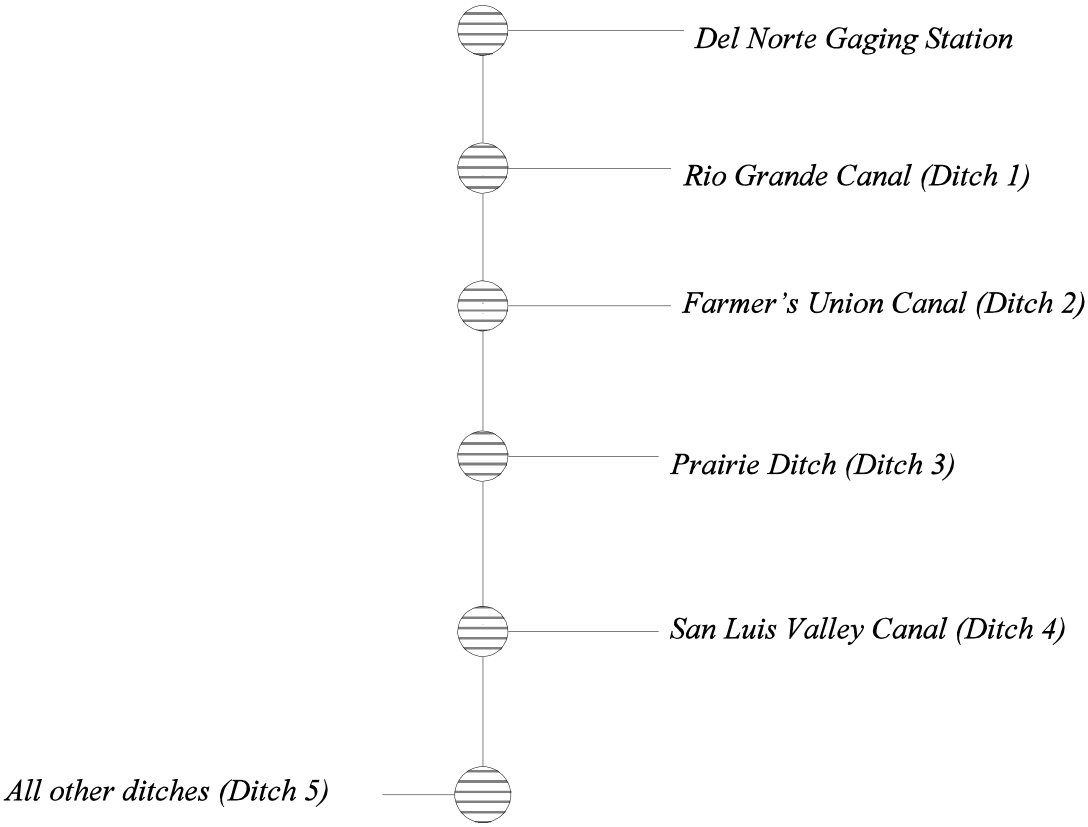

Figure 3-5. Schematic of Irrigation Ditches/Canals and Ditch Number Identifier used in Simulation Model, San Luis Valley, CO.

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.

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

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

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).

$$Flow_{i,t} = Inflow_{t}, \quad for\ i = 1-123;\ t = 1-6 \tag{3.19a}$$

$$Flow_{i,t} = Flow_{i,1t} - Divert_{i-1,t} \tag{3.19b}$$

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.

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

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

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

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:

$$Y = a + bX + cX^2 + dX^3 \tag{3.23}$$

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.

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

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.

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

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.

[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)
- Φ = soil water content
- Φ_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)
- Φ = soil water content
- Φ_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).

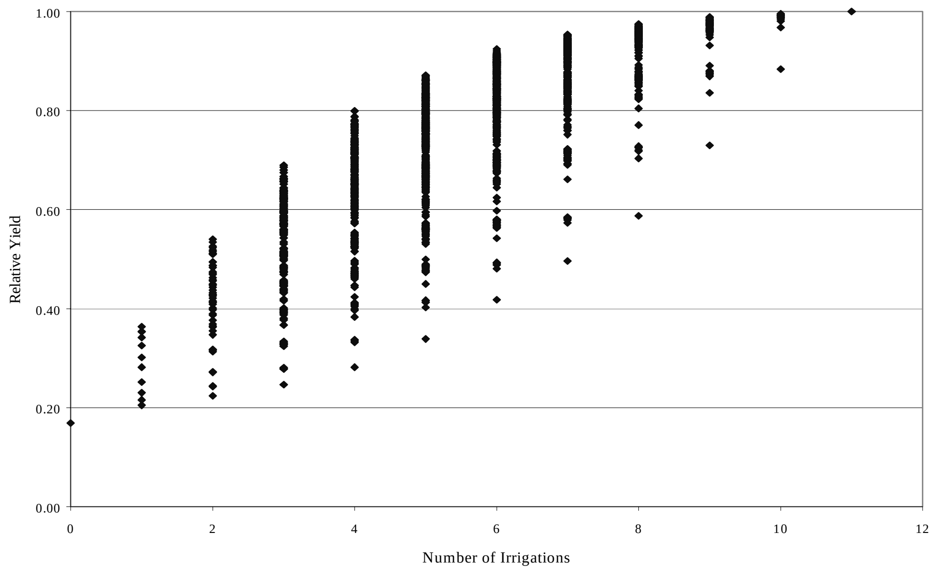

Figure 3-6. Relative Yield from Crop Growth Simulation Model with Each Possible Irrigation Combination for Alfalfa on Sandy Soil

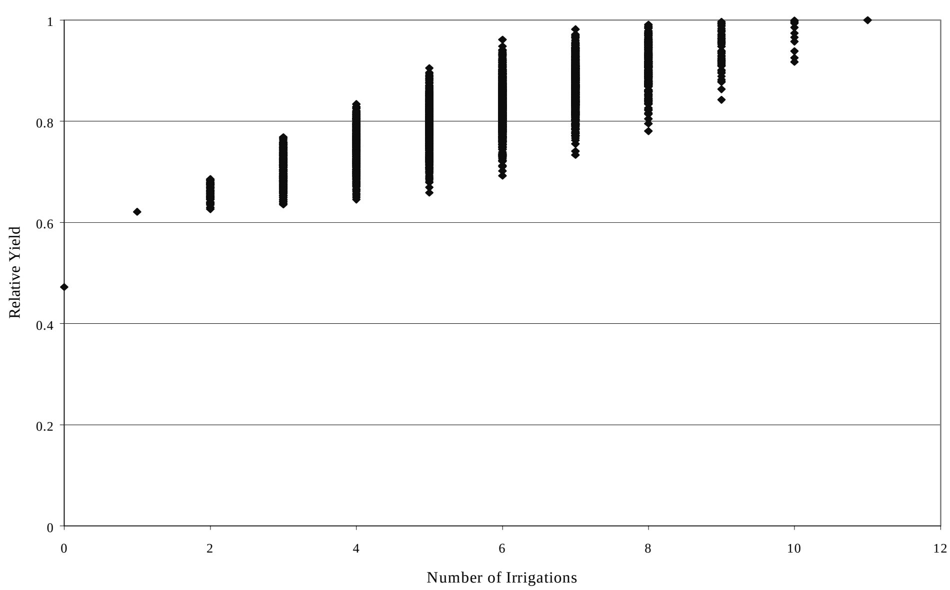

Figure 3-7. Relative Yield from Crop Growth Simulation Model with Each Possible Irrigation Combination for Alfalfa on Sandy Loam Soil

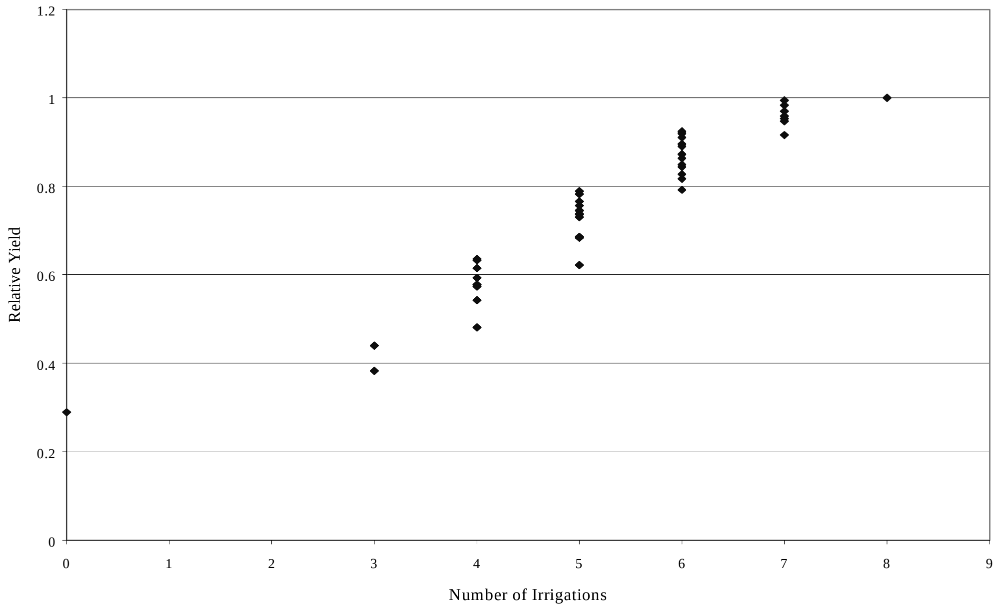

Figure 3-8. Relative Yield from Crop Growth Simulation Model with Each Possible Irrigation Combination for Barley on Sandy Soil

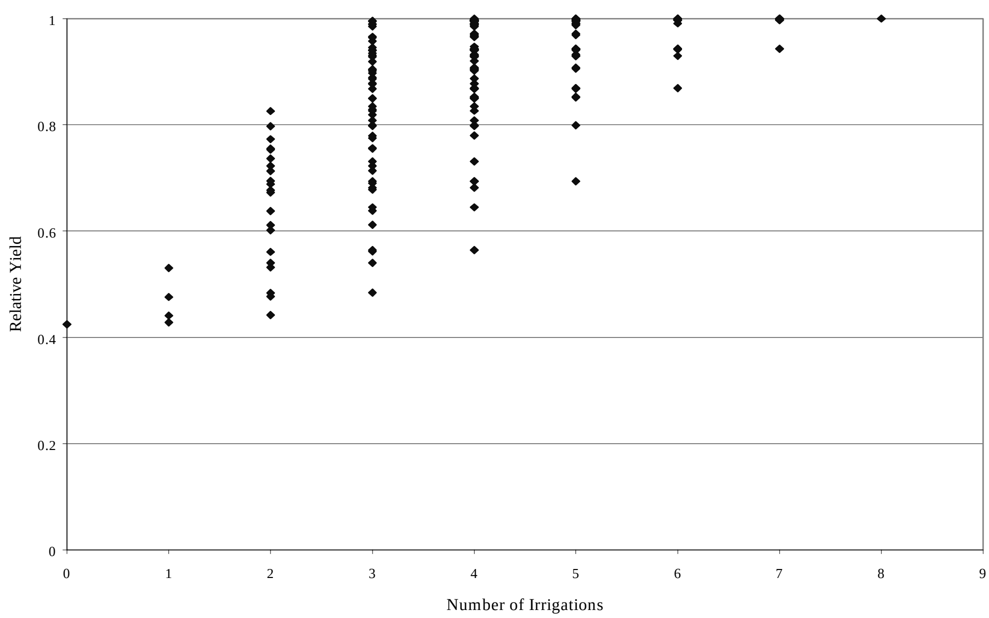

Figure 3-9. Relative Yield from Crop Growth Simulation Model with Each Possible Irrigation Combination for Barley on Sandy Loam Soil

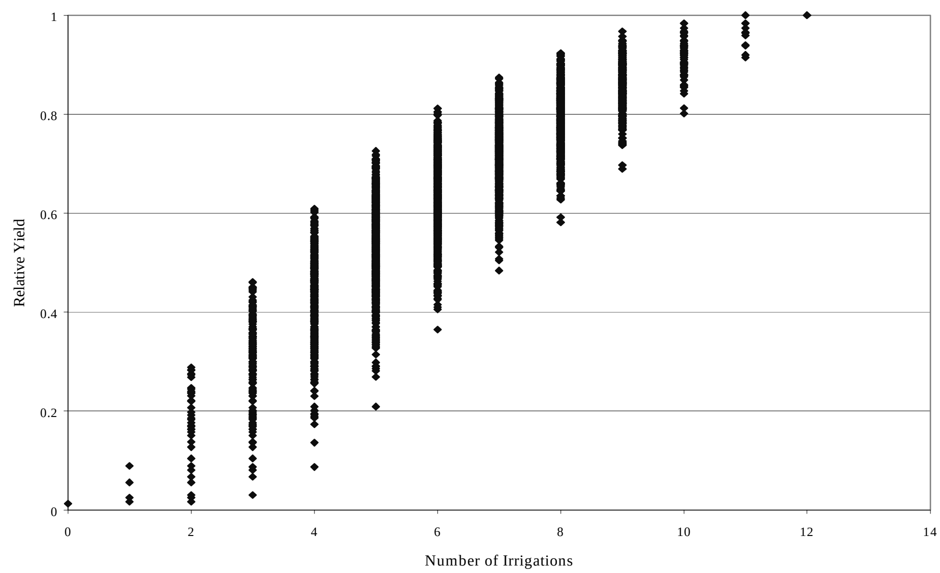

Figure 3-10. Relative Yield from Crop Growth Simulation Model with Each Possible Irrigation Combination for Potatoes on Sandy Soil

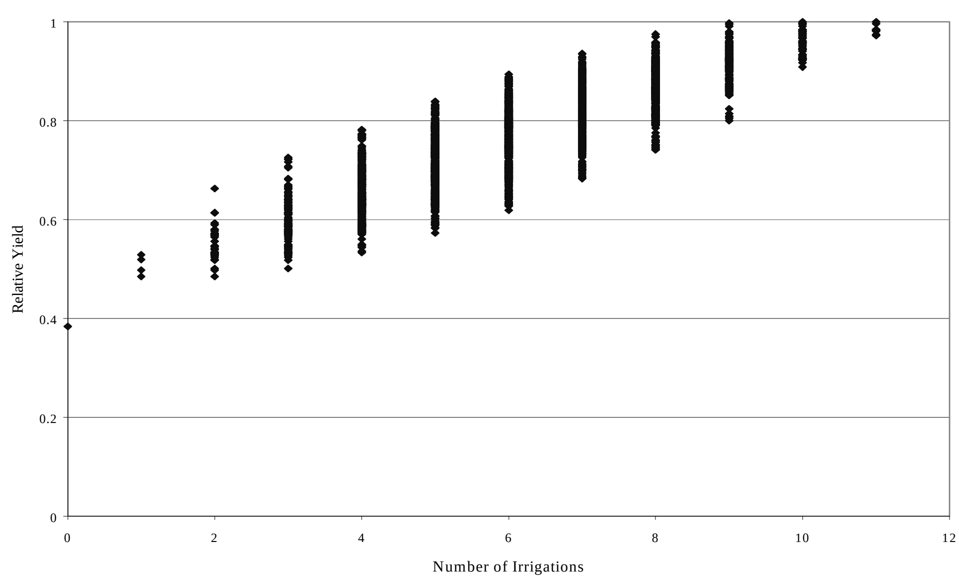

Figure 3-11. Relative Yield from Crop Growth Simulation Model with Each Possible Irrigation Combination for Potatoes on Sandy Loam Soil

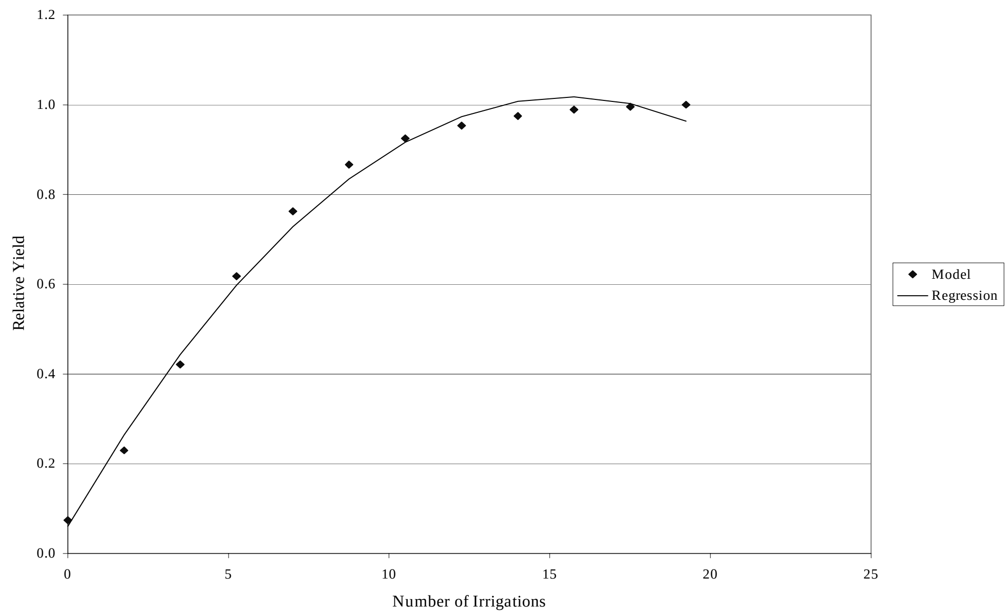

Figure 3-12. Regression Results to Derive Crop Growth Coefficients for Alfalfa on Sandy Soil

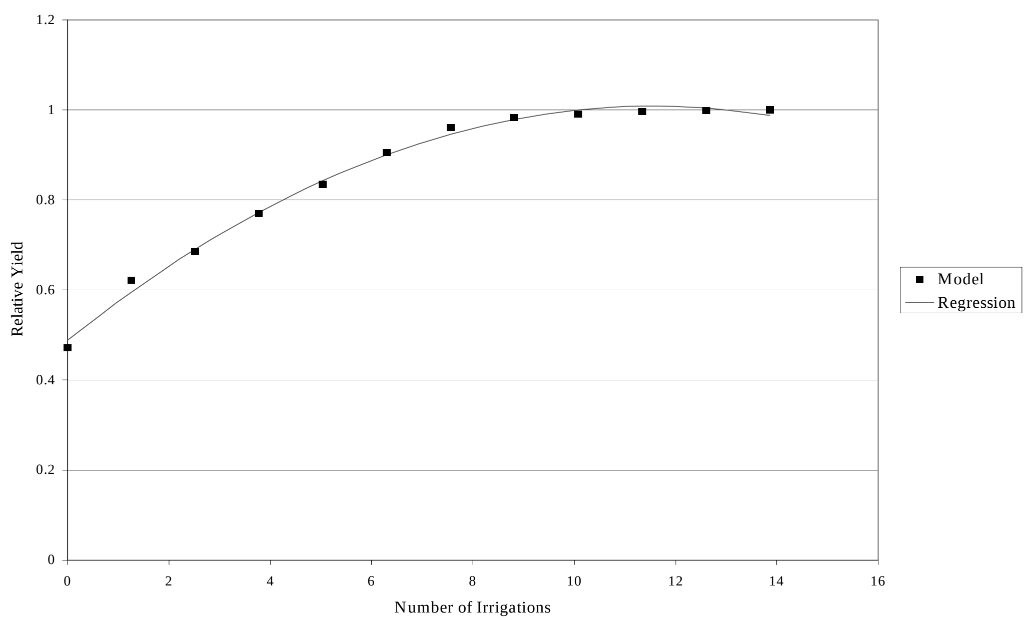

Figure
3-13. Regression Results to Derive Crop Growth Coefficients for Alfalfa on Sandy Loam Soil

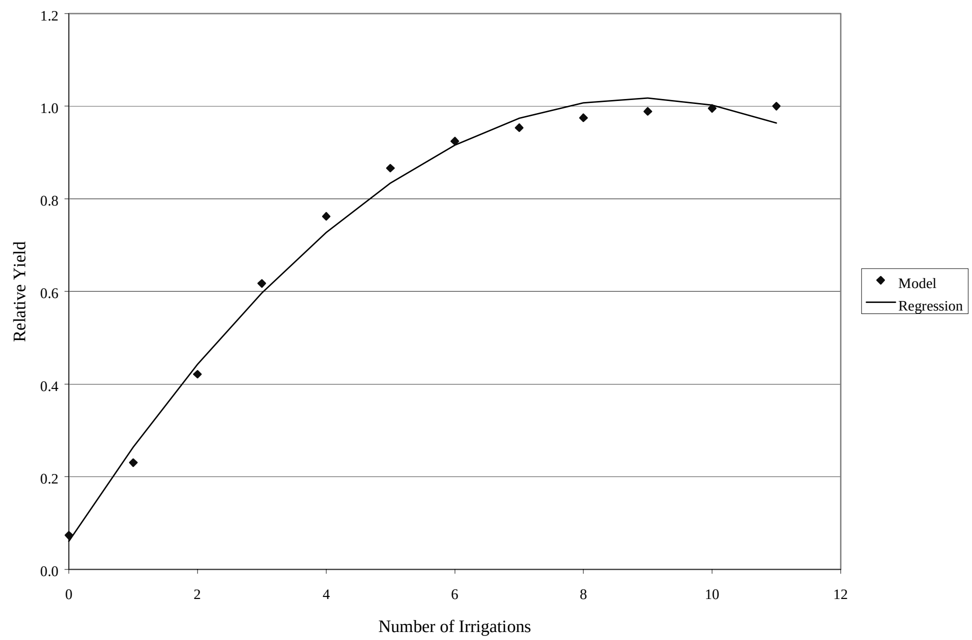

Figure 3-14. Regression Results to Derive Crop Growth Coefficients for Barley on Sandy Soil

