Economic impact of alternative policy responses to prolonged and severe drought in the Rio Grande Basin

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[1] In the Rio Grande Basin, water is overallocated, demands are growing, and river flows and uses are vulnerable to drought and climate change. Currently, the basin is in the third year of severe drought; irrigation and municipal water diversions have been severely curtailed; extensive diversions threaten endangered species, and reservoir volumes are nearly depleted. A central challenge is development of policies that efficiently and equitably allocate the basin's water resources among competing uses across political and institutional jurisdictions. A basin-wide, nonlinear programming model optimizes resource allocations and water use levels for the upper part of the Rio Grande Basin to test whether institutional adjustments can reduce damages caused by drought. Compared to existing institutions, we find that future drought damages could be reduced by 20 and 33% per year through intracompact and interstate water markets, respectively, that would allow water transfers across water management jurisdictions. Results reveal economic tradeoffs among water uses, regions, and drought control strategies.

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1. Introduction

[2] In most of the western United States, existing water supplies are claimed and diverted largely for irrigation and growing municipal and industrial demands. Remaining flows are increasingly protected for in-stream flows and environmental purposes. Most easily accessible groundwater is developed or is depletable. Throughout the region, drought and climate change aggravate the increasing competition for water. With increasing demands, incidents of drought will have increasingly serious impacts [*Young*, 1995], and the choice of water allocation policies will become particularly critical.

[3] The United States federal government recently identified the Upper Rio Grande as among river basins having the highest potential for conflict and crisis, especially in drought conditions [*U.S. Department of Interior*, 2003]. The Rio Grande exemplifies the problems faced by many arid regions (e.g., Colorado, USA; Yellow, China; Jordan, Middle East; Murray-Darling, Australia; and Nile, Africa) in which water is overallocated, there are growing competing demands, and river flows and uses are vulnerable to drought and climate change. These factors have highlighted the interest by policymakers, scientists, and water managers to examine systematically water management alternatives.

[4] A central challenge is the development of policies that complement existing water management institutions and which allocate water resources efficiently and equitably during drought. This requires approaches that encompass hydrologic river basins, political and institutional boundaries, and which cover a range of economic impacts. In this work we focus on the impacts of transfers resulting from water markets as one approach to reducing the economic damages from drought. Market-based transfers have been suggested as one response to coping with scarce supplies and limited storage [e.g., *Vaux and Howitt*, 1984], particularly during drought.

[5] In previous research, integrated hydrologic-economic models at the basin scale have focused on the economic impacts of transfers under typical supply conditions [e.g., *Oamek*, 1990]. Other work developed extensions to managing water quality [*Lee et al.*, 1993] and incorporated additional nonconsumptive use values [*Booker and Young*, 1994]. Under drought conditions, the impacts of several market institutions were estimated by *Booker* [1995]. At the subbasin scale, integrated modeling of economic impacts of water transfers for protecting in-stream flows was devel-

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Figure 1. Map of study region. See color version of this figure at back of this issue.

oped by *Hamilton et al.* [1999] and by *Willis and Whittlesey* [1998]; impacts of water markets for protecting water quality were examined by *Weinberg et al.* [1993].

[6] Despite these circumstances facing the basin and the contributions of this previous work, little comprehensive analysis of drought and its impact in the basin has been conducted to date. With increasing demands on the basin's water resources, droughts will have growing economic and environmental impacts, and the choice of drought-coping policies will take on increasing importance to the region. This paper's objective is to take a first step toward comprehensive analysis of drought and its impact to the basin by comparing current institutions that govern the allocation and use of the basin's water during drought periods with alternative designs. This objective is accomplished through the development and application of a comprehensive basin-wide nonlinear programming model of the hydrology, economics, and institutions in the Rio Grande. The model is applied to evaluate the hydrologic and economic effectiveness of selected potential drought-coping policies.

[7] In this research we provide an example of mitigating economic impacts of drought through market-based water transfers in a region containing complex institutions and hydrology, the upper part of the Rio Grande Basin (see Figure 1). We extend previous work by developing an integrated hydrologic-economic model at the basin scale that incorporates ground and surface water interactions and tracks hydrologic and economic relationships over several time periods. We apply the model to estimate impacts of coping with drought through market-based water transfers.