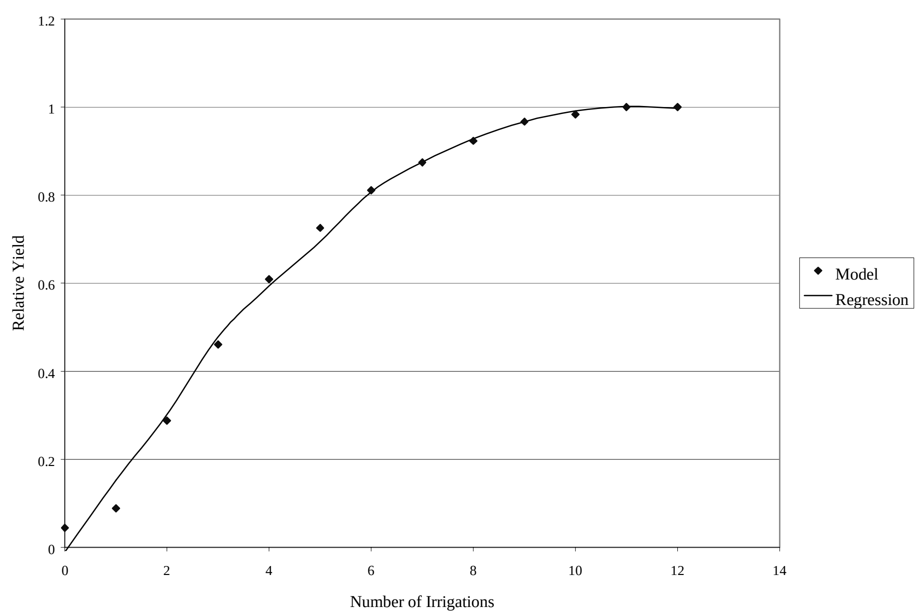

Figure 3-15. Regression Results to Derive Crop Growth Coefficients for Barley on Sandy Loam Soil

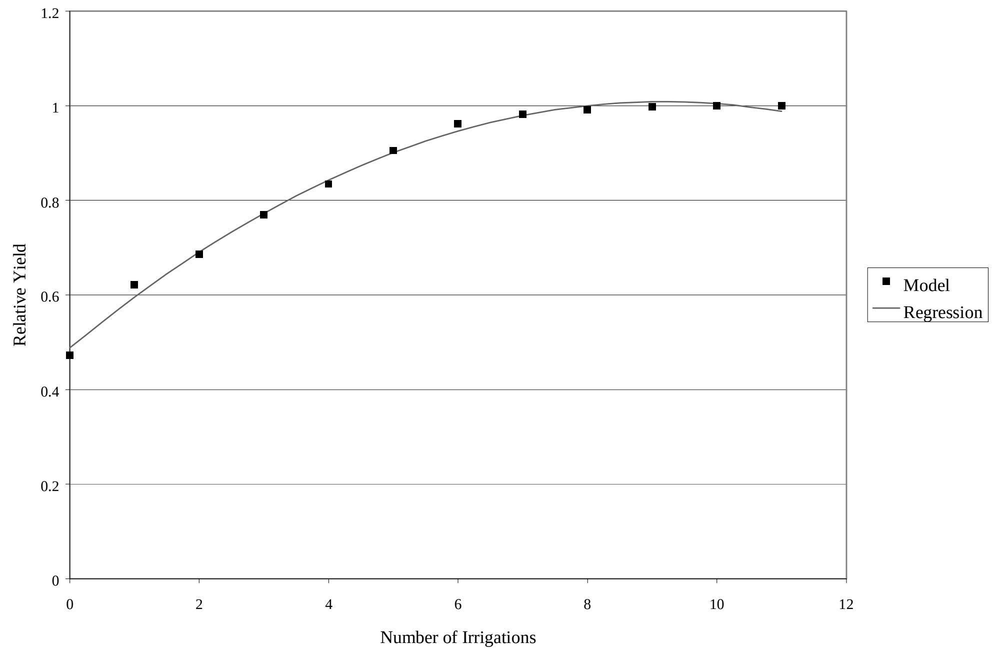

Figure 3-16. Regression Results to Derive Crop Growth Coefficients for Potatoes on Sandy Soil

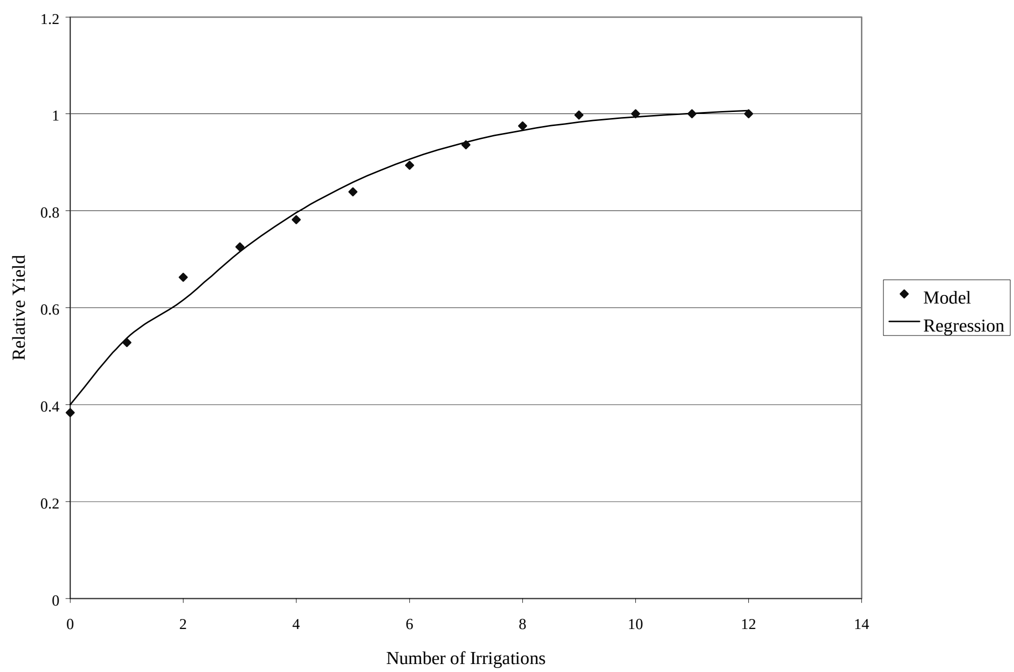

Figure 3-17. Regression Results to Derive Crop Growth Coefficients for Potatoes on Sandy Loam Soil

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 ith crop up to n crops,
- net returns per acre as NR_i for each ith crop,
- resource use a_{ij} for each ith 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:

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

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

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

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:

$$\sum_{k} VEG_k \leq \max propveg * TOTVEGACRE \tag{3.31}$$

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 0.3 Historically min proportion 0.1 Midpoint of range (.1 + .3)/2 = .2
2.	Surface water supply in given drought 2.0 ac ft/ac Ground water supply 1.0 ac ft/ac Total water supply 3.0 ac ft/ac Full water supply 6 ac ft/ac Percent change (1.0 - 3.0/6.0) = 50% decline from full supply
3.	Percent widening to be added/subtracted from full water supply crop proportions = 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 = 0.3 + 0.10 = 0.40 Modified lower bound proportion = original lower bound minus change = 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:

$$\sum_{k} VEG_k \leq 1.1 * \max propveg * BASEVEGACRE \tag{3.32}$$

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 ($/ac-ft) surface	Added value + 1 a-f ($/ac-ft) ground	Acres Planted (acres)
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 ($/a-f) surface	Added value +1 a-f ($/a-f) ground	Acres Planted (acres)
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: surface	Added value of one more acre-foot: ground	Acres Planted (acres)
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:

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

In order to express a separate equation for each of the six reservoirs, each of the six has its own β_0 and β_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:

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

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:

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

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:

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

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)	
	β_0	β_1	λ_0	λ_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: 8.26×10^{-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.

ψ_r	Initial volume in million acre-feet for a representative water year (1990)	
	0.106	0.134
κ_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 ----	6800 6800
δ_r	Minimum useable water volume of reservoir r in maf	
	0.025	0.025

ι_m	Inflow to El Vado (cfs)
μ_m	Lower bound on outflow from Abiquiu Reservoir
η_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

$\epsilon_{0\,r}$	6.77×10^{3} (9842.285)	6.16×10^{3} (18153.795)
$\epsilon_{1\,r}$	3.44×10^{3} (21.586)	4.21×10^{2} (89.373)
$\epsilon_{2\,r}$	-9.21×10^{4} (-9.932)	-6.57×10^{2} (-28.855)
$\epsilon_{3\,r}$	1.54×10^{6} (7.274)	8.22×10^{2} (16.251)
$\epsilon_{4\,r}$	-1.34×10^{7} (-6.013)	-6.20×10^{2} (-11.138)
$\epsilon_{5\,r}$	$5.\ 76 \times 10^{7}$ (5.238)	2.49×10^{2} (8.453)
$\epsilon_{6\,r}$	-9.58×10^{7} (-4.698)	-4.08×10^{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 = 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}] = 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 = 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}] = 29.18 * Use - 0.5 * [2.12 * Use ^{2}]				

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

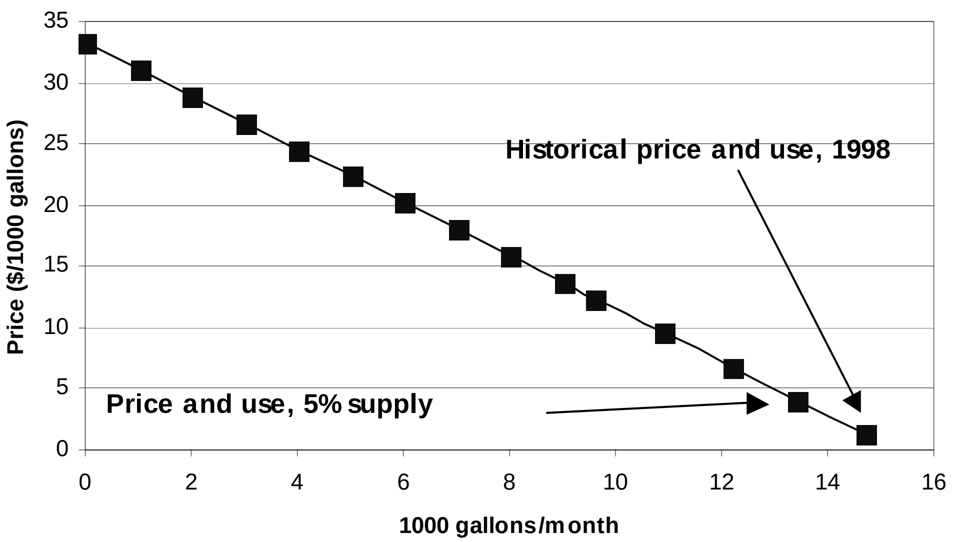
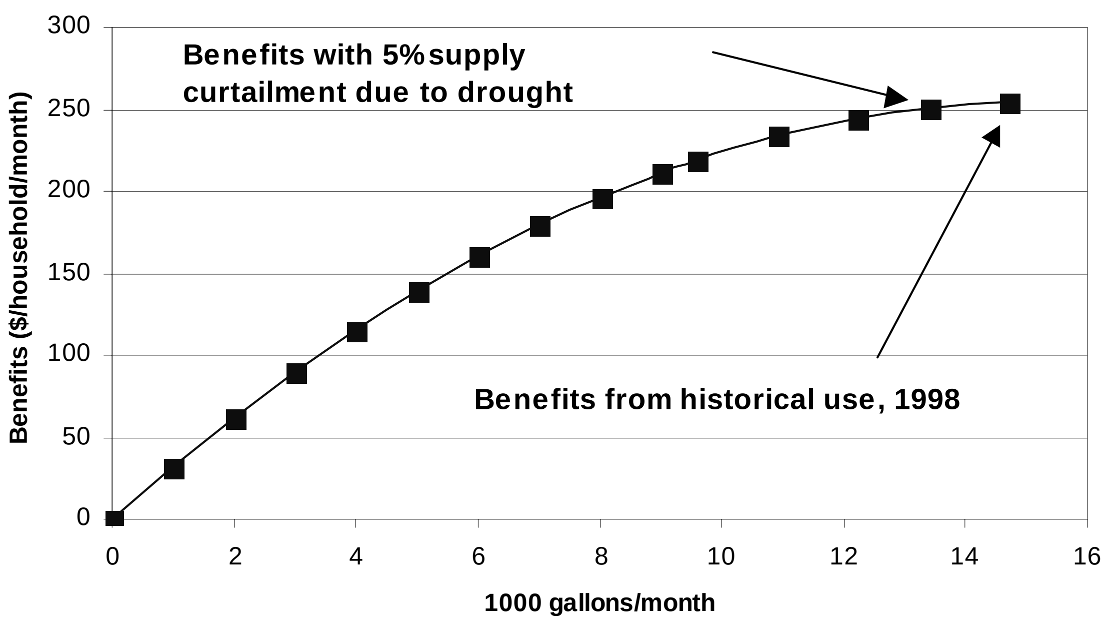


Figure 3-18b. Economic Value of a Range of Water Uses-Per Household, Albuquerque



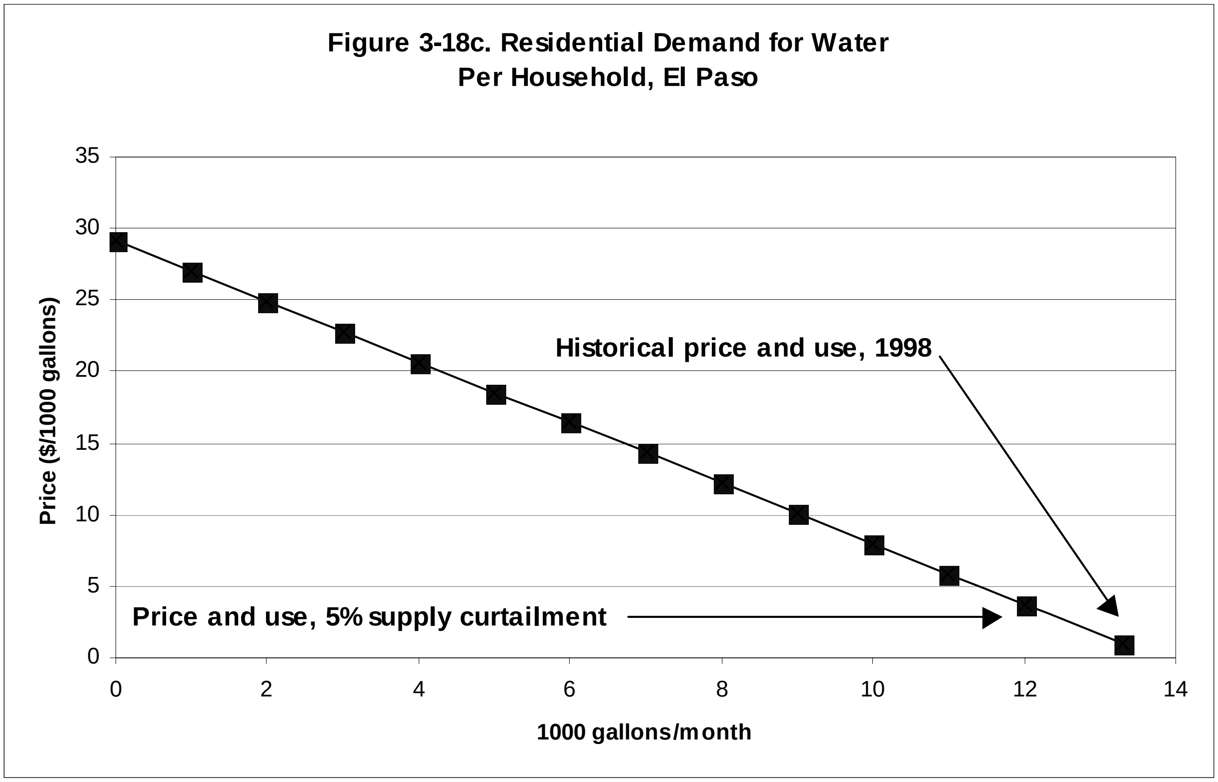


Figure 3-18c. Residential Demand for Water
Per Household, El Paso
Price ($/1000 gallons)
35
30
25
20
15
10
5
0
Historical price and use, 1998
Price and use, 5% supply curtailment
0
2
4
6
8
10
12
14
1000 gallons/month

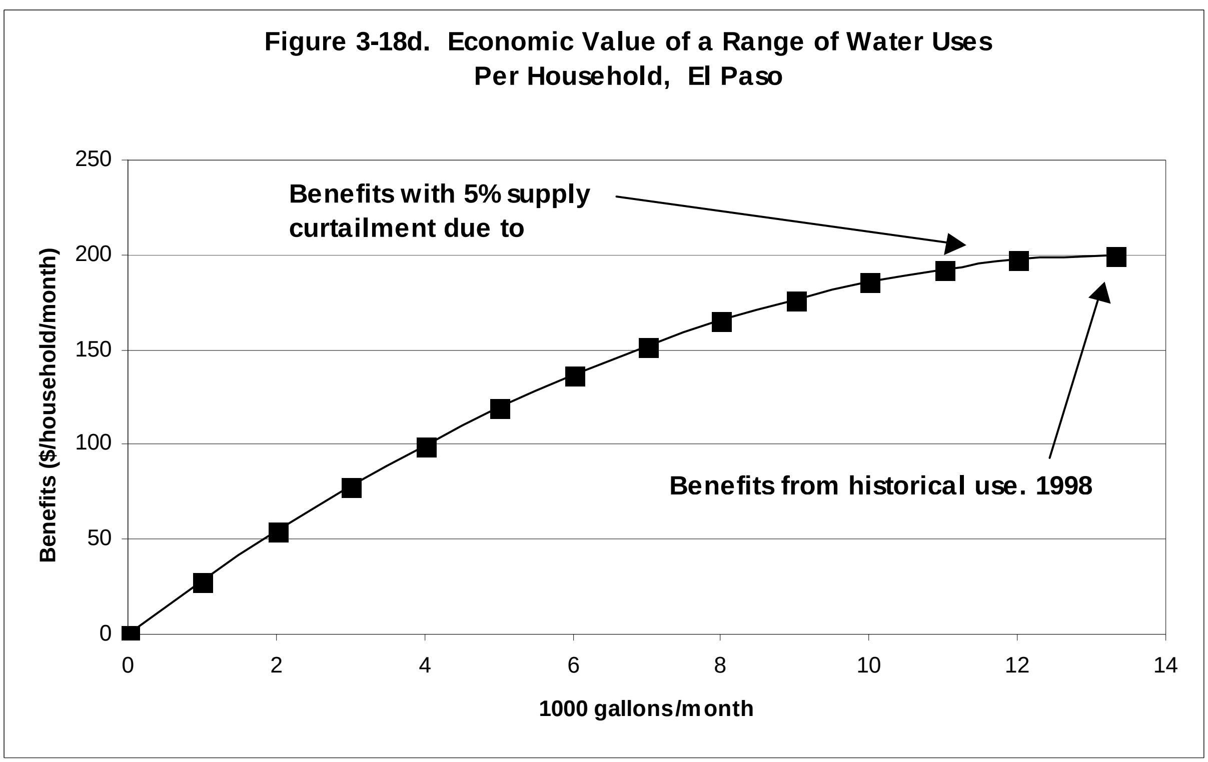


Figure 3-18d. Economic Value of a Range of Water Uses
Per Household, El Paso
Benefits ($/household/month)
250
200
150
100
50
0
Benefits with 5% supply
curtailment due to
Benefits from historical use. 1998
0
2
4
6
8
10
12
14
1000 gallons/month

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,

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

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.

<u>Benefits from Consumption</u>. 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.

<u>Benefits from Recreation</u>. 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.

<u>Total benefits</u>. 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 (Rio Grande at Del Norte, plus Conejos River near Mogote)	**Colorado Use** (Based on total Compact obligation at Lobados)	**New Mexico Use** (Between Otowi and Elephant Butte, from water delivered at Lobados)	**Texas Use** (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

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

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 β_i. This supply index β_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

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

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

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

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

respectively. The proportion of Rio Grande Project water allocated to Texas, γ =43%, and to New Mexico, (1- γ)= 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.

CHAPTER 4 -- RESULTS

Analysis of Institutional Adequacy for Drought Response in the Rio Grande Basin

Summary

Existing institutions for managing water supply have considerable room for improvement in reducing economic damages from severe and sustained drought in the Rio Grande Basin. Multi-disciplinary data development teams, such as used for this study, have great potential in being used to develop common databases for understanding river systems by basin. Examples are presented for what has occurred in another major river systems in the southeastern United States and shows how that approach has evolved through decision support methods like computer generated models that reflect the operations of the river systems. The detailed operation of the Rio Grande Compact and how it serves as a regional water allocation mechanism is described. Next, this section explains how this study is the first step in developing a river operations and policy evaluation model that could serve in the Rio Grande Basin. Finally, it sets out the components of such a model and concludes that this study and the economic analysis conducted could serve as a fist step toward the development of such a complex river operations and policy evaluation model.

Background

On virtually all of New Mexico’s stream systems, water utilization is nearing or has reached physical limits. Water resources conflicts are increasing accordingly and, most often, where waters cross or define political boundaries. Thus, inter-jurisdictional water disputes are a possibility facing every county, independent water district, town, city, tribal reservation, government agency, and state in the country. Today those conflicts also include conflicts between environmental groups and agencies promoting those agendas and traditional water users.

Need for New Water Management Approaches in the Rio Grande Basin

For most of the 20th century, water issues revolved around development of reservoir and diversion projects. In the last thirty years, the spectrum of demand for water has broadened dramatically: the needs of cities have grown faster than the ability to serve them, while water pollution and wildlife and river protection have become serious public concerns. Reduced slack in the system has reduced the range of workable choices available to water managers. A season's drought, a new flow regulation, a jump on the population chart, may trigger a full-fledged public controversy or a multi-party lawsuit over water rights, water regulations, or water allocation.

Many water management institutions are poorly suited to address today's complex, high-risk, high-consequence water conflicts. The legislation establishing government institutions with management authority lack the scope and resources to arbitrate competing water claims that go beyond traditional water rights and, often, are active claimants themselves on behalf of particular constituencies or traditional principles of water law. Water markets, while serving to allow water to move to higher valued economic uses, are criticized as insensitive to the external costs of water delivery and consumption and, therefore, unsuitable to the task of comprehensively resolving the issues. The courts often fare no better. The costs of lawyers and the litigation process have become prohibitive.

As we enter the next century of water management, there is a tremendous need for mechanisms that address these conflicts that can reach resolution and do so with at a minimum: 1) impartiality; 2) early intervention to diffuse tensions; 3) development of multi-disciplinary technical-support teams; and finally, 4) a fact-driven consensus process through which local water users) develop a common data set and indices of desired future conditions, negotiate compatible objectives, reach a provisional agreement, and establish mechanisms for continuing cooperation.

Scarcity uncovers latent discord. When water budgets tighten, users and values that are compatible in times of abundance realize a capacity for opposition. The following are specific examples.

Historic vs. New Water Uses – Value in Tradition vs. Economic Value

In economic terms, new water uses may have greater value than historical water uses. That is, the ratio of monetary value produced/unit of water consumed tends to be higher in new water uses (urban domestic, recreation, light industry such as semi-conductor production) than in most historical uses (agriculture, ranching, transportation, and heavy industry). At the same time, our society respects traditional uses of water and does not allow the market alone to determine how it will be distributed. Reduced water supplies bring to the surface the tension between these two values.

Material Standards of Living vs. Sustainable Quality of Life

Urban vitality depends on a continuing expansion of municipal revenues, fed by ever-improving standards of living. Cities with large tax bases can offer residents dependable infrastructure and services, well-equipped schools, and many other amenities. These benefits give residents reason to stay and attract new ones, including corporations bringing high-salaried jobs.

The desirable results of expanding cities are not guaranteed indefinitely, however. There are points of diminishing returns. Water availability is such a milestone, a physical constraint on municipal growth. Water quality is another. Prosperity at the cost of degraded ground and surface waters eventually will unravel. Such prospects raise questions of inter-generational equity. That is, when multiple water needs push hard enough against one another, and cannot all be satisfied, water consumers may end up choosing—for their children, if not for themselves—between economic security and a high quality of life.

Needs of Human Species vs. Needs of Other Species

No living thing survives long without water. River basins were home to wildlife and flora before they were to people. Water quantities needed by these other life forms vary widely and differ from our own requirements. Whose needs should come first? In dry places, when spring runoff is stored for planting-schedule releases, a river's flow can be slowed to a trickle. Such practices, like dumping wastes in a channel, reduce the survival odds of riverine ecosystems and, in the short-term at least, decimate them. Aside from questions of their irreplaceable contributions to their ecosystems, plant and animal communities claim water resources. It has become increasingly clear that these claims are important matters for people to decide.

Streams as Aquatic Systems vs. Utilitarian Plumbing and Power Systems

Dams and other waterworks accentuate the role of streams in storing and delivering water and generating power. In addition to these engineered functions, however, hydrosystems have other values, some of which require noninterference with their natural behavior. For example, aesthetic appreciation of rivers and lakes—hearing water splash rocks or lap the keel of a boat, seeing light and shadow play on a still pool, being cooled by a breeze across an undisturbed stream surface--may clash with their more utilitarian purposes.

All surface and groundwaters are part of a relatively discrete hydrologic system. For purposes of water management, however, stream systems are often subdivided not by hydrologic units, but by political units. That is, water management superimposes on hydrologic systems another policy system. And, in perfect twenty-twenty hindsight, we would have devised regulator streams that integrated issues of conjunctive use of ground and surface water, anticipated new federal regulatory rights in water under laws such as the Clean Water Act and the Endangered Species Act. Of course that did not happen and we now face the consequences of these growing tensions among demands.

Types of Disputes in New Mexico

Interstate

Incompatible claims in inter-state rivers, lakes, and groundwater aquifers. Incompatibility may derive from mutually exclusive time of use (use now v. store for later release), type of use (consumptive v. non-consumptive), place of use (use upstream v. use downstream), or an interaction of all three variables. No better example of this kind of conflict exists than on the Rio Grande System.

Interagency

Missions, jurisdictions, and corresponding water demands of various government agencies may overlap. The resulting tensions may strain relationships within or among federal, state, tribal, municipal, or county offices. The demands for better water quality by the Isletas and the conflicts between the New Mexico Department of Fish and Game, the United States Fish and Wildlife Service, and the Office of the State Engineer provide good examples.

Federal/Tribal-State

Many state and local governments regard federal water rights (reserved and non-reserved, tribal and public land), which for the most part are unadjudicated, as limiting their own property rights in water. Issues between the non-Indian water users and the Navajo Nation provide an excellent example of this type of dispute.

Federal/State-Tribal

Tribal interests in on-reservation water use or in off-reservation water leasing may conflict with federal laws, reserved rights, or other priorities or with state water claims. Certainly, the Jicarillas and the long-term needs and goals of the Rio Grande Pueblos fall into this category.

Groundwater-Surface Water Conflicts

These conflicts are a final example of the inability of our institutions and laws to keep pace with the reality of man-created scarcity in aquifers hydraulically connected to surface waters.

Sorting out policies and science related to stream-related aquifers presents a particularly difficult issue. While all would agree that the need to conjunctively regulate ground and surface water together is evident—what this means in terms of policy and science is far from clear. For example, the State Engineer has recently drafted proposed guidelines for the Middle Rio Grande Basin. Some strenuously press to have all existing permits modified retroactively to reflect the new and "correct" knowledge of the aquifer. While retroactive application may appear to be a logical result, it is premised upon the assumption that we in fact have the final answer. In truth, the science of hydrology continues to evolve and is held back by the lack of underlying factual data to place into the models we have developed.

There is no issue more complex and more important to the residents of New Mexico and of the middle Rio Grande valley than understanding the hydraulic connection between the groundwater pumping in the region and the flows of the Rio Grande. Fortunately, New Mexico water law has made New Mexico a pioneer in this area.

In the 1950s, then State Engineer Steve Reynolds took the position, at the time unheard of in water law, that because of the hydraulic connection between the ground and the surface water, all new wells drilled by the City of Albuquerque must ensure that the total of water withdrawn from them did not deplete the flows of the Rio Grande. This meant simply that the well owner would have to do two things. First, calculate the amount of water that would come from the river by way of the well when the well was pumping at capacity and second, make sure that sufficient surface water use was retired from the river so that the new wells did not deplete the river’s flow.

This was essential for three basic reasons. First, the Rio Grande Compact commits an amount of water to our downstream users in Texas and Southern New Mexico. Second, senior Pueblo water users rely on its flows. Third, senior non-Indian irrigators who use surface water are protected by the prior appropriation doctrine. These facts still prevail and for many years, the amount of protection to be provided the river from groundwater pumping has been calculated by a conservative mathematical method called the Glover-Balmer calculation.

The State Engineer has recently proposed adoption of a numerical model utilizing sophisticated computer techniques that further refine our understanding of the hydraulic connection between the pumping of wells and the river. This new model, generated by Teideman and others (U.S. Geological

Survey) in 1998 has been modified by Barroll, of the office of the State Engineer in 1999 and is contained in the draft guidelines for review of water rights applications in the Middle Rio Grande Administrative Area.

Out of a sense of caution and in an exercise of conservative management, the State Engineer, for an interim period of five years, has tentatively chosen to not apply the new model retroactively. He is apparently not presently willing to relieve all existing well pumpers of their obligation to protect the river as calculated by the original method. This decision has raised concerns from the City of Albuquerque.

This is plainly an area where agreement on this risks of error associated with different data bases and methodologies could be helpful. The State Engineer would no doubt argue, that computer model results are not facts; they predict outcomes which may or may not ultimately be consistent with what occurs in the future. While some models are better than others, a change in input either as to the properties of the soils or sediments in the ground where the well is located or a change in the assumptions as to the velocity with which water moves through these soils can result in widely varying predictions. For example, as recently as 1995, Kernodle and others (1995), predicted that pumped wells would have between 44% and 66% of their water pumped from the river by the year 2020. Teideman and others (1998) model suggested there would be a 90% long-term impact, while the proposed Barroll modifications suggest around 75%. Thus, while all would agree that the revised numerical models are superior, they will continue to be refined and improved, and there is no final truth that has been learned from these models.

The State Engineer would also argue that any responsible administrator should have a safety factor built into all decisions. We now see through hindsight that Steve Reynolds was not so far wrong in applying the Glover-Balmer method since it probably results in a retirement requirement about 20% more conservative than the new Barroll model. Stated more simply, it may be prudent to ensure that in providing protection to the river, at least for the next five years while the matter is still under study, to err on the side of river protection by retaining a method that preserves the possibility of a 20 % margin of error. If there is error to be made, then it should probably be made on the side of protecting river flows rather than development of municipal and industrial water supply from wells.

Finally, there are practical reasons for not modifying all existing permits in place. All of those permits were granted only after notice and hearing to the public. If those permits are to be modified, recent law suggests they would have to be modified only after the public at large contributes. The administrative costs and the risks to those permits would seem to far outweigh any considerations to the contrary.

Wells, once pumped, may deplete the aquifer adjacent to the river and depending upon their distance from the river, create debts the river pays back over periods of thirty to fifty years. While one would wish to avoid allowing model errors to make that debt any larger than it should be, one should not be optimistic about relieving that debt while allowing pumping to continue.

The City would argue, just as strongly, that once a superior model is developed for calculating well impacts, we should use it immediately and that the risks of uncertainty are outweighed by the added water made possible by the new model calculations.

The Use of Multi-Disciplinary Technical Teams

The immediate result of uncertainty is distrust and from this distrust comes conflict. The remainder of this section describes a method of looking beyond conventional boundaries for water management in the 21st century built around development of common data sets first, and conflict resolution second. Such a system should include the following parameters: in the current climate of water scarcity, new agreements for the common use of transboundary streams are best constructed under the following conditions:

a. Participants in the common data collection process represent all stakeholder groups.

b. Fact-finding and technical modeling and negotiation is assisted by impartial expert outsiders.

c. The planning process advances from step to step by consensus.

d. Hydrological modeling is based on the most complete and accurate hydrologic record available

e. Legal, ecological, economic, and cultural implications of agreement provisions are fully explored.

f. Long-term hydrologic scenarios are precisely and variously modeled and validated.

g. Agreement provisions anticipate and adjust to many and diverse contingencies.

Hydrologic modeling is based on the most complete and accurate hydrologic record available. Critical to this process if it is to work is impartiality. Parties anticipating conflict over rivers, groundwater basins, or other shared resources will need impartial technical assistance in understanding the various kinds of issues involved in jointly planning a basin management strategy and implementing a related agreement. Predictably, this work will engage hydrological, ecological, economic, cultural, social, political, and legal issues. This multi-disciplinary team will be charged to complete the following tasks:

Construction of a Common Data Set

Compile and assess the most complete and accurate records available and, as necessary, collect new information, to arrive at a common data set concerning water supplies and water demands throughout the drainage basin.

Among other records, the common data set will include information such as the following:

a. hydrologic data: historical base flow in the watershed, relative contributions to the watershed's annual yield from rainfall and from tributary and groundwater inflow, and relative amounts and locations of annual diminution of water quality due to pollution.

b. climate and weather data: seasonal temperatures, precipitation averages, evaporation rates

c. formally permitted water rights: quantities of permitted water rights for diversionary and instream uses for all ground and surface sources

d. tribal water rights claimed but not permitted by the state engineer

e. seasonal or annual quantities of use in each type of use

f. continuing scheduled water delivery obligations: compact and treaty responsibilities, reservoir holding and release agreements

g. demographic statistics: basin area population, growth projections, and associated water-use information

h. measures of ecological resilience: in the watershed and general stream health

Build, Test, and Calibrate a Hydrologic Model of the Water System

Using as a base one of the industry standard hydrologic models such as HEC V, construct a model of the clients' drainage basin that takes account of tributaries and distributaries as well as requisite in-stream flow, and, of course, all withdrawals for municipal, industrial, agricultural, and riparian uses.

Model Water Quantity - Water Quality Conditions to Achieve or Avoid

Using the common data set, model flow rates and annual yield, at selected seasons and locations in the basin, under various water-use scenarios. For example, produce wet- and dry-year hydrographs for various stream reaches of particular interest. Or, explore and combine future possibilities involving increases and decreases in agricultural water demand, municipal and industrial water use, stream health, water-centered recreational activities, navigation, and wildlife habitat.

Run the model as many times and in as many ways as necessary to answer clients' questions.

Negotiate Tough Issues

In view of the constraints identified through exhaustive data collection and repeated modeling, thoroughly explore and weigh:

a. values in water as expressed by the clients' constituents,

b. related short- and long-term situations each client group wishes to achieve or avoid, and

c. legal factors affecting any water-management or water-sharing agreement by the clients.

The discussions and exercises immediately above, together with the previous, modeling steps, will have provided insights into water-use tradeoffs between, for example, river health in certain reaches and specific economic development possibilities. Thus, although the choices to be made will be no easier than they would have been without the steps described above, participants will make those choices with a clearer understanding of the likely consequences. Moreover, having taken pains to cooperatively construct knowledge about their shared water systems, the participants will have had numerous opportunities and every reason to acquire mutual understanding of each other's values and water needs and, in turn, to develop the mutual respect that is the hallmark of sustainable agreements.

Once negotiation results have been finalized and agreed upon they should be integrated into a memorandum of agreement containing monitoring and oversight responsibilities, routine updating of the database, regular meetings of an executive group chosen by the participants, and any other mechanisms needed to ensure continuing cooperation.

The agreement should provide all basin stakeholders with desk-top access to the common data base and the watershed– modeling software as well as simple instructions about how to use these materials to better appreciate the sources and uses of their common waters.[21]

Use of Multi-disciplinary Teams and Modeling – the Georgia Experience

An example of where this multi-disciplinary team approach has had some success is in the Apalachicola-Chattahooche-Flint (ACF) river basin in the south eastern United States.

The ACF basin originates in north Georgia and Alabama and terminates in Florida in Apalachia Bay. It extends a distance of approximately 385 miles and encompasses an area of 19,600 square miles. The drainage area is comprised of the Apalachicola, Chattahoochee, and Flint Rivers and their tributaries. During the last 160 years, the water resources in the basin have been developed to meet various demands for municipal and industrial water supply, flood control, hydropower, navigation, fish and wildlife conservation, recreation, and agricultural water supply. There are hundreds of reservoirs in the basin, but 16 (5 Federal and 11 non-Federal) are located on these three principal rivers. They provide for regional uses of the basin water resources for navigation, hydropower, flood control, water supply, recreation, and fish and wildlife.

Rapid growth in the metropolitan Atlanta area and north Georgia since 1950 has caused large increases in water demands. As a result, the US Army Corps of Engineers (Corps) received requests from several local municipalities in the 1980s to reallocate water in its north Georgia reservoirs. Droughts that occurred in 1981, 1986, and 1988 heightened the public's concern and awareness of water management in the basin. In the late 1980s water supply reallocations were being studied by the Corps for Lake Allatoona, Carters Lake, and Lake Lanier. In November 1989, Alabama requested suspension of the reallocations studies pending completion of comprehensive economic and environmental impact

[21]While these resources would be desirable to possess, few if any water conflicts have been resolved with access to such data, software, or instructions on their use.

analyses. In 1990, the Corps completed the Carters Lake report and recommended reallocation of reservoir storage to water supply for the City of Chatsworth, and the State of Georgia submitted plans for a water supply reservoir on the Tallapoosa River. Subsequently, the State of Alabama filed litigation challenging the proposed water reallocation in north Georgia. The states of Alabama, Georgia, and Florida and the Corps met to resolve this conflict outside the legal system. The initial meetings of the states and the Corps led to initiation of the Comprehensive Study of resources in the ACF basin and in the Alabama-Coosa-Tallapoosa River Basin (ACT basin) in 1992.

The Comprehensive Study was undertaken by Alabama, Florida, Georgia, and the Corps for both the ACF and ACT basins, as directed by a memorandum of agreement (MOA) among the three states and the U.S. Department of the Army. The study was consensus based, requiring the approval of all participants on all elements. The purpose of the Comprehensive Study was:

> ... to determine the capabilities of the Water Resources of the basins, to describe the water resource demands of the basins, and to evaluate alternatives which utilize the Water Resources to benefit all user groups within the basin.

The Comprehensive Study has provided technical understanding of the water resources in both river basins and basin-specific tools to evaluate the water management alternatives. Table 4-1 presents the various elements of the Comprehensive Study that were approved and funded.

Table 4-1. Elements of the ACT/ACF Comprehensive Study

Process Support Elements	Water Resources Availability	Water Demand Elements	Comprehensive Management Strategy
Population and employment forecasts Database Public involvement	Surface water Groundwater	Agriculture water demand Environmental water demand Power resources water demand Navigation water demand Recreation water demand Water quality water demand	Basinwide management Coordination mechanism

Source: Comprehensive Water Resources Study Partners, September 1995

In 1996, Alabama, Florida, and Georgia agreed to develop and implement an interstate water compact for the ACF basin with the purposes stated above. State negotiations for the compact began in September 1996, with a series of negotiating sessions held through January 1997. On January 13, 1997, each of the states and the Federal government, represented by the Department of Justice, reached agreement on the compact language.

The ACF River Basin Compact was passed by the Georgia legislature in January 1997, by the Alabama legislature in February 1997, and by the Florida legislature in March 1997. In a joint letter dated May 14, 1997, the three governors submitted the ACF Compact to the three States' congressional delegations, which introduced the Compact into Congress on June 27, 1997. On November 7, 1997, Congress passed the Compact and sent the bill to the President, who signed it into law (Public Law [PL] 105 –104) on November 20, 1997.

The Compact creates an interstate administrative agency, the ACF Basin Commission, which is composed of the Governors of Alabama, Florida, and Georgia (who make up the State Commissioners), and a Federal Commissioner appointed by the President of the United States.

The Compact directs the parties to the Compact to:

> ...develop an allocation formula for equitably apportioning the surface waters of the ACF basin among the States while protecting the water quality, ecology, and biodiversity of the ACF, as provided in the Clean Water Act, 33 U.S. Code (U.S.C.) section1251 et seq., the Endangered Species Act, 16 U.S.C. Sections 1532 et seq., the National Environmental Policy Act, 42 U.S.C. Sections 4321 et seq., the Rivers and Harbors Action of 1899, 33 U.S.C. Sections 401 et seq.. and other applicable federal laws.

After the water allocation formula is developed and unanimously approved by the State Commissioners, it becomes binding:

> ...upon receipt by the commission of a letter of concurrence with said formula from the Federal Commissioner. If, however, the Federal Commissioner fails to submit a letter of concurrence to the commission within 210 days after the allocation formula is agreed upon by the State Commissioners, the Federal Commissioner shall within 45 days thereafter submit to the ACF Basin Commission a letter of nonconcurrence with the allocation formula setting forth therein specifically and in detail the reasons for nonconcurrence; provided, however, the reasons for nonconcurrence as contained in the

> letter of nonconcurrence shall be based solely upon Federal law. The allocation formula shall also become effective and binding upon the parties to this Compact if the Federal Commissioner fail to submit to the ACF Basin Commission a letter of nonconcurrence.

In ratifying the Compact, Congress clarified that:

> ...the Federal Commissioner may submit a letter of concurrence with the allocation formula adapted by the State Commissioners 255 days after such adoption.

The competition for the river resource includes interests ranging from navigation for barges to water retained upstream for recreation and from consumptive uses from Lake Lanier above Atlanta to minimum flows to sustain the Apalachicola Bay in Florida. Based upon the results of the comprehensive study, a model was constructed that integrated all of these factors by allowing manipulation of various scenarios while holding others constant. Thus, one could include in the model a scenario that limited hydropower and navigation use and honored first delivery of water for municipal and industrial uses. These could also be limited further by allowing river releases to mimic the traditional hydrograph to the greatest degree possible. The flow duration curves attached to this paper demonstrate the results of a such a scenario offered by the State of Georgia in these negotiations. According to Georgia officials, the operation of the model in this manner optimizes both economic and environmental values while diverting water from the lower valued uses such as barge traffic and navigation. At the same time, it closely mimics the traditional hydrograph to address the concerns of environmentalists.