[8] The remainder of the paper is organized as follows: First, the physical and institutional context of water use and allocation in the basin are summarized. Then, we analyze the current "law of the river" water allocations and develop baseline conditions from which to consider potential drought-coping institutions. Next, model results are presented in which a comparison is made of the law of the river and two drought-coping institutions that harness market forces. These two institutions are water trading within existing political boundaries and water trading across boundaries. Finally, we present our conclusions. Appendix A contains a detailed mathematical description of the basin model.

2. Physical and Institutional Context

[9] Known as the Rio Bravo in Mexico, the Rio Grande is the fifth longest river in North America. Originating in the southern Colorado Rocky Mountains, the Upper Rio Grande extends 600 miles (960 km) from its headwaters and flows through New Mexico to the border cities of El Paso, Texas, USA, and Ciudad Juárez, Chihuahua Mexico (see Figure 1). Downstream of El Paso, the river forms the international border between the United States and Mexico on its way to the Gulf of Mexico.

[10] Spring runoff from mountain snowpack in the north is the primary source of surface water for the basin. The southern area of the upper basin flows through the Chihuahuan desert where annual precipitation registers an average eight inches (about 20 cm), most of which comes as widely scattered summer monsoon thunderstorms [*Schmandt*, 2002]. Flows in the basin are highly variable from year to year and there have been prolonged periods of drought. Average annual surface supply produced by the headwater gauges is 1.57 million acre feet.

[11] The upper basin has been in drought conditions for the last seven years and has faced severe drought the last three years. Basin inflows for the previous two years were 11% and 10% of the 30-year average and were, respectively, the eighth and fifth lowest flows on record [*Michelsen and Cortez*, 2003]. In the fall of 2004, water storage in Elephant Butte, the largest reservoir in the basin, was only 5.6% of capacity. After an unprecedented 25-year period of full water supplies, in part made possible from carryover reservoir storage, water allocations for 2003 were reduced to just one third of full supply conditions.

[12] The upper basin supports a rapidly growing population of more than three million people [*Michelsen and Wood*, 2003; *Paso del Norte Water Task Force*, 2001], extensive irrigated agriculture, and fish and wildlife habitat in Colorado, New Mexico, Texas, and the Mexican state of Chihuahua. Some 80–90% of the water in the Rio Grande is used for irrigated agriculture. The main crops produced are forage, cotton, pecans and vegetables. Only a portion of the applied water is consumptively used, varying from a low of about 30% in central New Mexico agriculture to a high of about 70% in southern New Mexico and west Texas agriculture. The remainder is an important source for groundwater recharge, supply for riparian habitat and return flows to the river.

[13] While municipal and industrial (MI) water demands in the major basin have historically been met by groundwater, this pumping is not sustainable at current withdrawal

rates, let alone additional pumping for growth. El Paso is rapidly increasing its use of surface water; Albuquerque plans to begin withdrawing surface water; and the largest basin municipality, Ciudad Juárez is projected to deplete its fresh groundwater reserves in less than a decade and is in need of alternate supplies [*Paso del Norte Water Task Force*, 2001].

[14] Environmental demands continue to grow. The Rio Grande silvery minnow (*Hybognathus amarus*) was listed as an endangered species by the U.S. Fish and Wildlife Service in 1994. Despite continuing and lengthy litigation, minimum river flows have been mandated by the federal courts [e.g., *Parker*, 2002] and so far carried out by the federal agencies to sustain remaining minnow populations even in periods of drought. As a result, the federal government has temporarily acquired and reallocated water from existing uses to provide 50 cfs of instream flows (in which one cubic foot per second (cfs) = 0.028321 m^3/s) for the minnow in the San Acacia reach of the river near Socorro, New Mexico (see Figure 1).

[15] Water managers in the Rio Grande face a complex set of international, federal, state and local institutions regulating flows and water allocation. These include an international treaty between Mexico and the United States; a tristate compact involving Colorado, New Mexico and Texas; involvement of multiple federal agencies; state statutes; ongoing litigation and numerous water delivery contracts. Collectively, these rules are described as the law of the river.

[16] The 1938 Rio Grande Compact between Colorado, New Mexico and Texas, approved by the U.S. Congress, is the overriding mechanism for interstate water allocation under the law of the river in the upper basin. The compact guarantees that a stated percentage of changing river flow is allocated to each state, largely maintaining water allocations among the three states that existed prior to 1929. Central to the compact is a set of supply indices specifying the proportion of inflows from one state delivered to the downstream state. For example, Colorado may use varying percentages of its total runoff, from 40% at high flows to 80% at low flows [*Ward and Booker*, 2003].