The central point is not whether Georgia is correct. Rather, the point is that all parties are starting with the same baseline—the comprehensive study results and the common model. A disagreement will not be resolved on the accuracy of the data being used, but whether, in fact, the value judgments as to relative value of uses within each state are correct.

The way in which we think today cannot solve the problems we will confront in the future. It may be time to acknowledge that the way we are thinking about resolution of water problems today is no different from how we were thinking about those issues twenty years ago. And, for these and other reasons, we still have many water problems to solve. A multi-disciplinary technical team approach may provide a first step in addressing these issues that will take us properly into the next century. The following section addresses how this approach can be utilized in the Rio Grande Basin.

The Rio Grande Compact

In a famous article, Ray Hill describes the development of the Rio Grande Compact.[22] A little background on Mr. Hill's involvement is useful because it gives some measure of the accuracy of Mr. Hill's article. "Mr. Hill was intimately connected with the investigations that led to the Compact" and with the Compact negotiations.[23] Mr. Hill was asked, on behalf of the Attorney General of Texas, to prepare the report for use in Texas and New Mexico v. Colorado.[24] His assignment was to "review the history of the Rio Grande Compact of 1938 and to analyze its provisions for the benefit of those who wish to clarify their understanding of the Compact."[25]

History

Pre-1938 Compact History. The motivating factor behind the Compact negotiations was the insufficient supply of water in the Rio Grande for irrigation in the three states and Mexico. By 1896, irrigated lands in the San Luis Valley used all of the natural flow of the Rio Grande.[26] Increasing diversions from the

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[22]Raymond A. Hill, *Development of the Rio Grande Compact of 1938,* 14 Nat. Resources J. 163 (1974). Another excellent history of the Rio Grande Compact was conducted by Littlefield (1987).

[23]*Id.* at 163

[24]*Id.* at 163. 386 U.S. 901 (1967), 389 U.S. 1000 (1967), 390 U.S. 933 (1968), 391 U.S. 901 (1968).

[25]*Id.* at 163.

[26]*Id.* at 166.

Rio Grande in Colorado and New Mexico caused water shortages in the Mesilla and El Paso valleys beginning in the early 1890s.[27] The water shortages quickly led to legal disputes.

The Mexican Government, alleging that the water shortages near Juarez were caused by increasing diversions in Colorado and New Mexico, filed a claim against the United States for damages.[28] This dispute between Mexico and the United States was settled by the Treaty of 1906. Under the Treaty, Mexico relinquished all claims for damages.[29] In return, the United States guaranteed an annual delivery to Mexico, in perpetuity, of 60,000 acre-feet of water in the Rio Grande.[30] The Treaty, however, did not resolve the disputes between Colorado, New Mexico and Texas.

One result of the U.S. Department of State's investigation of the Mexican claim was the "embargo" of 1896.[31] An order by the Secretary of the Interior suspended all applications for rights-of-way across public lands in Colorado and New Mexico for use of Rio Grande water.[32] The order prevented further irrigation development in the Rio Grande Basin in both states by not allowing for storage of water.[33] In Colorado's San Luis Valley, storage was needed not only for further development but also to maintain existing irrigation developments.[34] Colorado's attempt to get permission to build reservoirs continued up to the date of Hill's report, 1937. New Mexico and Texas also had problems.

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[27]*Id.* at 165.

[28]*Id.* at 165.

[29]*Id.* at 166.

[30]*Id.* at 166.

[31]*Id.* at 165.

[32]*Id.* at 166.

[33]*Id.* at 166.

[34]*Id.* at 166.

The decreased flow in the Rio Grande caused by depletions in the San Juan Valley affected New Mexico and Texas in two ways. First, and most obvious, there was a shortage of water for irrigation.[35] Second, the decreased flow resulted in aggradation of the river bed by deposition of sediment that caused the water table to rise under the valley floor.[36] Saturation of the land by the rising water table resulted in failure of irrigated acreage.[37] Colorado, New Mexico, and Texas decided to negotiate a compact which would provide for the equitable apportionment of the river.

The Compact of 1929 served as a guideline for the Compact of 1938.[38] In fact, "many of the provisions in the 1929 Compact were incorporated verbatim or substantially so in the Rio Grande Compact of 1938."[39] The basic goal of the 1929 Compact was to maintain the status quo on the river.[40] But remember, none of the three states was happy with the status quo. Colorado could not increase storage, New Mexico was water-logged, and Texas was water short. The solution to this problem was initiated by President Franklin D. Roosevelt.

Based on information from the National Resources Committee, President Roosevelt concluded that future federal investments in the Rio Grande Basin that promote increased use of water would have several detrimental effects.[41] Because the reliable water supply in the basin had already been completely appropriated, future investments promoting increased use would impair the security of extensive prior investments of Federal funds, violate an interstate compact to which the Federal Government is a party,

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[35] *Id.* at 166.

[36] *Id.* at 166.

[37] *Id.* at 166.

[38] *Id.* at 167.

[39] *Id.* at 167.

[40] *Id.* at 167.

[41] *Id.* at 169

and promote social insecurity.[42] The President's solution was to require that applications for projects using Rio Grande waters be approved only after getting a thorough opinion from the National Resources Council.[43]

The National Resources Council proposed a conference with the three states to see if there could be a cooperative effort to gather facts that might be helpful in solving the interstate water problem on the Rio Grande.[44] The three states agreed and the result was the Rio Grande Joint Investigation. The cooperative effort, including Federal funds and services, was summarized in a massive, five-part report. The report, prepared by the U.S. Geological Survey, the U.S. Bureau of Agricultural Engineering, the U.S. Bureau of Plant Industry, and the U.S. Bureau of Reclamation, provided the scientific/engineering basis for negotiations of the 1938 Compact.[45] The Rio Grande Joint Investigation was completed in July, 1937 with a final report submitted to the President in December. Negotiations for the 1938 Compact began on September 27, 1937.

<u>The Rio Grande Compact of 1938</u>. The Rio Grande Compact Commissioners signed the final Compact on March 18, 1938. The Compact was designed to provide for the maximum beneficial use of water in the basin of the Rio Grande above Fort Quitman without impairment of any supplies beneficially used under the conditions prevailing in 1929.[46]

The preamble indicates that the Rio Grande Compact was developed by the states of Colorado, New Mexico, and Texas because of their desire to remove all causes of present and future controversy

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[42]*Id.* at 169.

[43]*Id.* at 169

[44]*Id.* at 169.

[45]*Id.* at 170.

[46]Raymond A. Hill, Development of the Rio Grande Compact of 1938, 14 Natural Resources Journal 163, 198 (1974).

with respect to the use of the waters of the Rio Grande above Fort Quitman, Texas.[47] Another purpose of the Compact is to effect an equitable apportionment of the waters of the Rio Grande.[48] The articles in the Compact were agreed to by the three states after negotiations.[49] The first five articles of the Compact operate without any regard to the amount of water in, or releases from, project storage. Article I provides definitions of terms used in the Compact. Article II describes the maintenance, operation and location of stream gaging stations. Article III establishes Colorado's obligation to deliver water at the Colorado-New Mexico state line. Article IV establishes New Mexico's obligation to deliver water at San Marcial.[50] Article V requires that the replacement of gaging stations not affect rights or obligations to deliver water.

The next three articles operate based on the releases from, and the amount of water in, project storage. Article VI describes the requirements on the credits and debits of Colorado and New Mexico. Article VII precludes Colorado and New Mexico from increasing water in storage under certain conditions. Article VIII allows Texas to demand that Colorado and New Mexico release of water in storage under certain conditions. These three articles were negotiated and agreed to by Colorado, New Mexic,o and Texas, and are discussed in detail below.

None of the remaining nine articles describe any rights or obligations that are conditioned on the amount of water in, or releases from, project storage. In Article IX, Colorado consents to diversion of San Juan into Rio Grande so long as Colorado's uses by other diversions from the San Juan River are protected. The United States, Colorado, and New Mexico are credited for any water they import into the Rio Grande Basin under Article X. In Article XI, New Mexico and Texas agree that all controversies

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[47]Preamble, Rio Grande Compact.

[48]Preamble, Rio Grande Compact.

[49]Preamble, Rio Grande Compact.

[50]The 1948 Resolution adopted by the Rio Grande Compact Commission abandoned the San Acacia and San Marcial gaging stations, and replaced them with the Elephant Butte Effective Index Supply.

between them relative to the quantity and quality of the water of the Rio Grande are settled. Article XII establishes the Rio Grande Compact Commission and describes the administration of the Compact by the Commission. Article XIII provides for periodic review of Compact provisions. Article XIV states that the delivery schedules and water quantity allocations will not change by reason of any change in delivery to Mexico. Article XV reflects the states' agreement that none of the provisions in the Rio Grande Compact establishes any principle or precedent applicable to other interstate streams. Article XVI states that nothing in the Compact shall be construed as affecting the obligations of the United States to Mexico under existing treaties, or to Indian tribes or as impairing rights of Indian tribes. Article XVII establishes the effective date of the Compact.

Rio Grande Compact Commission Rules and Regulations. The Rio Grande Compact Commission has adopted rules and regulations for the administration of the compact. Those rules and regulations fall under the following headings: Gaging Stations;[51] Reservoir Capacities;[52] Actual Spill;[53] Departures From Normal Releases;[54] Evaporation Losses;[55] Adjustment of Records;[56] New or Increased

[51]The gaging station rules define the responsibility for the operation of the gaging stations.

[52]The reservoir capacity rule requires that States file the areas and capacities of the reservoirs with the Compact Commission and that the Commission check the accumulation of silt in Elephant Butte Reservoir periodically.

[53]Defines how water released from Elephant Butte in excess of Project requirements is deemed to be an actual spill.

[54]Does not allow for any difference between actual and hypothetical evaporation in the hypothetical spill computation and deems under-releases of usable water in excess of 150,000 acre-feet as equal to that amount.

[55]Defines evaporation losses.

[56]Requires that records be kept for each gaging and evaporation stations. When the location of stream gaging stations are changed, the change in flow between the locations must be ascertained for all stages.

Depletions;[57] Transmountain Diversions;[58] Quality of Water;[59] Secretary;[60] Costs;[61] and Meeting of Commission.[62]

The Goals of the 1938 Compact. The primary goal of the Compact is to divide the waters of the Rio Grande among users in Colorado, New Mexico and Texas.[63] A secondary goal is to maximize the beneficial use of water in the Rio Grande Basin above Fort Quitman without impairment of pre-existing uses.[64] The Compact divides all the waters of the Rio Grande, from its headwaters down to Fort Quitman, among Colorado, New Mexico, and Texas, except for the annual delivery of 60,000 acre-feet guaranteed to Mexico under the 1906 treaty. While this simple description neatly summarizes the general goals of the 1938 Compact, the specific goals of the three signatory states are more interesting and provide a basis for interpreting the provisions of the 1938 Compact as agreed to by the individual commissioners.

Colorado basically felt that there was enough water in the Rio Grande Basin to maintain the status quo of 1929, so long as the water was properly regulated and used.[65] But Colorado had a problem.

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[57]The Commissioner of a state which constructs new works, which may alter the flow at a gaging stations must file all available information to the Commission in order that appropriate adjustments may be made to the delivery schedules.

[58]Water imported into the Rio Grande Basin shall be measured at the point of delivery with allowances made for losses in transit to the index gaging station.

[59]Samples of any water delivered from the Closed Basin into the Rio Grande must be analyzed to determine whether the quality is within Compact limits.

[60]Requires the Commission to employ the U.S. Geological Survey for engineering and clerical aid necessary for the administration of the Compact. The duties of the U.S. Geological Survey are defined.

[61]Requires the Commission to adopt a budget each year with the costs allocated equally to the three states.

[62]Requires the Commission to meet at least annually and states that no action of the Commission shall be effective until approved by each of the three states.

[63]*Id.* at 167.

[64]*Id.* at 168.

[65]*Id.* at 171.

The works of the Middle Rio Grande Conservancy District and the Rio Grande Project from Elephant Butte to Fort Quitman provided the middle and lower Rio Grande Basin with a relatively constant supply of water, that is, storage of excess water in wet years that could be used later in dry years.[66] Colorado, as a result of the "embargo," had been denied the right to increase storage and thereby regulate the supply of water to irrigate lands that Colorado had developed prior to the construction of the works in the middle and lower reaches of the Rio Grande Basin. Colorado estimated its losses over the previous 40 years at $200,000,000.[67] Colorado’s goal was to "construct and operate the reservoirs required in the San Luis section of the Basin to place the water supplies of that section on a parity with the water supply of the Middle and Elephant Butte-Fort Quitman sections of the river."[68] Colorado maintained that it could increase its storage to a sufficient capacity without adversely affecting water supplies in New Mexico and Texas.[69]

New Mexico was in a unique position by having to negotiate with both an upstream and a downstream state. New Mexico also had the most detailed position. With respect to Colorado, New Mexico would agree to increased storage in the San Luis Valley with two provisos, the first being that the interests of New Mexico users be protected and the second being that the San Juan/Chama diversion be made.[70] With respect to Texas, New Mexico was willing to negotiate as to the right to use water claimed by Texans under the Elephant Butte Project.[71] With respect to both states, New Mexico had

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[66]*Id.* at 171-172

[67]*Id.* at 172.

[68]*Id.* at 172.

[69]*Id.* at 172.

[70]*Id.* at 173.

[71]*Id.* at 173.

three additional requirements.[72] First, that the Middle Rio Grande Conservancy District would not be deprived of its existing rights.[73] Second, that all existing rights to use water in the Rio Grande Basin in New Mexico be recognized.[74] And third, that New Mexico be allowed to construct flood protection works.[75]

Texas did not really insist on much. Texas recognized that it was impracticable to separate the requirements of Texas from those of lands in New Mexico below Elephant Butte.[76] Texas felt "it should share in the benefits from new works for the augmentation of the water supply of the Rio Grande, (but) it will not insist thereon, provided that" Colorado and New Mexico deliver enough water at San Marcial to assure the annual release from Elephant Butte of 800,000 acre-feet of the same quality as during the past 10 years.[77]

So, Colorado wanted to increase storage, New Mexico wanted to protect existing users and get San Juan/Chama water, and Texas wanted a guaranteed annual release from Elephant Butte reservoir to irrigate lands in New Mexico and Texas. With these state-specific goals, and the general goal of maintaining the status quo conditions of 1929, in mind, the negotiations proceeded, and the Compact of 1938 was concluded.

How the 1938 Compact Achieves Those Goals. The 1938 Compact achieves the goals of the individual states by two means, delivery schedules and an accounting system. Both are oriented toward maximizing beneficial use of the Rio Grande and avoiding adverse effects to users in all three states.

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[72] *Id.* at 173.

[73] *Id.* at 173.

[74] *Id.* at 173.

[75] *Id.* at 173.

[76] *Id.* at 173.

[77] *Id.* at 173

The first way the 1938 Compact achieves some of the states' goals is through delivery schedules. There are two schedules; one for the amount of water that Colorado must deliver to New Mexico and the other for the amount of water that New Mexico must deliver to the primary storage facility for Texas, Elephant Butte Reservoir. The Colorado delivery schedule is based on the relationship between the natural flow of the Rio Grande and Conejos rivers from the mountains into the San Luis Valley and the depleted flow of the Rio Grande across the state line into New Mexico under the "status quo" conditions of 1928-1937.[78] The New Mexico schedule[79] reflects the relationship between the discharge of the Rio Grande above the principal agricultural areas in New Mexico, Otowi Bridge, and the inflow to Elephant Butte Reservoir at San Marcial. Later, because of difficulties in maintaining the San Marcial gaging station, the New Mexico delivery schedule was modified to use the gaging station below Elephant Butte Dam.[80]

The delivery schedules achieve one goal of the states, that is, to maintain the status quo conditions of 1929. Because there was no increase in irrigation development after the 1929 Compact, fluctuations in the annual discharge of the Rio Grande from 1929 -1937 presumably reflected natural factors such as increased precipitation and drought. Thus the delivery schedules apportion the waters of the Rio Grande between Colorado, New Mexico, and the lands below Elephant Butte Dam by setting the status quo conditions down on paper for wet and dry years. The Compact does not apportion the water released from Elephant Butte Reservoir between New Mexico and Texas. Contracts between irrigation districts in both states and the Bureau of Reclamation have resulted in a constant ratio of irrigated land,

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[78] *Id.* at 175. Rio Grande Compact of 1938, Art. III.

[79] Rio Grande Compact of 1938, Art. IV, modified by resolution adopted February 22-24, 1948.

[80] *Id.* at 180.

57% in New Mexico and 43% in Texas.[81] Although the delivery schedules provide a measuring stick by which to determine the status quo condition for subsequent years, they do nothing for some of the other goals of the states.

For example, New Mexico's goal to import San Juan/Chama water to the Rio Grande Basin is not achieved via the delivery schedules. This goal was, however, easily achieved by Article IX of the 1938 Compact where Colorado agreed to consent to the diversion provided that Colorado's uses of San Juan River water were protected. A related article of the Compact gives credit to any state importing water into the Rio Grande Basin.[82] A far more interesting and challenging problem was that of achieving Colorado's goal of increasing storage while at the same time satisfying Texas with a guaranteed annual delivery to Elephant Butte Reservoir of about 800,000 acre-feet, later deemed to be 790,000 acre-feet.

The problem was challenging because in a normal year, Colorado could not increase storage without decreasing the amount of water delivered to Elephant Butte below the normal annual delivery. Dry years were worse because the delivery to Elephant Butte Reservoir would be less than the normal standard of 790,000 acre-feet. The Compact negotiators recognized that the solution to this problem was the storage of flood waters in wet years.

During some wet years, more than 790,000 acre-feet of water would be released from Elephant Butte Reservoir. Because the 790,000 acre-feet standard was determined from the status quo conditions, that amount of release would satisfy the irrigation needs in Texas and New Mexico below Elephant Butte Dam. Any amount over 790,000 acre-feet would exceed the irrigation demand and thus would flow unused down the Rio Grande past the irrigated lands. If Colorado and New Mexico could capture that

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[81] City of El Paso ex rel. Pub. Serv. Bd. v. Reynolds, 563 F.Supp. 379, 383 (D.N.M. 1983). "The two irrigation districts and the Reclamation Service entered into water contracts for irrigation of approximately 66,500 acres of land in Texas and 88,350 acres in New Mexico. This ratio of irrigated lands -- 57% in New Mexico and 43% in Texas -- has remained constant"

[82] Rio Grande Compact of 1938, Art. X.

excess water, they could increase storage without any adverse effects on users in Texas and New Mexico below Elephant Butte Dam.

Now the problem became one of predicting the future. If Colorado or New Mexico wait until year's end to determine if there is excess water, then it is too late to capture and store it. On the other hand, if Colorado and/or New Mexico increase storage early in the year, and it is a normal or dry year, the delivery to Elephant Butte will be less than the 790,000 acre-feet standard. To solve this problem, the negotiators essentially turned Elephant Butte Reservoir into an escrow account with its own set of accounting rules.

Article VI of the Compact, gives Colorado and New Mexico the flexibility to deviate from the delivery schedules. Each year the amount of water delivered by Colorado and New Mexico is compared to the appropriate delivery schedule. A state delivering more water than required is given credit for the excess water. Likewise, a state that delivers less than the required amount of water accrues a debit. Each year, the annual credits and debits for the previous years are combined to determine the total accrued credits or debits of each state. The benefit to Colorado and New Mexico is that they can store water early in the year without risking a violation of the Compact. If it happens to be a wet year, then Colorado and New Mexico have captured excess water, that is, water above that needed to meet the 790,000 acre-feet irrigation demand below Elephant Butte.[83] If it happens to be a dry year, a state that stores water has the choice of either accruing a debit thus owing water to Elephant Butte Reservoir or releasing water from storage to meet its delivery obligation.

The Compact has several provisions that protect the interests of irrigators below Elephant Butte Dam. First, the Compact limits the accrued debits of Colorado and New Mexico to 100,000 and 200,000

[83]If a post-Compact reservoir stores water during a year that is not released, that water is added to the index station below it and is considered as if it had crossed the index. Therefore the obligation goes up accordingly. When the water is released it is deducted from the index supply. Rio Grande Compact of 1938, Art. VI.

acre-feet, respectively,[84] thereby preventing both states from draining the river dry every year and from having ever increasing accrued debits. Second, both states are required to retain water in storage equal to the amount of their accrued debits.[85] The stored water is essentially security for the debt the states owe to Elephant Butte Reservoir as a result of not meeting their delivery obligations. Texas can demand that Colorado and New Mexico release that stored water, up to the extent of their accrued debits, when there is less than 600,000 acre-feet of water stored in Elephant Butte.[86] In other words, irrigators below Elephant Butte Reservoir can collect the water owed by Colorado and New Mexico when the amount of water in Elephant Butte will not be sufficient to meet the 790,000 acre-feet irrigation demand. Should the amount of water stored in Elephant Butte drop below 400,000 acre-feet, then neither Colorado nor New Mexico can increase the amount of water stored in their reservoirs, unless they relinquish their accrued credits with Texas' approval.[87] Thus, these provisions achieve Texas' goal of being assured an annual release from Elephant Butte Reservoir sufficient to meet the irrigation demand below the Reservoir.

The Compact also helps Colorado achieve its goal of increasing storage. In a really wet year, it is possible that Elephant Butte Reservoir will be full to the point of overflowing. The term "actual spill" refers to times when water is released in excess of the current irrigation demand, either via the spillway

[84]Rio Grande Compact of 1938, Art. VI.

[85]Rio Grande Compact of 1938, Art. VI.

[86]Rio Grande Compact of 1938, Art. VIII. New Mexico can also demand that Colorado release water from storage to the extent of Colorado's accrued debits. Actually, the 600,000 acre-feet criterion refers to the amount of water in "Project Storage" which is defined in the Compact to include storage in reservoirs below Elephant Butte, for example Caballo Reservoir, but above the first diversion to project lands. For practical purposes, and to be less confusing, I refer to Elephant Butte Reservoir instead of using the term "project storage." The same applies to the 400,000 acre-feet criterion that prevents Colorado and New Mexico from increasing storage.

[87]Rio Grande Compact of 1938, Art. VII.

or via operation of the dam.[88] Thus, under the status quo irrigation conditions, the actually spilled water, because it exceeds the irrigation demand, flows down the river unused and is essentially wasted in terms of project goals. Colorado and New Mexico would increase the amount of water wasted if they released water from storage to decrease their accrued debits when Elephant Butte Reservoir is filled. The Compact avoids this problem and allows Colorado, and New Mexico, to increase the amount of water in storage by canceling all accrued debits whenever there is an actual spill.[89] On the other hand, an actual spill will reduce any accrued credits by the amount of the spill. Table 4-2a summarizes debit cancellation and credit reduction based on the accrued status of Colorado and New Mexico.

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[88]Rio Grande Compact of 1938, Art. I (p).

[89]Rio Grande Compact of 1938, Art. VI.

Table 4-2a. DEBIT CANCELLATION AND CREDIT REDUCTION BY SPILL [90]		
ACCRUED STATUS		RESULT
NM	CO	
Credit	Credit	Accrued credits of both states are reduced in proportion to their respective credits by the amount of the actual spill.[91]
Credit	Even	NM’s accrued credits reduced by the amount of the actual spill
Credit	Debit	NM’s accrued credits reduced by the amount of the actual spill. If the amount spilled exceeds NM's credits, then all of CO’s accrued debits are canceled.[92]
Even	Credit	CO’s accrued credits are reduced by the amount of the actual spill.
Even	Even	No debits to cancel and no credits to reduce.
Even	Debit	CO’s accrued debits are canceled.
Debit	Credit	CO’s accrued credits reduced by the amount of the actual spill. If amount spilled exceeds CO’s credits, then NM’s accrued debits are canceled.
Debit	Even	NM’s accrued debits are canceled
Debit	Debit	NM’s and CO’s accrued debits are canceled

Similarly, when the amount of water in Elephant Butte Reservoir is close to capacity but does not actually spill, releases by Colorado and/or New Mexico to reduce their accrued debits could cause an actual spill, thereby wasting water. The Compact reduces both states’ accrued debits to an amount equal

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[90]Debit cancellation applies when there are actual or hypothetical spills. Art. VI. However, the distinction between actual and hypothetical spills is relevant to the issue of whether annual credits or debits are computed. "[I]n a year of *actual* spill no annual credits nor annual debits shall be computed for that year." Art. VI (emphasis added). Presumably, in a year of *hypothetical* spill annual credits or annual debits are computed for that year because "actual spill" does not include "hypothetical spill." Art. I(p), (q).

[91]"[P]rovided, that the amount of actual spill shall be deemed to be increased by the aggregate gain in the amount of water in storage, prior to the time of the spill, in reservoirs above San Marcial constructed after 1929; provided, further, that if the commissioners for the states having accrued credits authorized the release of part, or all, of such credits in advance of spill, the amount so released shall be deemed to constitute actual spill." Art. VI.

[92]Accrued credits are canceled only when there is an actual spill of usable water. Art. VI. An actual spill of usable water occurs only after all credit water has been spilled. Art. I(p). Further, to be an actual spill of usable water, the water spilled must be in excess of the current demand on project storage and cannot be stored in another reservoir. Art. I(p).

to the minimum unfilled capacity of Elephant Butte Reservoir.[93] In other words, Colorado and New Mexico can keep any water that would cause an actual spill if they were to release that water in order to reduce their accrued debits. Table 4-2b summarizes debit reduction to an amount equal to the minimum unfilled capacity based on the accrued status of Colorado and New Mexico.

Table 4-2b. DEBIT REDUCTION WHEN THERE IS NO SPILL[94]

ACCRUED STATUS		RESULT
NM	CO	
Credit	Credit	No debits to reduce.
Credit	Even	No debits to reduce.
Credit	Debit	If CO's debits exceed minimum unfilled capacity[95] of project storage, then CO's debits reduced to an amount equal to the minimum unfilled capacity.
Even	Credit	No debits to reduce.
Even	Even	No debits to reduce.
Even	Debit	If CO's debits exceed minimum unfilled capacity of project storage, then CO's debits reduced to an amount equal to the minimum unfilled capacity.
Debit	Credit	If NM's debits exceed minimum unfilled capacity of project storage, then NM's debits reduced to an amount equal to the minimum unfilled capacity.
Debit	Even	If NM's debits exceed minimum unfilled capacity of project storage, then NM's debits reduced to an amount equal to the minimum unfilled capacity.
Debit	Debit	If the aggregate of NM's and CO's accrued debits exceeds the minimum unfilled capacity, then NM's and CO's debits are reduced proportionally to an aggregate amount equal to the minimum unfilled capacity.

[93]Rio Grande Compact of 1938, Art. VI.

[94]Annual debits or credits computed for the year for each case in this table.

[95]"Unfilled capacity" is the difference between the total physical capacity of project storage and the amount of *usable* water then in storage. Art. I(n) (emphasis added). "Usable water" is all water, *exclusive of credit water*, which is in project storage and which is available for release in accordance with irrigation demands, including deliveries in Mexico. Art. I(l) (emphasis added).

Of course, whether or not an actual spill occurs depends on the balance of inflow to outflow. The Compact negotiators recognized that a greater than normal release rate from Elephant Butte could prevent an actual spill from occurring. The hypothetical spill computation is performed to determine if a greater than normal release rate prevented an actual spill from occurring.[96] If a greater than normal release, which is a departure from the status quo conditions, prevented an actual spill from occurring, then all accrued debits of Colorado and New Mexico are canceled just the same as if an actual spill occurred.

Delivery Obligations in Drought

During drought years there will be less than normal flow in the Rio Grande in Colorado and northern New Mexico. Consequently the amount of water obligated to be delivered to Elephant Butte Reservoir decreases. With continued normal releases from Elephant Butte during drought years, the amount of water in project storage will decrease. When the amount of usable water in project storage decreases below 600,000 and 400,000 acre-feet, two articles of the Rio Grande Compact become relevant and may increase the amount of water in project storage. Usable water is all water, exclusive of credit water, which is in project storage and which is available for release in accordance with irrigation demands.

Less than 600,000 Acre-Feet of Usable Water in Project Storage. When the amount of water in project storage falls below 600,000 acre-feet (23 percent of capacity), Texas may demand that both Colorado and New Mexico release water from storage. New Mexico may also demand that Colorado release water from storage. The amount of water that Colorado and New Mexico may be required to release is limited by the amount of accrued debits and may be less if both Colorado and New Mexico

[96]Rio Grande Compact of 1938, Art. I (q).

have accrued debits. The demand to release water must be made in January and applies only to reservoirs constructed after 1929.

The goal of Article VIII is to have a normal release of 790,000 acre-feet from project storage each year. Article VIII tries to achieve its goal by requiring Colorado and New Mexico to release water in storage from post-1929 reservoirs when the amount in project storage is too low. If both Colorado and New Mexico have accrued debits, then the amount of water each state must release is determined proportionally according the amounts of each state's accrued debits until the amount of water in project storage reaches 600,000 acre-feet by March 1 and remains at 600,000 acre-feet until April 13. Table 4-2c shows when Colorado, New Mexico, or both, may be required to release water from storage. Article VIII releases may be demanded when the total amount of water in project storage exceeds 600,000 acre-feet so long as the amount of *usable* water in project storage is less than 600,000 acre-feet. The amount of credit water in project storage must be subtracted from the total amount of water in project storage to determine the quantity of usable water in project storage. However, even when the amount of usable water in project storage is less than 600,000 acre-feet, there are two limitations on Article VIII releases.

Table 4-2c. REQUIRED RELEASE WHEN THERE IS LESS THAN 600,000 ACRE-FEET OF USABLE WATER IN STORAGE [97]		
ACCRUED STATUS		RESULTS
NM	CO	
Credit	Credit	TX cannot require either state to release water. NM cannot require CO to release water.
Credit	Even	TX cannot require either state to release water. NM cannot require CO to release water.
Credit	Debit	TX cannot require NM to release water. TX and/or NM may require CO to release water up to the amount of CO's accrued debits.
Even	Credit	TX cannot require either state to release water. NM cannot require CO to release water.
Even	Even	TX cannot require either state to release water. NM cannot require CO to release water.
Even	Debit	TX cannot require NM to release water. TX and/or NM may require CO to release water, up to the amount of CO's accrued debits.
Debit	Credit	TX cannot require CO to release water. TX may require NM to release water, up to the amount of NM's accrued debits.
Debit	Even	TX cannot require CO to release water. TX may require NM to release water, up to the amount of NM's accrued debits.
Debit	Debit	TX may require CO and NM to release water in storage, up to the amount of their respective accrued debits, and in proportion to the total debit of each. NM may also require CO to release water.

[97]"Usable water" is all water, *exclusive of credit water*, which is in project storage and which is available for release in accordance with irrigation demands, including deliveries in Mexico. Art. I(l) (emphasis added). Thus, total amount of water in storage could exceed 600,000 acre-feet.

TX and NM may only demand release of water from storage reservoirs constructed after 1929. Art. VIII. Such releases "shall be made . . . at the greatest rate practicable under the conditions then prevailing, and in proportion to the total debit of each [state, CO and NM], and in amounts, limited by their accrued debits, sufficient to bring the quantity of *usable* water in project storage to 600,000 acre-feet by March first and to maintain this quantity in storage until April thirtieth . . . ." Art. VIII.

Demand to release water must be made in January. Art. VIII.

The first limitation is that a state must have accrued debits before it can be required to release water from storage. The maximum amount of water that Colorado and New Mexico must release is limited to the amount of their accrued debits. A state without accrued debits cannot be required to release water from storage.

The second limitation as contained in a clause in Article VIII, requires Colorado and New Mexico to release water at the greatest rate practicable under the prevailing conditions. The prevailing conditions clause may limit any release required of Colorado due to the timing of the required releases. Under Article VIII, Texas may, during the month of January, demand the release of water by Colorado and New Mexico. In order to reach and maintain the goal of 600,000 acre-feet of water in project storage for March and April, Colorado and New Mexico must release water, up to the amount of and in proportion to their accrued debits, from some date after Texas' demand in January until late April at the latest. Thus, the release would occur during the winter and early spring when prevailing conditions are likely to include frozen rivers and streams. Release of water from storage into frozen rivers could cause flooding. Thus, any releases under Article VIII may be limited to rates that would not cause flooding.

<u>Less than 400,000 Acre-Feet of Usable Water in Project Storage</u>. Colorado's and New Mexico's ability to increase the amount of water in upstream storage is limited by the amount of water in project storage. When the amount of water in project storage is less than 400,000 acre-feet (about 15 percent of capacity), Colorado and New Mexico may be prevented from increasing the amount of storage in reservoirs constructed after 1929.

Article VII derives from two premises. The first is that lands in New Mexico and Texas supplied with water from Elephant Butte Dam have a superior right to storage of flood waters of the Rio Grande. The second is that flood waters cannot be stored in new upstream reservoirs when the supply in Elephant

Butte Reservoir is insufficient to meet the needs of downstream users, in order to maintain the status quo as of 1929 conditions of development.[98]

There are two exceptions in Article VII that would allow Colorado and New Mexico above Elephant Butte to increase storage when the amount of water in project storage is less than 400,000 acre-feet.

The first of two exceptions to the limitation on increasing storage relates to larger than normal releases from Elephant Butte Reservoir. Normally, Colorado cannot increase the amount of water in storage whenever there is less than 400,000 acre-feet in project storage. However, when releases from project storage are greater than the average 790,000 acre-feet per year, the time when project storage goes below 400,000 acre-feet is adjusted to compensate for the increased release rate. So, with a greater than average release rate and the amount of water in project storage less than 400,000 acre-feet, Colorado and New Mexico would be allowed to increase storage until some later time. That later time is the calculated time project storage would have gone below 400,000 acre-feet had the release rate been at the average of 790,000 acre-feet per year.

The second exception to the limitation on increasing storage also allows Colorado and New Mexico to increase storage when the amount of water in project storage is less than 400,000 acre-feet. This exception only applies to either state when that state has accrued credits, relinquishes those credits, and Texas accepts the relinquished water. In that case, the state relinquishing credits can store water in amounts up to the amount of the credits relinquished provided that Texas accepts the relinquished credits.

Table 4-2d shows that the limitation on increasing storage applies when the amount of usable water in project storage drops below 400,000 acre-feet, unless a state relinquishes credits that are

[98] Hill, 194.

accepted by Texas. Because "usable" water does not include credit water, the limitation on increasing storage may apply when the total amount of water, usable plus credit, in storage exceeds 400,000 acre-feet. In addition to the limitation on increasing storage, low amounts of usable water in project storage may result in Colorado or New Mexico, or both, being required to release water from storage.

Table 4-2d. LIMITATION ON INCREASING STORAGE WHEN THERE IS LESS THAN 400,000 ACRE-FEET OF USABLE WATER IN STORAGE [99]

ACCRUED STATUS		RESULTS
NM	CO	
Credit	Credit	CO and NM can increase storage by the amount of credits they relinquish if TX accepts the credits.
Credit	Even	NM can increase storage by the amount of credits NM relinquishes if TX accepts the credits. CO cannot increase the amount of water in storage.
Credit	Debit	NM can increase storage by the amount of credits NM relinquishes if TX accepts the credits. CO cannot increase the amount of water in storage.
Even	Credit	CO can increase storage by the amount of credits CO relinquishes if TX accepts the credits. NM cannot increase the amount of water in.
Even	Even	Neither CO nor NM can increase the amount of water in storage.
Even	Debit	Neither CO nor NM can increase the amount of water in storage.
Debit	Credit	CO can increase storage by the amount of credits CO relinquishes if TX accepts the credits. NM cannot increase the amount of water in storage.
Debit	Even	Neither CO nor NM can increase the amount of water in storage.
Debit	Debit	Neither CO nor NM can increase the amount of water in storage.

[99]Limitation on increasing storage applies only to reservoirs constructed after 1929. "Usable water" does not include credit water. Art. I(l). Thus, total amount of water in storage could exceed 400,000 acre-feet.

Limitation is subject to two provisions. First, "if the actual releases of usable water from the beginning of the calendar year . . . following actual spill, have aggregated more than an average of 790,000 acre-feet per annum, the time at which such minimum stage is reached shall be adjusted to compensate for the difference between the total actual release and releases at such average rate . . . ." Art. VII. Thus, all credit water must be released and then some "usable water" must be released for this provision to operate.

Second, "Colorado or New Mexico, or both, may relinquish accrued credits at any time, and Texas may accept such relinquished water, and in such event the state, or states, so relinquishing shall be entitled to store water in the amount of the water so relinquished." Art. VII.

General Provisions

The 1938 Compact divides the waters of the Rio Grande between Colorado, New Mexico, and Texas. In doing so, it maximizes the beneficial use of the water without impairment of any beneficial uses under the conditions prevailing in 1929. Colorado and New Mexico can increase their storage using excess flood water and Texas is assured that 790,000 acre-feet will be released to the lands below Elephant Butte Reservoir. However, as noted above, during drought conditions Colorado and New Mexico may be required to release water from storage and may be precluded from increasing the amount of water in storage. Whether or not these Compact requirements apply to either state during a drought depends on the accrued debit/credit status of each state, the ability of each state to enforce the Compact vis a vis the other state and a host of other factors as yet undefined, except by ad hoc practice. It is at this point that the models such as those developed in the ACF may be helpful.

Role of Models in Drought Policy Analysis

This project has developed a model that responds to relative scarcity as those scarcities are reflected through Compact deliveries and other institutions. While the model is not designed to generate the exact detail as to how all of the institutions would respond and with what economic consequences, it is in fact a first step toward the kind of effort that has been generated in the ACF basins involving Georgia, Alabama and Florida. There is no doubt that a great deal of value could be generated by beginning with the basic effort of this study, and expanding it to integrate with existing detailed hydrologic models. And, while this integration between the economic models and the hydrologic models is critical, the problems with these hydrologic models generate their own concerns. The work on the middle Rio Grande is a case in point. A debate is currently raging between the City of Albuquerque and the New Mexico State Engineer on which hydrologic model to use in calculating the amount of surface water that is being withdrawn each year by the City of Albuquerque through its wells.

This example is relevant because in designing a drought model that predicts outcomes in times of drought, someone must make a choice. Or, at a minimum run a set of scenarios. Of course, too wide a range of scenarios is no prediction at all. Thus, we must reluctantly conclude that hydrologic modeling is no less "certain" than economic modeling and is only as valuable as the accuracy of the assumptions that go into the model.

Still, this discussion does not argue against constructing the model and developing the common data set. Rather, it argues in favor of continued testing and validation of the model when possible and caution in describing its results. What then would be the form of this ideal model? At a minimum it should contain:

- A mass surface water balance for the region studied so that when various rates of snow pack run off and flood events occur at the upper reaches and should reach the accounting point at the end of the compact at Elephant Butte.
- A set of hydrologic assumptions regarding the impacts of groundwater pumping on the system based upon the best data available using estimates that reflect good water conservation policy.
- A set of hydrologic assumptions regarding return flows, evaporation losses, transpiration losses, seepage and all other losses to the system.
- A set of institutional entitlements under the Rio Grande Compact that permit or do not permit storage and withdrawal at key points in the river such that one is able to estimate rates of flow at various points in the river system.
- A set of the best estimates of environmental needs in the river for rates of flow throughout the system that most closely resemble the traditional hydrograph, since these amounts will be required in the future by environmental interests.
- A set of anticipated consumptive needs throughout the system broken down by user and coupled with calculations of return flows from each type of user.

Based upon the above hydrologic supply and demand, a prediction can be made of where and under what circumstances the water will be allocated among the above listed users, including an analysis of priority dates and relative legal strengths of the positions of the parties intrastate, the bulk water entitlements will be allocated under the Rio Grande Compact. These allocations in New Mexico include the Middle Rio Grande Conservancy District, the municipalities, the Indian Pueblos, and the Middle Rio Grande Silvery Minnow.

Tied to the above outcomes as to where the water goes in times of shortage and to whom, is the kind of economic analysis contained in this report that ties economic outcomes to water scarcity. This should be supplemented by an analysis of the impact on water quality at various reaches of the river.

Finally, once this model is constructed and running, it must be capable of being altered by various institutional adjustments to the current Law of the River, for example, water banking as a form of transfer of interests in water, water leasing, forbearance programs and any other hydrologically realistic institutional fix that could move water to other uses.

All of the model pieces must be tied together so that if we move water, for example, from farming to municipal in response to drought, the effect on all other variables is reflected including stream flow, water quality and other institutional consequences.

The drought study performed under this grant is only a beginning in this direction, but it is, we believe, a step in the right direction.

Law of the River, Normal Inflows

Water Use Patterns

Table 4-3 shows long-run average annual model-forecasted water use patterns by major system users and inflows to the system for the next 44 years.[100] Long-run average annual gaged inflows to the

[100]These forecasts do not match historical use patterns because of projected population growth in Albuquerque and El Paso.

basin were 1.57 million acre-feet per year.[101] These six long-run average flows are as follows: 659,000 acre-feet per year from the Rio Grande at Del Norte; 345,000 from the three Conejos Index gages; 581,000 from the Chama watershed; 45,170 from the Jemez; 32,238 from the Rio Puerco; and 40,515 from the Rio Salado.

Under the scenario that the above long-run average flows recur over the next 44 years, Colorado agriculture diverts about 857,000 acre-feet per year of total water, of which about 678,000 comes from surface water and the remaining 179,000 from groundwater pumping.[102]

In New Mexico, the major users divert the following amounts: Middle Rio Grande Conservancy District (MRGCD) agriculture above Albuquerque: diverts 513,630 acre-feet surface water per year; Albuquerque area M&I use: diverts 158,240 acre-feet of groundwater pumping and 63,360 acre-feet of surface diversions; MRGCD agriculture below Albuquerque: diverts 207,220 acre-feet surface water; Elephant Butte Irrigation District: diverts 495,000 acre-feet of surface water and 115,900 acre-feet of pumping. Albuquerque water uses are based on future projected population growth and on planned surface water treatment development beginning in year 10.

In Texas, El Paso M&I diverts 140,080 acre-feet of surface water and 77,830 of groundwater (El Paso population growth included); while El Paso agriculture diverts 236,800 acre-feet of surface water.

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[101]Runoff from the Sangre de Cristo mountain range in northern New Mexico to the Rio Grande in New Mexico below the Lobatos gage produces a significant amount of water for New Mexico.