[17] Disputes between Mexico and the United States over the distribution of Rio Grande waters led to the creation of the Convention of 1906 [*Schmandt et al.*, 1999]. After complicated negotiations, the United States promised to deliver to Mexico 60,000 acre-feet (in which one acre foot is 1233 m^3) of water annually to the bed of the Rio Grande at the International Dam, Ciudad Juárez.

[18] The U.S. Bureau of Reclamation constructed Elephant Butte Reservoir in 1916 for water storage and delivery to farmers in New Mexico and Texas above Fort Quitman (see Figure 1) and to provide protection from flooding of the Rio Grande. The capacity of the reservoir is just over two million acre-feet. A flood control reservoir, Caballo, was constructed below Elephant Butte with a capacity of two hundred thousand acre-feet. The Elephant Butte-Caballo Reservoir System and the associated distribution system make up the Rio Grande Project. Under historical operation by the Bureau of Reclamation, New Mexico lands receive 57% of the annual flows while Texas lands receive 43%. The New Mexico allocation all goes to irrigated agriculture, while the Texas allocation is distributed between the City of El Paso MI and Texas irrigated agriculture.

[19] While existing institutions for allocating water have served the basin well in recent decades, there is still considerable interest in the design and evaluation of alternatives [e.g., *Tidwell et al.*, 2004] that could better meet the needs of people who live there. The status of institutions governing the basin's water use conflicts is summarized by *DuMars* [1999, p. 21]:

> Legal rules for the allocation of water resources in the Western United States and in this region, in particular, have not been intentionally developed in a manner that promotes either efficiency or conservation. While all have recognized the scarcity of the resource, the legal rules for their use do not necessarily reflect this understanding. Any solution aimed at long-term sustainable use of the resource must accommodate existing rules and if they are inadequate to serve the purpose, propose the change.

Section 3 describes the development and application of an integrated model designed to test whether alternative institutions for water management and allocation could substantially reduce damages produced by the inevitable drought.

3. Methods of Analysis

[20] The analysis provides a framework in which to estimate impacts of drought on basin water users under existing and alternative institutions. This section describes the development of the empirical model. First, modeling of law of the river and two drought-coping institutions is described. Second, representation of the basin hydrology is described. Finally, the economic value of water in alternative uses is identified for evaluating both existing and potential drought-coping institutions.

3.1. Analysis of Potential Institutions: Integrated Basin Model

[21] A framework for estimating future drought impacts and testing alternative policies was developed to account for the critical hydrologic relationships, institutions and economic sectors in the basin. This integrated model is formulated as a mathematical optimization problem, using either basin water diversions for off-stream uses or economic benefits of off-stream use plus in-stream use (recreation) as the objective, depending on the drought-coping institution being analyzed. Constraints are used to characterize basin hydrology and institutions. This analysis is in the spirit of similar previous work by *Vaux and Howitt* [1984], *Booker* [1995], and *Hurd et al.* [2002, 2004] all of which developed integrated basin-wide hydrologic models for policy analysis containing an economic objective. Appendix A contains details of the model formulation. Three institutions are modeled by applying an appropriate objective function and set of institutional constraints. The to the baseline institution is the existing law of the river discussed above. The two alternative policies model implementation of water marketing within existing Rio Grande Compact jurisdictions and between jurisdictions, respectively. All policies include minimum flows for endangered species as described in Appendix A. For this work, the model is formulated and solved on an annual time step, with reservoir contents and aquifer conditions in each year carried

forward to the next time period. A perfect foresight model could be useful in establishing a benchmark for measuring the economic value of improved streamflow forecasts. The model code supports dynamic solutions as well. For example, reservoir contents could be managed over a predetermined period to achieve the greatest benefits. While the model and its documentation were developed for the Rio Grande Basin, it was designed to be adaptable elsewhere.

3.1.1. Modeling Institutions

[22] Solutions representing water allocations under the law of the river are obtained through a single optimization, by maximizing the basin's total water use, subject to hydrologic equations (equations (A1)–(A11)) and institutional constraints (equations (A12)–(A14)). Institutional constraints identify the most important rules that characterize historical application of the system: the compact, the 1906 U.S.-Mexico treaty, streamflows reserved for the silvery minnow and water allocation within the Rio Grande Project.