[102]The model underestimates Colorado's historical water use. Historically Colorado records show diversions of about 1.5 million acre-feet per year of total water, of which about 1.0 million comes from surface water and 500,000 from groundwater (Vandiver, 2001). Still, with considerable groundwater pumping and recharge and surface water and groundwater return flows to the river, measurement of 'use' is difficult, both in the model and on the ground. The model correctly produces the right quantity of Colorado's index flows (supplies) to meet its delivery obligations to New Mexico at the Lobatos gage.

Table 4-3. Long Run Average Annual Water Use Patterns in Drought, by State, Location, and User (1000s acre-feet)

Baseline Institution: **Law of the River**

Drought Scenario: **Long-Run Average Flows (1.57 million acre-feet per year at six headwater gages)**

	Colorado	**New Mexico**				**Texas**	
	San Luis Valley Ag	Middle Rio Grande Ag above Albuq	Albuq M&I	Middle Rio Grande Ag below Albuq	Eleph Butte Ag	El Paso M&I	El Paso Ag
Average annual total water use[103] (surface diversions + pumping)	857.49	513.63	221.60	256.82	610.90	217.41	236.80
Average annual surface water use (diversion)	678.17	513.63	63.36	256.82	495.00	140.08	236.80
Average annual groundwater use (pumping)	179.32	0.00	158.24	0.00	115.90	77.33	0.00
Elephant Butte Volume	685.55						
Average total water use by state (surface diversions + pumping)	857.49				1,602.95		454.21
Average surface water use by state (diversion)	678.17				1,328.81		376.88
Average groundwater use by state (pumping)	179.32				274.14		77.33

[103] In these results, the term ‘use’ means surface diversions plus groundwater pumping. It does not refer to net consumption.

Economic Benefits

Table 4-4 shows economic benefits produced by water use patterns when long-run average inflows to the system are available. Results are shown by state, location, and user. These are the benefits produced by the institution of the current Law of the River, when this level of inflow, equal to the long-run average inflow to the Basin, occurs over the next 44 years.

Colorado agriculture in the San Luis Valley earns about $72 million in net income from its 145,000 acres in potatoes, alfalfa, and barley by diverting 857,490 acre-feet of water predicted by the model. This is an average of about $84 per acre-foot diverted.

In New Mexico, Middle Rio Grande Conservancy District (MRGCD) agriculture earns about $6.9 million per year in the region above Albuquerque and about $2.1 million south of Albuquerque from the 770,000 acre-feet of water diverted, about $11 per acre-foot diverted. Albuquerque area M&I water use produces about $1.25 billion in total benefits from a predicted 221,600 acre-feet of water use.[104] This total benefit amounts to slightly over $5,600 per acre-foot diverted. Elephant Butte Irrigation District agriculture earns about $31.1 million per year of net income producing its major crops of alfalfa, chile, pecans, onions, lettuce, and cotton, on about 82,600 acres of irrigated land, which is about $50 per acre-foot diverted.

In Texas, El Paso M&I water use produces about $1.06 billion of total benefit, of which less than 10 percent accrues as a direct water bill to ratepayers. Like Albuquerque, the very high percent of total benefit accruing as consumer surplus occurs because the price elasticity of demand for water is quite low, and the price is quite low compared to what people would pay as a maximum. El Paso area agriculture earns $18.5 million per year in farm income from 236,800 acre-feet of water, or about $ 78 per acre-foot.

[104]Most of this M&I benefit accrues to water buyers as consumer surplus because of the relatively low price of water compared to what people are willing to pay rather than go without.

Table 4-4. Long-Run Average Annual Economic Benefit from Water Use Patterns, by State, Location, and User ($1000s)

Baseline Institution: **<u>Law of the River</u>**

Baseline Water Supply: **<u>Long-Run Average Inflows, Period of Record (1.57 million acre-feet per year at six headwater gages)</u>**

	Colorado	**New Mexico**				**Texas**	
	San Luis Valley Ag	Middle Rio Grande Ag above Albuq	Albuq M&I	Middle Rio Grande Ag below Albuq	Eleph Butte Ag	El Paso M&I	El Paso Ag
	-- ($1000s per year) --						
Average annual economic benefit, from surface + groundwater	72,193	6,941	1,246,362	2,153	31,111	1,059,073	18,532
Average annual recreation benefits summed over five basin reservoirs: Heron, El Vado, Abiquiu, Cochiti, Elephant Butte	9,761						
Average annual economic benefit (from surface diversions + pumping) totaled by state	72,193	1,286,567				1,077,605	

Law of the River, 1942-1985 Drought Inflows

Water Use Patterns

Table 4-5 shows water use patterns in the system under drought inflow conditions. These drought inflows replicate historical drought flows of the 1950s through late 1970s. In order to have a "lead up" and "wind-down" period, the ‘spill to spill’ period of 1942-1985 was included. Elephant Butte Reservoir spilled in both 1942 and 1985. Under the Rio Grande Compact, a spill wipes out all accumulated debts and credits. For these reasons, future drought inflows to the system were defined to equal the historical 1942-1985 headwater flows. That is, this section’s analysis is based on a drought of 1942-1985 repeating itself in absolute water quantities, but with economic activity in the region based on future expected population growth of Albuquerque and El Paso. The method of coping with this drought is based on the current Law of the River.

Historical inflows for 1942-1985 averaged about 1.4 million acre-feet per year. By headwater gage, these long-run average flows were as follows: 617,402 acre-feet per year from the Rio Grande at Del Norte, 309,000 from the three Conejos Index gages, 390,757 from the Chama watershed, 44,735 from the Jemez, 32,238 from the Rio Puerco, and 40,515 from the Rio Salado.

Over this drought period where the system is operated under the Law of the River, Colorado agriculture diverts about 788,000 acre-feet per year of total water, of which about 616,000 comes from surface water and the remaining 172,000 from groundwater pumping.

New Mexico water users who face 1942-1985 drought flows in the future are forecasted to divert different amounts than they diverted in the actual 1942-1985 period because of expected growth in Albuquerque M&I use and because Albuquerque plans to start using surface water, assumed to occur in year 10. The future New Mexico long-run average annual water use under the drought condition described is estimated as the following amounts, averaged over all 44 years: MRGCD agriculture above Albuquerque: 471,000 acre-feet surface water per year, Albuquerque area M&I use: 153,330 acre-feet of groundwater pumping and 68,280 acre-feet of surface diversions; MRGCD agriculture below

Albuquerque: 235,500 acre-feet surface water; Elephant Butte Irrigation District: 428,010 acre-feet of surface water and 133,960 acre-feet of groundwater.

Long-run average future Texas water use is projected as follows: El Paso area M&I diverts 120,180 acre-feet of surface water and 93,370 acre-feet of groundwater, which is 16,000 acre-feet/year more pumping compared to non-drought conditions. This increase in pumping is to make up for the surface water shortfall. El Paso area agriculture diverts a long-run average of 205,700 acre-feet of surface water per year, about 31,000 less the 236,800 diversion under long-run average flows. The reduced diversion occurs because of less surface water available under drought conditions than under normal supplies.

Table 4-5. Long-Run Average Annual Water Use Patterns in Drought, by State, Location, and User (1000s acre-feet)

Baseline Institution: **<u>Law of the River</u>**

Drought Scenario: **<u>1942-1985 Historical Inflows (1.40 million acre-feet per year)</u>**

	Colorado	**New Mexico**				**Texas**	
	San Luis Valley Ag	Middle Rio Grande Ag above Albuq	Albuq M&I	Middle Rio Grande Ag below Albuq	Eleph Butte Ag	El Paso M&I	El Paso Ag
Average annual total water use (surface diversions + pumping)	787.85	471.00	221.61	235.50	561.97	213.55	205.70
Average annual surface water use (diversion)	616.27	471.00	68.28	235.50	428.01	120.18	205.70
Average annual groundwater use (pumping)	171.58	0.00	153.33	0.00	133.96	93.37	0.00
Elephant Butte Volume	477.21						
Average total water use by state (surface diversions + pumping)	787.85	1,490.08				419.25	
Average surface water use by state (diversion)	616.27	1,202.79				325.88	
Average groundwater use by state (pumping)	171.58	287.29				93.37	

Economic Benefits

Table 4-6 shows annual economic drought damages brought about by changed water use patterns in drought flows compared to normal flows, assuming, as before, projected future population growth in the Albuquerque and El Paso areas.. Results are presented as economic losses, defined as the reduction in economic benefits under drought conditions compared to similar economic benefits produced by long-run normal flows. Drought damages are presented by state, location, and user in which the current Law of the River deals with the above-described drought inflows.

Colorado agriculture in the San Luis Valley suffers drought losses from reduced flows of about $5.8 million in net income per year. In New Mexico, MRGCD incurs long-run average losses of about $479,000 per year from the reduced flows above Albuquerque and about $149,000 per year below Albuquerque. Albuquerque area M&I water use is virtually unchanged, but substitutes surface water for groundwater of about 5,000 acre-feet per year, thereby reducing costs by about $49,000 compared to conditions under normal flows. Elephant Butte Irrigation District agriculture suffers drought damages of about $2.8 million per year due to reduced surface water flows, although groundwater pumping increases slightly to mitigate drought damages.

In Texas, El Paso M&I use suffers loses of about $6.1 million per year (0.6 percent of benefits under normal flows). Total M&I use is reduced by about 3,000 acre-feet per year over the long-run, with groundwater pumping increasing by about 16,000 acre-feet per year to make up for reduced surface water diversions of about 19,000 acre-feet. El Paso area agriculture incurs $1.8 million per year in direct farm income losses (10 percent of benefits under normal flows) due to the reduced surface flows under drought.

Table 4-6. Long-Run Average Annual Drought Damages by State, Location, and User ($1000s)

Baseline Institution: **Law of the River**

Drought Scenario: **1942-1985 Historical Inflows (1.40 million acre-feet per year)**

	Colorado	**New Mexico**				**Texas**	
	San Luis Valley Ag	Middle Rio Grande Ag above Albuq	Albuq M&I	Middle Rio Grande Ag below Albuq	Eleph Butte Ag	El Paso M&I	El Paso Ag
	($1000s per year)						
Average annual economic drought damage	5,803	479	(49)	149	2,800	6,106	1,884
Average annual recreation drought damage, summed over 5 Basin reservoirs: Heron, El Vado, Abiquiu, Cochiti, Elephant Butte	419						
Average annual economic drought damage totaled by state	5,803	3,379				7,990	

Carryover Storage at Elephant Butte for Use in Drought

Under the current Law of the River, the scheduled "full release" for the Rio Grande Project is 790,000 acre-feet per year. However, as described earlier in this report, actual historical releases made by the districts have fallen considerably with reduced water available in Rio Grande Project storage. These releases are shared by three U.S. users: Elephant Butte Irrigation District in New Mexico, El Paso area M&I, and El Paso area agriculture. While not in the Rio Grande Compact, the method of sharing this water allocates 57% to New Mexico lands and 43% to Texas lands, based on proportions of historically irrigated acreage.

The Institutional Adjustment considered for this policy analysis reduces the historical release by 25,000 acre-feet per year, using the concept of the savings account. Current water release is reduced with the intent of putting additional water in the project storage savings account. The effect of increasing storage by 25,000 acre-feet in wetter years is to make more water available for use in drought years, when project storage would have otherwise fallen to critically low levels had the stored water summed over previous years not been available.

This proposed carryover storage would slightly reduce water use in full years, when its economic value at the margin is small, leaving the saved water instead in Elephant Butte Reservoir.[105] In dry years this accumulated saved water would be available for use, when its economic value at the margin is much higher because of its considerably greater scarcity. However, unlike ordinary bank accounts, Elephant Butte Reservoir pays negative interest in the form of nearly 10 feet of evaporation per year. So reducing wet year releases by 25,000 acre-feet per year contributes to less than 25,000 acre-feet available for future use, since a small amount of it will evaporate.[106]

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[105] Rio Grande Project storage occurs at both Elephant Butte and Caballo reservoirs. The model was coded to treat these as a single reservoir, with storage capacity equal to the sum of the two volumes. We refer to Project storage as occurring at Elephant Butte reservoir, recognizing that both reservoirs contribute.

[106] If the storage reservoirs had vertical canyon walls, the negative interest rate would be zero because releasing less water increases water in storage, but does not increase evaporation, which depends only on exposed surface area. However Elephant Butte reservoir exposes larger amounts of surface area with higher volumes of water, so increasing carryover storage also increases evaporation slightly; hence the interest rate on water saved is slightly negative.

Water Use Patterns

Table 4-7 shows water use patterns throughout the system, under the carryover storage management institution for coping with drought. It also shows the equations coded into the model to compare the institutions of current law of the river to carryover storage.

Over this future period, Colorado agriculture diverts the same 788,000 acre-feet per year of total water, of which about 616,000 comes from surface water and the remaining 172,000 from groundwater pumping. The carryover storage at Elephant Butte has no effect on Colorado delivery requirements and therefore has no impact on water use in Colorado.

In New Mexico above Elephant Butte Reservoir, for the reasons described previously, New Mexico pays for the slightly increased evaporation at Elephant Butte resulting from the carryover storage institution. So, for a long-term 44 year average, MRGCD diverts 8,380 acre-feet less above and 4,190 acre-feet less below Albuquerque per year, for a total of 12,570 fewer acre-feet diverted. MRGCD's depletions from the river fall by much less than the 12,570 acre-feet, since only a small part of their reduced diversions are reduced stream depletions needed to offset increased evaporation at Elephant Butte.

Albuquerque M&I water use is virtually unaffected by the carryover storage program, diverting 66,400 acre-feet of surface water with and 68,280 acre-feet without Elephant Butte carryover storage (1,780 acre-feet net reduction), and 155,200 acre-feet of pumping with and 153,330 acre feet without the carryover storage. M&I is a higher valued use of water, at the margin. Because the model is coded to seek the the least cost method to deliver water, increased delivery requirements to Elephant Butte Reservoir are produced mostly by reduced diversions by MRGCD agriculture, equal to 88 percent from MRGCD and 12 percent from Albuquerque M&I.

In New Mexico below Elephant Butte Reservoir, EBID agriculture uses about 1,000 less acre-feet surface water on average under the carryover storage program. Therefore, one can conclude that the proposed carryover storage program is not a significant help to EBID water users in getting through the drought, in terms of promoting more average long-run surface water use.

Future Texas water use under carryover storage is projected as follows: El Paso M&I has no significant change in surface or groundwater use under carryover storage. El Paso agriculture diverts an average of 205,380 acre-feet per year under carryover storage compared to the slightly lower 205,700 acre-feet of surface water per year under Law of the River.

The table also shows that carryover storage produces a considerably higher long-run average storage volume at Elephant Butte Reservoir. The reservoir increases from an average of 477,210 acre-feet over a typical year under the law of the river to an average of 527,530 under the carryover storage program. So, while the increased carryover storage produces a higher average reservoir volume, it does not produce higher use.

Table 4-7. Long-Run Average Annual Water Use Patterns under Drought Mitigation by State, Location, and User (1000s of acre-feet)

Alternative Institution: **<u>Carryover Storage--Reduce Elephant Butte Releases in Full Years by 25,000 Acre-feet /Yr for Use in Drought</u>**

Drought Scenario: **<u>1942-1985 Historical Inflows (1.40 million acre-feet per year)</u>**

	Colorado	**New Mexico**				**Texas**	
	San Luis Valley Ag	Middle Rio Grande Ag above Albuq	Albuq M&I	Middle Rio Grande Ag below Albuq	Eleph Butte Ag	El Paso M&I	El Paso Ag
Ave annual total use (surf diversions + pumping)	787.85	462.62	221.60	231.31	564.09	213.76	205.38
Average annual surface water use (diversion)	616.27	462.62	66.40	231.31	426.96	119.69	205.38
Average annual groundwater use (pumping)	171.58	0.00	155.20	0.00	137.13	94.07	0.00
Elephant Butte Volume	527.53						
Average total water use by state (surface diversions + pumping)	787.85				1,479.62		419.14
Average surface water use, totaled by state (diversion)	616.27				1,187.29		325.07
Average groundwater use, totaled by state (pumping)	171.58				292.33		94.07

Current Law of River: release = 672,000 + (0.14 * project storage) - (1.55 * tributary inflow), with enough water in storage

Modified Institution: release = 672,000 - 25,000 + (0.14 * project storage) - (1.55 * tributary inflow), with enough water in storage

Economic Benefits

Table 4-8 shows the impact on long-run average annual economic drought damages brought about by the carryover storage management institution for coping with drought, described above. We refer to these economic impacts of carryover storage as the value of drought damage mitigation accruing to that institution.

Results of the drought damage mitigation are reductions in economic losses, expressed as positive numbers. Negative numbers are in parentheses, which mean that the mitigation is negative. A negative mitigation means that total economic benefits for that user are lower with the carryover storage institution than with the baseline Law of the River.

Colorado agriculture in the San Luis Valley gains zero drought mitigation benefit under the carryover storage institution, because, under the Rio Grande Compact, Colorado's delivery obligations at the Colorado-New Mexico state line, in non-spill drought years is unaffected by operation of Elephant Butte Reservoir.

MRGCD agriculture in New Mexico suffers small losses from increased carryover storage at Elephant Butte equal to an average of $112,000 per year above Albuquerque and $35,000 below Albuquerque. This small loss occurs because of reduced agricultural diversions described above. This reduced water use in agriculture produces economic values in agriculture of $13 less per acre-foot not diverted ($112,000/8,380). This small loss in MRGCD agriculture per acre-foot of water not diverted occurs because reduced irrigated agriculture acreage in that part of New Mexico comes mostly at the expense of alfalfa and other cattle feed displaced. These enterprises produce low farm incomes per added acre-foot diverted.

Table 4-8. Long-Run Average Annual Drought Damage Mitigation from Alternative Institution, by State, Location, and User ($1000s)

Alternative Institution: **<u>Carryover Storage--Reduce Elephant Butte Releases in Full Years by 25,000 Acre-feet Per Year for Use in Drought</u>**

Drought Scenario: **<u>1942-1985 Historical Inflows (1.40 million acre-feet per year)</u>**

	Colorado			**New Mexico**			**Texas**
	San Luis Valley Ag	Middle Rio Grande Ag above Albuq	Albuq M&I	Middle Rio Grande Ag below Albuq	Eleph Butte Ag	El Paso M&I	El Paso Ag
	-- ($1000s per year) --						
Average annual <u>economic drought damage mitigated</u>	0	(112)	(18)	(35)	(35)	(425)	(8)
Average annual <u>recreation drought damage mitigation</u>, summed over 5 Basin reservoirs: Heron, El Vado, Abiquiu, Cochiti, Elephant Butte	84						
Average annual <u>economic drought damage mitigation</u> totaled by state	0				(200)		(433)

These reduced diversions of 12,570 acre-feet per year on average result in a much lower reduction in river depletions, as described in some detail below. This "second order" effect of the carryover storage institution results from the treatment of evaporation charges under the Rio Grande Compact. Under the Compact, New Mexico is responsible for increased deliveries into Elephant Butte resulting from actions that increase its evaporation.

The model follows the Compact, under which New Mexico is responsible for deliveries into Elephant Butte as a function of flows at the Otowi gage. New Mexico deliveries to Texas are defined as "...the recorded flow of the Rio Grande at the gaging station below Elephant Butte Dam during the calendar year plus any net gain in storage in Elephant Butte Reservoir during the same year or minus the net loss in storage in said reservoir, as the case may be..." (1948 resolution adopted by Rio Grande Compact Commission regarding changing the gaging station and measurements of deliveries by New Mexico).

This passage of the Compact has important implications for who is responsible for making water deliveries resulting from actions producing increased evaporation at Elephant Butte. A simple example taken directly from the Compact delivery table linking Otowi flows and Elephant Butte effective supply clarifies the issue. If the Otowi index supply is 1.2 million acre-feet, then New Mexico is responsible for delivering 800,000 acre-feet at the Elephant Butte gage plus the net gain in storage at the reservoir.

Suppose the net gain in Elephant Butte storage is zero, with New Mexico complying with the Compact by delivering annual flow at the Elephant Butte gage of 800,000 acre-feet. Now, if Rio Grande Project water users downstream of Elephant Butte set up a carryover storage plan that reduces releases to 700,000 acre-feet, then for the same inflows into the reservoir delivered by New Mexico, the gain in storage at Elephant Butte is higher. But the gain is less than the full 100,000 acre-feet reduction in flows leaving the reservoir. The gain in storage is less than 100,000 because with the now higher volume of water at the reservoir, evaporation is also slightly higher. And under the Compact, New Mexico will deliver more water into Elephant Butte to avoid being out of compliance.

What all this means is that policies taken by Rio Grande Project water users that reduce releases from Elephant Butte also increase evaporation at Elephant Butte slightly, and this added evaporation must be made up by increased inflows to the reservoir delivered by New Mexico. Similarly, when project water users enact policies that increase releases from Elephant Butte, the reservoir falls in volume, evaporation falls slightly, and New Mexico needs to deliver less water into the reservoir.

Albuquerque area M&I users receive slightly negative benefits ($18,000 per year) from the proposed carryover storage program because they too deliver slightly more surface water to Texas. The model is set up to allocate shortages among users by minimizing total economic losses from drought, while being consistent with the Rio Grande Compact. Since agriculture produces fewer economic benefits per acre-foot of water used than M&I uses, economic losses from shortages are minimized by taking more water from agriculture than from M&I. And when New Mexico delivers extra water into Elephant Butte to pay for added evaporation under the carryover storage proposal, the least costly way to deliver the water from the reservoir is to take most of the water from agriculture and less from M&I. [107]

Elephant Butte Irrigation District agriculture loses about $35,000 per year from the carryover storage program. Over the 44-year time horizon, EBID diverts on average 2,050 less acre-feet of surface water per year under the carryover storage program. This reduced water diversion produces an economic loss of water in EBID agriculture of about $17 per reduced acre-foot diverted ($35,000/2,050) due to the program.

[107] In fact, MRGCD arguably has more senior water rights than Albuquerque M&I, so some or all of the added Compact required deliveries to Texas may come from Albuquerque.

In Texas, El Paso area M&I use incurs a loss due to the program of about $425,000 per year, resulting from reduced reservoir releases and an increased cost of substituting more groundwater for less surface water. However, since this result depends strongly on the assumptions of the relative cost of pumping versus surface water delivery, it is difficult to assign much precision to this damage estimate.

Similarly, El Paso agriculture incurs a small loss of $8,000 per year under the carryover storage program for the same reasons that EBID loses. There is an annual average of 320 fewer acre-feet of surface water available for agriculture (205,700 compared to 205,380), with low-valued surface water used less in wet years and high-valued surface water used more in wet years. The $8,000 gain to El Paso area agriculture of the carryover storage program is valued at $19 per acre-foot of reduced water ($8,000/0.42).

Increase Irrigation Efficiency in Middle Rio Grande Conservancy District

The next institutional adjustment considered is increased irrigation efficiency in the Middle Rio Grande Conservancy District. This could occur from better irrigation scheduling, more efficient technology, gated pipes, or installation of sprinkler systems. Any of these measures would reduce the river diversion required to deliver a given quantity of water to crops.

Under the current Law of the River for MRGCD, the return proportion is taken to be 0.557,[108] which means that 55.7 percent of its diversions in that year from the river return to the river in the same year. The seepage proportion is taken to be 0.19, in which 19.0 percent of water diverted percolates into deep groundwater in the same year. A reduction of the seepage proportion reduces the proportion of

[108]The model is designed to permit interaction between surface and groundwater. Each region is defined to have a known proportion of both return flow and seepage. The return flow proportion is the proportion of surface water diversion that returns to the river in the same period. The seepage proportion is the proportion of the diversion that percolates into deep groundwater in the same period. Percolation in the current period together with groundwater pumping determines net seepage for the region. Net seepage determines the lagged response of the river to pumping.

diverted water that returns to the river in the same period. Numerically, one minus the sum of these two coefficients is the proportion of diverted water that returns to the river.

The institution of increased irrigation efficiency was defined to reduce the base return proportion from 55.7 percent to 45.7 percent of MRGCD's diversion. The seepage proportion was held constant. This institution would maintain constant crop water consumption (evapotranspiration) and constant crop yields, while reducing river diversions required to maintain that constant crop water use.

The net effect on the river of the increased irrigation efficiency proposal is to increase river flows but only slightly, because of two virtually offsetting effects. They are the reduced diversion and a reduced return flow percentage on the water that is diverted.

Water Use Patterns

Table 4-9 shows water use patterns throughout the system, under the increased irrigation efficiency management institution for coping with drought. It also shows the pre- and post-irrigation efficiency return flow percentages for MRGCD.

Over this future period, Colorado agriculture diverts the same 788,000 acre-feet per year of total water, of which about 616,000 comes from surface water and the remaining 172,000 from groundwater pumping. Thus, increased irrigation efficiency at MRGCD in New Mexico has no effect on Colorado delivery requirements and therefore has no impact on water use in Colorado.

In New Mexico above Elephant Butte Reservoir, increasing MRGCD irrigation efficiency by 10% has a considerable effect on reducing river diversions both above and below Albuquerque. Recall that under the current Law of the River, MRGCD diverts 471,000 acre-feet per year on average above and 235,500 acre-feet below Albuquerque (Table 4-5). However, under the increased irrigation efficiency plan, MRGCD diverts 336,500 acre-feet above and 168,250 acre-feet below Albuquerque. Most of those reductions in diversions are not reductions in river depletions, since much of the diversions under the Law of the River by MRGCD return to the river through seepage. Reductions in diversions are not necessarily reductions in depletions to the river. In fact, estimates produced by our model show that average annual inflows to Elephant Butte Reservoir under Law of the River are about 669,410 acre-feet per year. Under the increased irrigation efficiency program at MRGCD, inflows increase slightly to 688,407 acre-feet per year, so reduced river depletions due to the program are only 18,996 acre-feet per year. This reduced depletion puts a long-run average of 18,996 more acre-feet per year into Elephant Butte Reservoir.

A comparison of tables 4-7 and 4-11 shows that total Albuquerque M&I water use is unaffected by the irrigation efficiency program, diverting 68,280 acre-feet of surface water with and without the program, and 153,330 acre-feet of pumping with and without the program. Municipal and Industrial is a higher economic valued use of water at the margin, than agriculture. Since the model is programmed to seek the least cost method to deliver a given amount of water consistent with the Rio Grande Compact, reduced depletions by MRGCD agriculture causing increased deliveries to Elephant Butte Reservoir are produced by reduced diversions by MRGCD agriculture.

The above-mentioned 18,996 acre-foot per year increase into project storage permits Rio Grande Project water use by EBID agriculture to increase on average very slightly from 428,010 to 428,160 acre-feet per year. El Paso area M&I surface water use increases slightly from 120,180 to 120,220 acre-feet per year, while El Paso area agriculture surface water use increases from 205,700 to 205,770 acre-feet per year on average.

Although not shown in Table 4-9, flows at the Elephant Butte gage show a very small increase from an average of 642,250 to 642,500 acre-feet per year. Maximum project releases past this gage to project users are unchanged at 790,000 both under Law of the River and under increased irrigation efficiency. However, releases past this gage are increased slightly in drought years, by about 250 acre-feet in drought years when larger project releases are not possible.

Table 4-9. Long-Run Average Annual Water Use Patterns under Drought Mitigation by State, Location, and User (1000s of acre-feet)

Alternative Institution: **Increase Irrigation Efficiency at Middle Rio Grande Conservancy District by 20%**

Drought Scenario: **1942-1985 Historical Inflows (1.40 million acre-feet per year)**

	Colorado	**New Mexico**				**Texas**	
	San Luis Valley Agr	Middle Rio Grande Ag above Albuq	Albuq M&I	Middle Rio Grande Ag below Albuq	Eleph Butte Ag	El Paso M&I	El Paso Ag
Average annual total water use (surface diversions + pumping)	787.85	336.50	221.61	168.25	562.07	213.54	205.77
Average annual surface water use (diversion)	616.27	336.50	68.28	168.25	428.16	120.22	205.77
Average annual groundwater use (pumping)	171.58	0.00	153.33	0.00	133.91	93.32	0.00
Elephant Butte Volume	478.70						
Average total water use by state (surface diversions + pumping)	787.85	1,288.43				419.31	
Average surface water use, totaled by state (diversion)	616.27	1,001.19				325.99	
Average groundwater use, totaled by state (pumping)	171.58	287.24				93.32	
Percent MRGCD irrigation diversion returned to river in same year, **baseline** efficiency	56						
Percent MRGCD irrigation diversion returned to river in same year, **increased** efficiency	46						

Economic Benefits

Increased irrigation efficiency has only a small impact on mitigating drought damages. The impact on drought damages mitigated is small because the impact on reducing depletions to the river below MRGCD is small -- reduced diversions of 174,150 acre-feet reduce depletions by only 1,340 feet since such a large percent of the diversions reduced are also a large reduction in return flows to the river.

Like the institution of increased storage at Elephant Butte, Colorado agriculture in the San Luis Valley gains zero drought mitigation benefit under increased downstream irrigation efficiency. Under the Rio Grande Compact, Colorado's delivery obligations at the Lobatos gage at the Colorado-New Mexico border, in drought (non-spill) years is unaffected by downstream action in New Mexico.

Table 4-10 shows that drought damage mitigation for MRGCD, through increased irrigation efficiency is zero. This zero impact measure is based on the assumption that MRGCD farmers experience no change in crop yield, but that total water applied to crops is unchanged. Any of these technologies for conserving on river water delivered to crops would come at a cost to the irrigators.

Over the 44-year period of analysis, average flows at the Elephant Butte gage increase from 642,250 to 642,500 acre-feet per year, for a slight gain in agricultural benefits to EBID, measured as drought damage reductions. Table 4.8 shows these damage reductions average a modest $7,000 per year, which permit a slight increase in crop production from economically marginal crops.

Table 4-10 shows the economic effect of the small addition of water to Rio Grande Project deliveries. This added water is allocated in the amount of 43 percent to Texas and 57 percent to New Mexico lands. Within Texas, the water allocation between El Paso area M&I and El Paso agriculture occurs to maximize the total economic gains across the two sectors. That water allocation produces added benefits (drought damages mitigated) of about $11,000 per year to area M&I, with a much smaller increase in El Paso area agriculture of $4,000 per year.

Table 4-10. Long-Run Average Annual Drought Damage Mitigation from Alternative Institution, by State, Location, and User ($1000s)

Alternative Institution: **Increase Irrigation Efficiency at Middle Rio Grande Conservancy District by 20%**

Drought Scenario: **1942-1985 Historical Inflows (1.40 million acre-feet per year)**

	Colorado	**New Mexico**				**Texas**	
	San Luis Valley Ag	Middle Rio Grande Ag above Albuq	Albuq M&I	Middle Rio Grande Ag below Albuq	Eleph Butte Ag	El Paso M&I	El Paso Ag
	($1000s per year)						
Average annual economic drought damage mitigated	0	0[109]	0	0	7	11	4
Average annual recreation drought damage mitigation, summed over 5 Basin reservoirs: Heron, El Vado, Abiquiu, Cochiti, Elephant Butte							3
Average annual economic drought damage mitigation totaled by state	0				7		15

[109]Assumes no change in water applied to crops and no reduction in yields, but a smaller diversion from the river. In fact, the cost of the water savings technology, such as sprinklers, gated pipes, irrigation scheduling, is an added but unknown cost, which makes drought damage mitigation negative.

Build Reservoir Storage in Northern New Mexico

One widely discussed option throughout the west for saving water is to build more reservoir storage in high mountain areas, where evaporation is lower. For this study area, increased storage in southern Colorado or northern New Mexico would reduce evaporation compared to storage in hotter, lower desert areas. Evaporation in the low-desert areas of New Mexico consumes large amounts of water. For example, Elephant Butte Reservoir loses nearly 10 feet to evaporation, or nearly 300,000 acre-feet per year when the reservoir is near its capacity of about 30,000 surface acres. To implement this institutional option, we modified the model to build 100,000 added acre-feet of reservoir storage above Cochiti Reservoir in northern New Mexico. Despite the added storage, we required the river system to be operated consistent with the Rio Grande Compact.[110] The Rio Grande Compact permits New Mexico to build added storage as long as deliveries to Texas are maintained. There are two potential advantages to Mexico of building added storage: (1) New Mexico need not overdeliver to Texas in wet years when high flows at Otowi are beyond its maximum capacity to beneficially use water; (2) total evaporation inside New Mexico can be reduced, thereby making more water available for use inside the state. In fact, both of these benefits are borne out as shown below.

Water Use Patterns

The overall impact of building 100,000 acre-feet of added storage in northern New Mexico is to reduce overdeliveries to Texas in wet years, increase agricultural water use in New Mexico above Elephant Butte Reservoir, reduce use by agriculture below Elephant Butte, increase surface water use by El Paso area M&I use, and increase reservoir-based recreation benefits (Table 4-11).

[110]For example, this scenario does not consider reallocating Rio Grande Project storage at Elephant Butte and Caballo reservoirs upstream in any way.

Table 4-11. Long-Run Average Annual Water Use Patterns under Drought Mitigation by State, Location, and User (1000s of acre-feet)

Alternative Institution: **Build 100,000 Acre-Foot Reservoir on Rio Grande Mainstem above Cochiti Reservoir in Northern NM**

Drought Scenario: **1942-1985 Historical Inflows (1.40 million acre-feet per year)**

	Colorado	**New Mexico**				**Texas**	
	San Luis Valley Ag	Middle Rio Grande Ag above Albuq	Albuq M&I	Middle Rio Grande Ag below Albuq	Eleph Butte Ag	El Paso M&I	El Paso Ag
Average annual total water use (surface diversions + pumping)	787.85	480.74	221.60	240.37	562.10	213.66	205.32
Average annual surface water use (diversion)	616.27	480.74	70.55	240.37	427.45	120.13	205.32
Average annual groundwater use (pumping)	171.58	0.00	151.05	0.00	134.65	93.53	0.00
Elephant Butte Volume	444.82						
Cochiti Volume + New Reservoir Volume	116.01						
Average total water use by state (surface diversions + pumping)	787.85	1,504.81				418.98	
Average surface water use, total by state (diversion)	616.27	1,219.11				325.45	
Average groundwater use, totaled by state (pumping)	171.58	285.70				93.53	

Reduced overdeliveries to Texas in wet years occur through reduced average inflow to Elephant Butte at San Marcial from about 704,591 to 694,522 acre-feet per year (not in table). MRGCD agriculture water use increases, on average to 489,740 acre-feet above Albuquerque and 240,370 acre-feet below Albuquerque. Under the current Law of the River MRGCD's average use would have been 471,000 above and 235,000 below Albuquerque. The composition of Albuquerque M&I water use is affected only slightly by the reservoir construction, in which surface water uses increase from 68,280 to 70,550 acre-feet per year, thus prolonging the life of Albuquerque's aquifer.

EBID's long-run average agricultural use falls to 427,450 surface water from 428,101 under the Law of the River, while El Paso area agriculture similarly falls to 205,320 from 205,700. El Paso M&I use also falls very slightly from 120,180 acre-feet of surface water to 120,130.

Recreation benefits expand under the added storage. This added benefit occurs because the gain in reservoir volume in northern New Mexico is about 63,010 acre-feet compared to 53,000 acre-feet average storage at Cochiti under Law of the River, while Elephant Butte storage falls from about 685,550 acre-feet on average to about 444,820 acre-feet, for a net basin-wide loss of about 126,720.

Economic Benefits

Table 4-12 shows that drought damage mitigation overall for New Mexico is $134,000 per year with Texas gaining $685,000 per year. Colorado is unaffected. Reservoir recreation benefits gain $158,000 in drought damage mitigation because the recreational value of added storage in northern New Mexico is larger than the recreational value of lost storage at Elephant Butte.

In New Mexico, MRGCD agriculture receives $99,000 net gain per year in farm income above Albuquerque and $31,000 per year gain in farm income below Albuquerque. The major cause of this increased benefit produced by building this added storage is to reduce New Mexico's overdeliveries in wet years to Texas at Elephant Butte Reservoir. The largest overdeliveries occur in high-flow years, and are most pronounced when Otowi flows exceed 1.5 million acre-feet per year. These wet year overdeliveries increase storage volume at Elephant Butte, increasing the basis for evaporation in future years. The increased delivery requirements by New Mexico in those years reduces water used by New Mexico agriculture. With the added storage built above Cochiti, average deliveries at San Marcial are 694,522 acre-feet, still consistent with New Mexico's Rio Grande Compact delivery requirements to Texas.

Below Elephant Butte, Rio Grande Project releases are reduced slightly from a long-run average of 642,250 to 640,068 acre-feet per year, because of the reduced overdeliveries to Texas described above. Drought damage mitigation accruing to EBID agriculture is a small negative $19,000 per year on average, with a similar negative mitigation for El Paso area agriculture of minus $5,000 per year, both due to reduced overdeliveries by New Mexico to Texas. El Paso M&I experiences positive drought damage mitigation to the amount of $690,000 per year.

Table 4-12. Long-Run Average Annual Drought Damage Mitigation from Alternative Institution, by State, Location, and User ($1000s)

Alternative Institution: **<u>Build 100,000 Acre-foot Reservoir on Rio Grande Mainstem above Cochiti Reservoir in Northern NM</u>**

Drought Scenario: **<u>1942-1985 Historical Inflows (1.40 million acre-feet per year)</u>**

	Colorado	**New Mexico**				**Texas**	
	San Luis Valley Ag	Middle Rio Grande Ag above Albuq	Albuq M&I	Middle Rio Grande Ag below Albuq	Eleph Butte Ag	El Paso M&I	El Paso Ag
	($1000s per year)						
Average annual economic <u>drought damage mitigated</u>	0	99	23	31	(19)	690	(5)
Average annual recreation <u>drought damage mitigation</u>, summed over 5 Basin reservoirs: Heron, El Vado, Abiquiu, Cochiti, Elephant Butte							158
Average annual economic <u>drought damage mitigation</u> totaled by state	0				134		685

CHAPTER 5 -- CONCLUSIONS

The objective of this work was to test the hypothesis that institutional innovations for interstate coordination of surface water withdrawal and reservoir operations could promote more economically efficient spatial and temporal water use patterns as measures for coping with severe and sustained drought. We selected the following institutional innovations for evaluation: Law of the River, increased irrigation efficiency, carryover storage, and construction of new reservoir storage.

A three-state research team of economists, hydrologists and a lawyer was formed to perform the analysis. We developed a linked hydrologic-economic model that extends the basin optimization procedures developed by Vaux and Howitt for California (1984) and by Booker and Young for the Colorado River (1994). The modeling effort is limited to the Upper Rio Grande Basin, from Colorado through New Mexico to Fort Quitman, Texas, downstream of El Paso. Modeling of the lower basin, including water uses and inflows from Mexico, is not yet attempted. The general approach reflects the stochastic supplies and uncertain demands (from economic growth and endangered species policies) for water and river and reservoir management rules. Water supplies, which include all major tributaries and interbasin transfers, and hydrologically connected groundwater, are represented in an annual time-step over a forty-four year planning horizon. The baseline drought scenario used was the 1942-1985 period, which contained the severe drought of the 1950s and the very low-flow period of the late 1970s. Agricultural water uses, the major source of demands, are identified, including the San Luis Valley of Colorado, Middle Rio Grande Conservancy District of New Mexico, Elephant Butte Irrigation District of New Mexico, and El Paso Irrigation District of west Texas. Municipal and Industrial (M&I) demands for the Albuquerque and El Paso metropolitan areas are also represented. The optimization procedure, which minimizes economic damages subject to hydrologic, engineering and institutional constraints, is solved with GAMS-Minos optimization software. The overriding institutional constraint is the Rio Grande Compact, an interstate compact signed in 1938 by Colorado, New Mexico, and Texas.

Intrastate and interstate innovations in allocative institutions are tested against the baseline "Law of the River." Each institutional innovation was tested for robustness and economic efficiency under the 1942-1985 drought scenario. Results are presented as economic and hydrologic impacts of drought by state, economic sector, and institutional alternative for coping with drought.

This project has developed a model that responds to relative scarcity as those scarcities are reflected through compact deliveries and other institutions. While the model is not designed to generate the precise detail on how all of the institutions would respond and with what economic consequences, it is an important first step in bringing objective science to bear on important water policy decisions.

There is no issue more complex and more important to the people of the Upper Rio Grande Basin than understanding the hydraulic connection between the groundwater pumping in the region and the flows of the Rio Grande. Computer model results are not facts; they predict outcomes which may or may not ultimately be consistent with what occurs in the future.

In designing a drought model that predicts outcomes in times of drought, someone must make a choice. Or, at a minimum run a set of scenarios. Of course, too wide a range of scenarios is no prediction at all. Thus, we reluctantly conclude that hydrologic modeling is no less "certain" than economic modeling and is only as valuable as the accuracy of the assumptions that go into the model.

Improved modeling work in the future could support water policy decisions. For a model to be used with confidence by policymakers, it should contain:

- A mass surface water balance for the region studied so that when various rates of snow pack run off and flood events occur at the upper reaches and should reach the accounting point at El Paso.
- A set of hydrologic assumptions regarding the impacts of groundwater pumping on the system based upon the best data available using estimates that reflect good water conservation policy.
- A set of hydrologic assumptions regarding return flows, evaporation losses, transpiration losses, seepage and all other losses to the system.

- A set of institutional entitlements under the Rio Grande Compact that permit or do not permit storage and withdrawal at key points in the river such that one is able to estimate rates of flow at various points in the river system.
- A set of the best estimates of environmental needs in the river for rates of flow throughout the system that most closely resemble the traditional hydrograph, since these amounts will be required in the future by environmental interests.
- A set of anticipated consumptive needs throughout the system broken down by user and coupled with calculations of return flows from each kind of user.

The model developed for this study has built in most of these factors, at least in a rudimentary way. Important future model improvements would focus on relations between streamflows and environmental benefits of various kinds. Endangered species requirements and human values and benefits associated with those requirements are important issues that are largely untouched by this study.

Tied to the above outcomes as to where the water goes in times of shortage and to whom, is the kind of economic analysis contained in this final report that ties economic outcomes to water scarcity. This needs to be supplemented in future work by an analysis of the impact on water quality at various reaches of the river. Despite the considerable need for more refinement that will always be present in this kind of large effort, the drought study performed under this grant, we believe, is a step in the right direction.

REFERENCES

Allee, D., L. Dworsky, and R. North (eds.). 1982. *Unified River Basin Management - Stage II.* Proceedings of a Symposium held Atlanta, Georgia, October 4-8, 1981. Minneapolis: American Water Resources Association.