[23] Intracompact marketing is a method for coping with drought in which water is traded for cash within each compact jurisdiction but not across jurisdiction boundaries. To implement this kind of market, an objective function maximizing economic benefits, defined as the net benefits of consumptive uses in addition to recreation benefits of reservoir recreation, is used. Historical rules governing water allocation among users are relaxed and water gravitates to uses that maximize benefits, while requiring that allocations strictly adhere to the Rio Grande Compact.

[24] Interstate marketing is a drought-coping method in which water is traded for cash among all users in New Mexico and Texas. In this case, the objective function again includes all economic benefits. Compact deliveries from Colorado to New Mexico are maintained, but in place of compact deliveries from New Mexico to Texas, we allow the trading of water for cash to determine the allocation among all users in these two states. The result is an estimate of allocations under interstate water marketing between New Mexico and Texas.

3.1.2. Hydrologic Modeling

[25] The basin hydrology is defined in both annual flows and reservoir stocks. The fundamental mass balance equation for flows includes headwaters inflows, off-stream diversions, current and lagged return flows, phreatophyte (bosque) depletion, evaporation, and net releases from storage. The maximum quantity of available groundwater for pumping and the level of phreatophyte depletion are given by lagged functions of past river flows. Conveyance functions are used to represent unexplained gains and losses. These conveyance functions calibrate the model through the use of simple linear regression relationships between flows at a pair of nodes, based on historic relationships. For example, suppose annual average historical streamflow at a node B produced 95% of measured streamflow at an upstream node A in which there is no known demands or supplies between the nodes. Then a conveyance function states that flow at node B = 0.95 times the flow at node A. Better and more extensive flow measurement, improved understanding of water use patterns, and better hydrologic and economic theory reduce the need for conveyance functions.

[26] Return flows to or from streams are calculated as the sum of immediate returns from diversions (e.g., tailwater collected in a drainage canal is proportional to diversions) and the interaction of ground and surface water. Ground and surface water interact using a lagged function of past changes in groundwater storage; the lag persists for decades in the case of Albuquerque's groundwater usage. The lag between Albuquerque's pumping and the impact of that pumping on reduced river flows is much longer than our 6 year simulation period. While we include the current hydrologic impact of previous Albuquerque pumping, the model captures too few of the future costs of Albuquerque's current water use activities. Changes in storage result from direct groundwater pumping (negative) and percolation of irrigation diversions (positive) which are neither consumptively used nor immediately returned as drainage water.

3.2. Economic Value of Water

3.2.1. Agriculture

[27] For the Colorado region, the economic value of basin water is determined using a two-stage optimization model that maximizes annual agricultural income in the San Luis Valley for various possible annual water supply conditions. Water supply conditions are defined by (1) the quantity of water in the aquifer and (2) total annual streamflow in the Rio Grande available for use in Colorado. The allocation of water by water right priority is addressed in the first stage of the model, which allocates streamflow from the Rio Grande to irrigation ditches and canals holding the highest priorities. Cropping patterns are dependent upon the amount of surface water that is available and whether groundwater pumping rights are owned by the producer. Those 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 major crops produced in the study area [*Dalsted et al.*, 1996; *Sperow*, 1998].

[28] Downstream in New Mexico and West Texas, the agricultural analysis uses similar methods as in the Colorado region, but with less detailed accounting of the explicit interaction between the economics and hydrology of surface water and groundwater. It is based upon estimating how cropping practices under full water supply conditions adapt to various degrees of drought severity. All three of the basin's major agricultural regions in New Mexico and west Texas were chosen for analysis: (1) Middle Rio Grande Conservancy District (MRGCD) near Albuquerque, New Mexico; (2) Elephant Butte Irrigation District (EBID) near Las Cruces, New Mexico; and (3) El Paso County Water Improvement District 1 (EP1) near El Paso, Texas. For each of these three farming areas, agricultural prices, yields, and production costs were incorporated for the area's most important crops. The analysis is based on farm cost and return enterprise budgets published by New Mexico State University and Texas A&M University. For each area, a linear programming model was developed and applied to represent behavior of commercial producers that maximize net returns, using standard methods for valuing water in agriculture [e.g., *Ward and Michelsen*, 2002]. Income-maximizing farm behavior is based on historical cropping patterns and is limited by constraints on available land by