Arnold, J.G., P.M. Allen, and G. Bernhardt. 1993. A Comprehensive Surface-Groundwater Flow Model. *Journal of Hydrology*. 142: 47-69.

Benjamin, J. R., C.A. Cornell. 1970. *Probability, Statistics, and Decision for Civil Engineers*. McGraw - Hill, pub, 684 pages.

Blomquist, W. and E. Ostrom. 1985. Institutional Capacity and the Resolution of a Common Dilemma. *Policy Studies Review*. 5(2):383-393.

Booker, J.F. and R.A. Young. 1994. Modeling Intrastate and Interstate Markets for Colorado River Water Resources. *Journal of Environmental Economics and Management* 26(1): 66-87.

Booker, J.F. and B. Colby. 1995. Competing Water Uses in the Southwestern United States: Valuing Drought Damages. *Water Resources Bulletin*, 31(5): 877-88.

Booker, J.F. 1995. Hydrologic and Economic Impacts of Drought under Alternative Policy Responses. *Water Resources Bulletin*, 31(5): 889-906.

Boyle, K.J., M.P. Welsh, R.C. Bishop, and R.M. Baumgartner. 1993. *Analyzing the effects of Glen Canyon Dam releases on Colorado River recreation using scenarios of unexpected flow conditions.* Paper presented at W-133 Western Regional Resource Economics Conference, Santa Fe, NM.

Brajer, V. and W.E. Martin. 1990. Water Rights Markets: Social and Legal Considerations: Resource's 'Community' Value, Legal Inconsistencies and Vague Definition and Assignment of Rights Color Issues. *Am. J. of Econ. and Soc.* 49(1): 35-43.

Bredehoeft, J.D. and R.A.Young, 1983. Conjunctive Use of Groundwater and Surface Water for Irrigated Agriculture: Risk Aversion. *Water Resource Research*. 19(5): 1111-1121.

Brooke, A., D. Kendrick, and A. Meeraus. 1988. *GAMS A User's Guide*. The Scientific Press, Redwood City, California.

Bryant, K.J., Mjelde, J.W. and R.D. Lacewell. 1993. An Intraseasonal Dynamic Optimization Model to Allocate Irrigation Water Between Crops. *American Journal of Agricultural Economics.* 75: 1021-1029.

Burness, H.S. and J.P. Quirk. 1979. Appropriative Water Rights and the Efficient Allocation of Resources. *Am. Econ. Rev.* 69(1): 25-37.

Campbell, G.S. 1974. A Simple Method for Determining Unsaturated Conductivity from Moisture Retention Data. *Soil Science.* 117(6): 311-314.

Cardon, G.E. 1990. *A Transient-State Model of Water and Solute Movement and Root Water Uptake for Multi-Seasonal Crop Production Simulation.* Unpublished Dissertation. Department of Soil Science, University of California, Riverside.

Ciborowski, P. and D. Abrahamson. 1987. Policy Responses to Climate Change: Opportunities and Constraints. In Meo, M. (ed.) 1987. Proceedings of the Symposium on Climate Change in the Southern United States: Future Impacts and Present Policy Issues. May 28-29, 1987; New Orleans, LA.

Cole, Richard A. and F.A. Ward. 1994. Optimum Fisheries Management Policy: Angler Opportunity versus Angler Benefit. *North American Journal of Fisheries Management.* 14(1): 22-33.

Cole, R.A., K. Green-Hammond, F.A. Ward, T. Ward and R.A. Deitner. 1990. User's Guide For RIOFISH: a comprehensive sportfishery management model. Technical Publication, New Mexico Water Resources Research Institute.

Cole, R., F. Ward, T. Ward, R. Deitner, J. Fiore, S. Bolin, and K. Green-Hammond. 1987. *A model for optimization of socioeconomic fishery values on the Rio Grande in New Mexico. New Mexico Water Resources Research Report No. 223, New Mexico Water Resource Research Institute, New Mexico State University, Las Cruces, NM.*

Cole, R.A., T.J. Ward, F.A. Ward, and R.A. Deitner. 1986. A simulation model for managing fisheries in reservoirs on the Rio Grande of New Mexico. In *Reservoir Fisheries Management Strategies for the 80's.* G. E. Hall and M.J. Van Den Avyle (eds). American Fisheries Society, Bethesda, MD, pp. 18-27.

Cook, M, and P. Balleau. 1998. *Groundwater Modeling in the Lower Rio Grande.* Balleau Groundwater, Inc.

Cordell, H.K. and J.C. Bergstrom. 1993. Comparison of recreation use values among alternative reservoir water level management scenarios. *Water Resource Research.* 29(2):247-258.

Creel, M. and J. Loomis. 1992. Recreation value of water to wetlands in the San Joaquin Valley: linked multinomial logit and count trip frequency models. *Water Resource Research.* 28(10): 2597-2606.

Dalsted, N.L., P.H. Gutierrez, D. Nitchie, R.L. Sharp, and J. Tranel. 1996. *Selected 1995 Crop Enterprise Budgets for Colorado, XCM-82.* Colorado State University Cooperative Extension. Fort Collins, CO, 1996.

Daubert, J.T. and R.A. Young. 1981. Recreational Demands in Maintaining Instream Flows. American Journal of Agricultural Economics. 63(2) :p. 667-671.

Doesken, N.J. and T.B. McKee. 1989. The Incredible Climate of the San Luis Valley. In *Water in the Valley: A 1989 Perspective on Water Supplies, Issues and Solutions in the San Luis Valley, Colorado.* Eighth Annual Field Trip, August 19-20, 1989. Colorado Ground-Water Association.

Dworsky, L.B. and G.R. Francis. 1973. *A Proposal for Improving the Management of the Great Lakes of the United States and Canada.* A Report by the Canada-United States University Seminar, 1971-1972. Cornell University: Ithaca, New York.

Easterling, W. 1988. *Coping with drought hazard: Recent progress and research priorities.* Prepared for International Workshop on Natural Disasters in European-Mediterranean Countries. Purugia, Italy. June 26-July 1, 1988.

Emery, P.A. 1970. *Electric Analog Model Evaluation of a Water-Salvage Plan, San Luis Valley, South-Central Colorado.* Circular 14, Groundwater Series. United States Geological Survey.

Foster, H.W. Jr. and B.R. Beattie. 1979. Urban Residential Demand for Water in the United States. *Land Economics.* 55: 43-58.

Fredericks, J.W., J.W. Labadie, and J.M. Altenhofen. 1998. Decision Support System for Conjunctive Stream-Aquifer Management. *Journal of Water Resources Planning and Management*,124(2):69-78.

Getches, David H. 1989. *Legal and Institutional Responses: Water Allocation During Drought in Arizona and Southern California* (Unpublished).

Ghosh, K.G. 1977. Note: Determination of Unsaturated Hydraulic Conductivity from Moisture Retention Function. *Soil Science.* 124(2): 122-124.

Gibbons, D. 1986. *The Economic Value of Water*. Resources for the Future: Washington, D.C.

Gleick, P.H. 1988. The Effects of Future Climatic Changes on International Water Resources: The Colorado River, The United States and Mexico. *Policy Sciences.*

Gray, S.L. and R.A. Young. 1983. Valuation of Water on Wildlands. In G.K. Peterson and A. Randall (ed.). *Wildland Resources Valuation*. Westview Press: Boulder.

Griffin, R.C. 1990. Valuing Urban Water Aquisitions. *Water Resources Bulletin.* 26 (1990): 219-225.

Griffin, R.C. and C. Chang. 1991. Seasonality in Community Water Demand. *Western Journal of Agricultural Economics*. 16(2): 207-217.

Haan, C.T. 1977. *Statistical Methods in Hydrology.* Iowa State University Press, Ames, Iowa.

Hansen, L.T. and A.J. Hallam. 1990. Single stage and two-stage decision modeling of the recreational demand for water. *J. Agri. Econ. Res*. 42(1):16-26.

Henderson, J.L. and W.B. Lord. 1995. A Gaming Evaluation of Colorado River Drought Management Institutional Options. *Water Resources Bulletin*. 31(5): 907-24.

Hill, R.A. 1974. Development of the Rio Grande Compact of 1938. 14 *Natural Resources Journal* 163.

Howe, C.W. 1983. Impact of Price on Residential Water Demand: New Insights. *Water Resources Research*. 18:713-716.

Howe, C.W. and H.C. Cochrane. 1992. *Guidelines for the Uniform Definition, Identification and Measurement of Economic Damages from Natural Hazard Events.* Special Publication 28, Institute of Behavioral Science, University of Colorado, Boulder, CO.

Hutson, J.C. and A. Cass. 1987. A Retention Function for Use in Soil-Water Simulation Models. *J. Soil Science.* 38:105-113.

Ingram, H., 1986. Replacing Confusion with Equity: Alternatives for Water Policy in the Colorado River. In G.D. Weatherford and F.L. Brown, eds. *New Courses for the Colorado River: Major Issues of the Next Century*. The University of New Mexico Press: Albuquerque.

Johnson, D.M. and R.G. Walsh. 1987. *Economic Benefits and Costs of the Fish Stocking Program at Blue Mesa Reservoir, Colorado.* Colorado Water Resources Research Institute Technical Report No. 49, Colorado State University, Fort Collins, Colorado.

Jones, C.V. and J.R. Morris. 1984. Instrumental Price Estimates and Residential Water Demand. *Water Resources Research*. 20: 197-202.

Kelso, M.M., W.E. Martin and L. Mack. 1973. *Water Supplies and Economic Growth in an Arid Environment: An Arizona Case Study*. University of Arizona Press: Tucson, Arizona.

Kenney, D. 1995. Institutional Options for the Colorado River. *Water Resources Bulletin*. 31(5): 803-14.

Kernodle, J.M., D.P. McAda, and C.R. Thorn. 1995. Simulation of ground-water flow in the Albuquerque Basin, central New Mexico. 1901-1994. with projections to 2020: U.S. Geological Survey *Water-Resources Investigations Report*. 94-4251. 114 p.

Kulshreshtha, S. and D. Tewari. 1991. Value of Water in Irrigated Crop Production Using Derived Demand Functions: A Case Study of South Saskatchewan River Irrigation District. *Water Resources Bulletin. 27(2): 227-236.*

Lansford, N.H. and L.L. Jones. 1995. Recreational and Aesthetic Values of Water Using Hedonic Price Analysis. *Journal of Agricultural and Resource Economics*. 20(2): pp 341-55.

Lansford, R. 1995. *Sources and Uses of Irrigation Water in New Mexico.* New Mexico State University Agricultural Experiment Station. Selected Years 1970-1995.

Lee, D.J., R.E. Howitt, and M.A. Marino. 1993. A Stochastic Model of River Water Quality: Application to Salinity in the Colorado River. *Water Resources Research* 29(12):3917-3924.

Libbin, James D. 1995. *Cost and Return Budgets for Selected New Mexico Crop Enterprises.* New Mexico State University Agricultural Experiment Station.

Livingston, M.L. 1985. Treating Water Institutions as Endogenous Variables: Demonstration of a Conceptual Model. *Water Resources Bulletin.* 21(1):23-29.

Lord, W.B. 1984. Institutions and Technology: Keys to Better Water Management. *Water Resources Bulletin.* 20(5):651-656.

Martin. W.E., H.M. Ingram, N.K. Laney and A.H. Griffin. 1984. *Saving Water in a Desert City*. Washington, DC, Resources for the Future, Inc.

McGuckin, J.T., N. Gollehon, and S. Ghosh. 1992. Water Conservation in Irrigated Agriculture: A Stochastic Production Frontier Model. *Water Resources Research*. 28(2):305-12.

McKean, J.R., R.G. Taylor, and R.A. Young. 1996. *Estimating Residential Water Demand in Colorado Under Alternate Price Specifications* (Working paper). Colorado State University Department of Agricultural and Resource Economics.

Meko, D., C.W. Stockton, and W.R. Boggess. 1995. The Tree-Ring Record of Severe Sustained Drought. *Water Resources Bulletin*. 31(5): 789-802.

Minton, G.R., R. Williams, and T. Murdock. 1980. Institutional Analysis Criteria for Water Supply Planning. *Water Resources Bulletin*. 16(3): 486-493.

Moore, M.R. and D.H. Negri. 1992. A Multicrop Production Model of Irrigated Agriculture, Applied to Water Allocation Policy of the Bureau of Reclamation. *Journal of Agricultural and Resource Economics.* 17(1): 29-43.

Moore, M.R., N.R. Gollehon, and M.B. Carey. 1994. Multicrop Production Decisions in Western Irrigated Agriculture: The Role of Water Price. *American Journal of Agricultural Economics.* 76 (November 1994): 859-874.

Morton, D. 1988. Librarian, Natural Hazards Research and Applications Information Center, Boulder. Personal Communication with P. Hathaway. October.

Nieswiadomy, M. 1985. The Demand for Irrigation Water in the High Plains of Texas. 1957-80. *American Journal of Agricultural Economics.* 67(3): 619-626

Nieswiadomy, M.L. 1992. Estimating Urban Residential Water Demand: Effects of Price Structure, Conservation, and Education. *Water Resources Research*. 28(3): 609-615.

Oamek, G.E. 1990. *Economic and Environmental Impacts of Interstate Water Transfers in the Colorado River Basin.* Monograph 90-M3, Center for Agricultural and Rural Development, Iowa State University.

Ogg, C.W. and N.R. Gollehon. 1989. Western Irrigation Response to Pumping Costs: A Water Demand Analysis Using Climatic Regions. *Water Resource Research.* 25(5): 767-773.

Opaluch, J.J. 1982. Urban Residential Demand for Water in the United States: Further Discussion. *Land Economics.* 58: 225-27.

Ostrom, V. and E. Ostrom. 1972. Legal and Political Conditions of Water Resource Development. *Land Economics.* 48(1): 1-14.

Ozuna, T. Jr., L.L. Jones, and O. Capps Jr. 1993. Functional Form and Welfare Measures in Truncated Recreation Demand Models. *American Journal of Agricultural Economics*. 75(4):1030-1035.

Ozuna, T. Jr. and I.A. Gomez. 1994. Estimating a System of Recreation Demand Functions Using a Seemingly Unrelated Poisson Regression Approach. *Review of Economics and Statistics*. 76(2):356-360. (Several sites in Texas).

Rawls, W.J., L.R. Ahuja, and D.L. Brakensiek. 1992. Estimating Soil Hydraulic Properties from Soils Data. In *Indirect Methods for Estimating the Hydraulic Properties of Unsaturated Soils.* Eds. Van Genuchten, M. Th., F.J. Leij, and L.J. Lund. University of California. Riverside, California. pp. 329-340.

Riebsame, W.E. 1987. Human Response to Climate Change: The Role of Decision-maker Perception. Meo, M. (ed.). 1987. In *Proceedings of the Symposium on Climate Change in the Southern United States: Future Impacts and Present Policy Issues*. May 28-29, 1987; New Orleans, LA.

Rosenthal, W.D., R. Srinivasan, J.G. Arnold. 1995. Alternative river management using a linked GIS-hydrology model. *Transactions of the ASAE.* 38(3):783-790.

Sanders, L.D., R.G. Walsh, and J.B. Loomis. 1990. Toward Empirical of Total Value of Protecting Rivers. *Water Resources Research.* 26(7): 1345-1357.

Sperow, M. 1998. *Three essays addressing production economics and irrigation: Managing for drought and pests transported in irrigation water.* Ph.D. dissertation, Department of Agricultural and Resource Economics, Colorado State University.

Srinivasan, R., and B.A. Engel. 1994. A spatial decision support system for assessing agricultural nonpoint source pollution. *Water Resources Bulletin*. AWRA, 30(3): 441-452.

Srinivasan, R., and J.G. Arnold. 1994. Integration of a Basin-Scale Water Quality Model with GIS. *Water Resources Bulletin*. AWRA, 30(3): 453-462.

Tarboton, D.G. 1995. Hydrologic Scenarios for Severe Sustained Drought in the Southwestern United States. *Water Resources Bulletin*. 31(5): 803-14.

Taylor, R.G. and R.A. Young. 1995. Rural-to-Urban Water Transfers: Measuring Direct Foregone Benefits of Irrigation Water under Uncertain Supplies. *Journal of Agricultural and Resource Economics*. 20(2): 247-62.

Tiedeman, C.R., J.M. Kernodle, and D.P. McAda. 1998. Application of nonlinear-regression methods to a ground-water flow model of the Albuquerque Basin, New Mexico: U.S. Geological Survey. *Water-Resources Investigations Report 98-4172.* 90 p.

Thomas, J.F., and G.J. Syme. 1988. Estimating Residential Price Elasticity of Demand for Water: A Contingent Valuation Approach. *Water Resources Research*. 24(11): 1847-1857.

Thomas, H.E. 1963. *Effects of Drought in the Rio Grande Basin: Drought in the Southwest 1942-56.* U.S. Geological Survey Professional Paper 372-D. U.S. Government Printing Office, Washington, D.C.

U.S.D.A. 1988. *Colorado Irrigation Guide.* U.S. Department of Agriculture, Soil Conservation Service. Denver, Colorado.

Vaux, H.J., and R.E. Howitt. 1984. Managing Water Scarcity: An Evaluation of Interregional Transfers. *Water Resources Research.* 20: 785-792.

Vandiver, Steve. 2001. Engineer Adviser to Colorado Rio Grande Compact Commissioner, personal conversation, January 9.

Ward, F.A., R.A. Cole, R.A. Deitner, and K.A. Green-Hammond. 1997. Limiting Environmental Program Contradictions: A Demand Systems Application to Fishery Management. *American Journal of Agricultural Economics.* 79 (August): 803-813.

Ward, F.A. B.A. Roach, J.B. Loomis, R.C. Ready, and J. Henderson. March 1995. *Regional Recreation Demand Models for Large Reservoirs: Database Development, Model Estimation, and Management Applications*. Final report to U.S. Army Corps of Engineers.

Ward, F.A. and D. Beal. 2000. *Valuing Nature with Travel Cost Models: A Manual*. Edward Elgar, London, UK.

Ward, F.A. 1987. Economics of water allocation to instream uses in a fully appropriated river basin: evidence from a New Mexico wild river. *Water Resource Research.* 23(3):381-392.

Ward, F.A. 1989. Efficiently Managing Spatially Competing Water Uses: New Evidence from a Regional Recreation Demand Model. *Journal of Regional Science*. 29(2): 229-246.

Ward, F.A. 1987. Economics of Water Allocation to Instream Uses in a Fully Appropriated Basin: Evidence from a New Mexico Wild River. *Water Resources Research*. 23(3): 381-392.

Ward, F.A. and T.P. Lynch. 1996. Integrated River Basin Optimization: Modeling Economic and Hydrologic Interdependence. *Water Resources Bulletin*. 32(6): 1127-1138.

Ward, F.A., B.A. Roach, and J.E. Henderson. 1996. The Economic Value of Water in Recreation: Evidence from the California Drought. *Water Resources Research*. 32(4):1075-1081.

Ward, F.A. and T.P. Lynch. 1997. Is dominant use management compatible with basin-wide economic efficiency? *Water Resources Research*. 33 (5): pp. 1165-1176.

Ward, F.A., R.A. Cole, R. Deitner, and K.A. Green-Hammond. 1997. Limiting Environmental Program Contradictions: A Demand Systems Application to Fishery Management. *American Journal of Agricultural Economics*. 79(3): 803-813.

Wilhite, D.A. and M. Glantz. 1987. Understanding the Drought Phenomenon: the Role of Definitions. D.A. Wilhite and W.E. Easterling, eds. In *Planning for Drought: Toward a Reduction in Societal Vulnerability.* Boulder, CO, Westview Press, 1987. 11-27.

Woodward-Clyde-Sherard and Associates. 1967. *Geo-Hydrologic Study of the Closed Basin, San Luis Valley, Colorado.* Prepared for the Colorado Water Conservation Board, State of Colorado.

Wurbs, R.A. and W.B. Walls. 1989. Water Rights Modeling and Analysis. *J. of Water Resources Planning and Management.* 115(4): 416-430.

Yevjevich, V. 1967. *An objective approach to definitions and investigations of continental hydrologic droughts.* Hydrology papers, No. 23. Colorado State University, Fort Collins.

Young, R.A. and S.L. Gray. March 1972. *Economic Value of Water: Concepts and Empirical Estimates*. Final Report to the National Water Quality Commission, Contract NWC-70-280. Colorado State University.

Young, R.A. 1973. Price Elasticity of Demand for Municipal Water: A Case Study of Tucson, Arizona. *Water Resources Research*. Vol. 8.

Young, R. A., ed. 1995. *Severe, Sustained Drought: Managing the Colorado River System in Times of Water Shortage.* Powell Consortium Issue No. 1, Tucson, University of Arizona Water Resources Research Institute.

Young, R.A. and R.H. Haveman. 1985. Economics of Water Resources: A Survey. In *Handbook of Natural Resource and Energy Economics*. Volume I. pp. 465-521. Edited by Allen V. Kneese and James L. Sweeney. North-Holland, New York.

Young, R.A. and L. Gray. 1985. Input-Output Models, Economic Surplus and the Evolution of State or Regional Water Plans. *Water Resources Research*. Vol. 21.

Young, R.A. and A. Michelsen. 1993. Optioning Agricultural Water Rights for Urban Water Supplies During Drought. *American Journal of Agricultural Economics*. 75(4): 1010-1020.