Table 1. Economic Damages From Selected Water Shortages, Elephant Butte Irrigation District, New Mexico

Water Supply		Total Net Returns, All Producers, Dollars	Total Economic Losses, All Producers, Compared to Full Water Allocation, Dollars
Surface Water, acre-feet/acre	Groundwater, acre-feet/acre		
3.0	3.0	31,085,082	0
2.5	3.0	29,718,155	1,366,927
2.0	3.0	27,769,403	3,315,679
1.5	3.0	25,778,949	5,306,133
1.0	3.0	23,788,495	7,296,587
0.5	3.0	21,798,040	9,287,042
0.0	3.0	19,807,586	11,277,496
3.0	2.5	31,085,082	0
2.5	2.5	29,718,155	1,366,927
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0.5	2.5	21,798,040	9,287,042
0.0	2.5	19,807,586	11,277,496

cropping area, and by crop water production technologies [*Ward et al.*, 2001].

[29] A total of 49 combinations of surface water and groundwater supplies were considered, ranging from a full supply of 3 acre-feet per acre of surface water and 3 acre-feet of groundwater to zero of both. Those 49 data points were used to fit regression models to the water use and resulting income patterns predicted by the linear programming models, for which a small sample of data points is shown in Table 1 for EBID. All drought response data points for all irrigation regions are available from the authors on request. The dependent variable for the regression model was total agricultural net income per acre, while the two independent variables were per acre quantity of surface water and per acre quantity of groundwater.

[30] Benefit functions under various water supply conditions for these four irrigation regions are summarized by Table A1 and also by equation (A16). Groundwater and surface water are typically good substitutes, but pumping costs make groundwater more expensive to deliver to farm fields than surface water. Groundwater and surface water are substitutes when both can be applied to the same use at the same time. If the two are available in two different regions without available conveyance between the regions, then they are not substitutes. In that case, separate benefits functions should be used for each source: once the supply of one is gone, there is no substitute backup. However, if conveyance can be built between the two sources at a cost less than the incremental value produced by each serving as a supplemental backup for the other, then that construction passes the test of economic efficiency. In this study region, many of those efficiency gains have already been developed: groundwater is available for the same use and time and conveyance systems are in place and are used to substitute for surface water supplies. For this reason, Table A1 shows groundwater entering the benefits function with a negative coefficient for all regions in which groundwater pumping occurs. That is, total benefits depend on the sum of surface water and groundwater used, but benefits are reduced on that part of the total supplied by groundwater because of its additional pumping delivery cost.

3.2.2. Reservoir-Based Recreation

[31] Water's economic value for recreation was estimated for the basin's largest, most heavily visited reservoir, Elephant Butte. An estimated regional travel cost model [*Ward et al.*, 1997; *Ward and Beal*, 2000] provides information to compute economic values of selected drought-coping institutions that would alter reservoir levels. Telephone surveys of water-based recreation visitor use patterns were collected monthly for two years in 1988–1989, updated by total visitor use counts in 2000. Although this was a wet period, reservoir fluctuations within each year were due largely to agricultural demands, so it was possible to observe recreational use over a wide range of reservoir levels:

$$\text{Benefits} = \lambda_0(\text{Reservoir Volume})^{\lambda_1} \qquad (1)$$

For Elephant Butte Reservoir, λ_0 = 172.4, measured in thousand dollars per year, and λ_1 = 0.51, where reservoir volume is measured in thousand acre-feet. Because λ_1 is less than 1, the equation predicts total recreation benefits that increase at a decreasing rate with policies that increase reservoir volume.

3.2.3. Municipal and Industrial

[32] The use of water produces considerable economic value in a modern household. Beyond satisfying basic human requirements, water has been extensively analyzed as an economic resource for which there is a considerable urban demand, particularly in the desert southwest. Similarly, water shortages resulting from drought cause economic damages for which people are willing to pay considerable amounts to avoid. Besides cooking, washing, cleaning and sanitation, the typical Rio Grande Basin-household in the United States uses water for outdoor cleaning and to sustain a domestic landscape environment. The empirical analysis for the current study for estimating drought's economic impact, measured as the willingness to pay to avoid drought damages, is based on earlier work by *Michelsen et al.* [1998]. In that study, seven study areas were selected. With cooperation of water utilities in California, Colorado, and New Mexico, information was collected on residential water use, rate structures, revenues from water sold and nonprice conservation programs covering the period from 1980 through mid-1994. The original study area cities were: 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 those areas provides an excellent cross section of factual data for cities in the southwestern United States. Across seven cities, water's demand was found to be quite price inelastic. A price inelastic demand means that a large percentage increases in price are required to induce small percentage decreases in water use.

[33] The highest price elasticity estimate was for summer landscape use (approximately −0.20). The current study applied the empirical demand schedule findings to the climatic and demographic conditions of Albuquerque and

El Paso [*Ward et al.*, 2001] with benefit function parameters summarized in Table A1. For each city, a linear demand schedule was defined to pass through the water use and price combination for 2003. The slope of each city's demand was defined to produce the known price elasticity and the 2003 combination of price and use. For a known price elasticity, the slope of a linear demand curve can be determined once the price and quantity are known. We used the integral of the marginal benefits of water use to measure total benefits of that use. A linear demand function produces a quadratic total benefits function, of which those total benefits peak at the level of water consumption produced by a zero price. For higher consumption levels, marginal benefits of additional water are negative. When water is scarce, a model that optimizes total benefits will assign water to only to uses for which marginal benefits are positive.

[34] Table A1 shows that for each city the marginal benefits of groundwater use are lower than for surface water, because of the higher pumping cost associated with groundwater use. Despite the higher marginal benefit of supplying water from surface water compared to use of groundwater resources, neither city currently has adequate capacity to meet all its demands from surface water sources. Each city's MI surface water use in the model is limited to the minimum of the city's surface water treatment capacity and that year's surface water supplies available from its water right. As of 2004, El Paso can meet just under half its total demand through surface water treatment in nondrought conditions. Albuquerque has not yet developed any surface treatment capacity, even though it has a water right to meet all its demands from surface supplies as that capacity becomes available. That is, Albuquerque currently meets all its demands through pumping no matter what the river's flow is. El Paso meets just over half its demands through pumping in a nondrought year.

4. Results

[35] Results show drought impacts starting from the severely depleted reservoir conditions existing at the end of 2003. We focus on seven scenarios representing a combination of three water supply conditions and two drought-coping institutions for dealing with shortage situation other than the existing law of the river. The hydrologic conditions produce three constant inflow levels to the basin for six consecutive future years, 2004–2009: 100%, 75%, and 50% of long-term mean annual flows. For comparison, the lowest historical annual inflow occurred in 2002 and produced only 37% of the annual mean.

[36] Basin supply and demands for the years 1998–2003 are used for model calibration and to provide a benchmark from which to gauge future drought damages. Results are presented to show the kinds of impacts associated with various levels of drought and different institutions for coping with drought. If basin inflows for years 2004–2009 equal levels typical of the years 1998–2003, about 75% of the historical mean, there will be no recovery of reservoir storage and little resiliency to cope with short-term droughts. While actual future basin inflows will certainly vary from one year to the next, results suggest that sustainable recovery is unlikely over the 2004–2009 forecast period with average inflows equal at the 75% level.

[37] Total basin consumptive use in New Mexico and Texas initially sustains levels similar to those in 1998–2001, but then falls as the City of Albuquerque replaces its current groundwater pumping with contracted surface withdrawals from the Rio Grande as it develops its surface treatment capacity. The temporary partial recovery of consumptive use levels comes at the continuing cost of groundwater depletion by Albuquerque, El Paso and Juárez. Surface water deliveries to Mexico are disproportionately impacted compared to the water use in the basin as whole. For the 2004–2009 forecast period, Mexican deliveries are only 73% of the full supply level of 60,000 acre-feet. Consistent with the 1906 U.S.-Mexico Treaty, total surface deliveries to all users (including Mexico) below Elephant Butte Reservoir average only 73% of full levels during the 6-year period.

4.1. Impacts of Alternative Water Supplies

[38] Table 2 shows impacts of the law of the river and the two alternative drought control institutions applied to each water supply scenario. The basic structure of each is identical in presenting impacts on the major agricultural and municipal sectors under the seven combined flow and policy scenarios. For 2004–2006, Albuquerque relies entirely on groundwater for its MI use. For 2007–2009, Albuquerque is presumed to have finished its surface water facility, diverting up to 97,000 acre-feet of surface water annually. Lagged impacts of previous pumping on river flows persist during this period. Table 2 shows total consumptive use in each sector, including use derived from surface water and pumped groundwater. Growth in MI water use from growing demand occurs each year from 2004–2009 for both Albuquerque and El Paso. Pumping is not shown in Table 2, but its effects can be inferred. Surface water use in each state under the Rio Grande Compact is a mathematical function of the basin's total surface supply. Consumptive use larger than amounts allowed by the Compact are supplied from pumping. The authors thank an anonymous referee for pointing this out.

4.1.1. Law of the River

[39] Under existing water allocation institutions, drought impacts are concentrated among Colorado agriculture, MRGCD, and in uses below Elephant Butte Reservoir, including Mexican irrigators. Municipal users are largely insulated from drought impacts for the 6-year model projections here, as they rely more heavily than agriculture on nontributary groundwater.

[40] Colorado agriculture has little reservoir storage, relying instead on groundwater storage, injecting surface water into their aquifer in wet years and withdrawing it in dry years. Reduced basin inflows produce surface water shortfalls of up to about 40% at the 50% basin supply level, compared to surface water use under 100% of normal supplies. Compensating for the low surface supply is considerable pumping capacity. With drought persisting over many years, shallow groundwater reserves resulting from irrigation recharge is largely exhausted, producing considerable economic damage. The resulting estimated benefits from for water in Colorado agriculture are highly sensitive to impacts of reduced recharge on groundwater availability, but suggest that groundwater is a critical buffer at moderate surface supply reductions, while substantial

Table 2. Average Annual Consumptive Use, by Institution, Drought Condition, State, and Sector, Rio Grande Basin 2004–2009[a]

Baseline Institution and Policy Adjustments to Drought	Drought Condition, Percentage of Average Annual Surface Water Supply	Colorado San Luis Valley (Ag)	New Mexico Albuquerque (MI)	New Mexico Middle Rio Grande Below Albuquerque (Ag)	Eleph Butte Irrigation District (Ag)	Texas El Paso (MI)	Texas El Paso (Ag)	Mexico Ciudad Juarez (Ag)	Total
Law of the river[b]	100% (baseline)	758	101	195	277	89	133	56	1609
Law of the river[b]	75%	625	101	195	234	89	105	44	1393[c]
Law of the river[b]	50%	445	101	177	146	88	49	20	1026
Intracompact water marketing[d]	75%	625	101	195	235	89	77	44	1366
Intracompact water marketing[d]	50%	445	101	153	81	89	55	20	944
Interstate water marketing[e]	75%	625	101	96	279	89	113	44	1347
Interstate water marketing[e]	50%	445	101	39	166	89	66	20	926

[a]Average annual surface supply produced by the headwater gauges is 1.57 million acre feet. Ag, agricultural; MI, municipal and industrial supplied from pumping.
[b]Current system operation rules are maintained in the face of drought. No trading of water for cash is permitted.
[c]Pumping is not shown here, but its effects can be inferred. Surface water use in each state under the Rio Grande Compact is a mathematical function of the basin's total surface supply. Consumptive use larger than amounts allowed by the compact are supplied from pumping. The authors thank an anonymous refere for raising this question.
[d]Trading water for cash is permitted within each Rio Grande Compact state.
[e]Water can be traded for cash both within a single state and across state lines.

damages occur under the largest supply reductions we consider.

[41] For MRGCD, drought impacts are modest. With incremental economic damages of $26 to $28 per acre-foot of consumptive use in forage crop production and MRGCD drought shortfalls of about 4% of typical use, drought damages are less than $1 million for both drought situations. Downstream of Elephant Butte Reservoir water use is limited by reservoir storage and by New Mexico's reduced compact deliveries to Texas produced by the ongoing severe drought. With reduced deliveries under the compact, Texas water users suffer considerable drought impacts. For the 2004–2009 period, surface water deliveries fall to 30% of normal under the 50% basin supply scenario. Elephant Butte Irrigation District (EBID) uses existing supplemental groundwater pumping to offset much of the shortfall but, as was seen in the 2003 irrigation season, still is able to maintain only just over 50% of full consumptive use under this lowest flow scenario. This model outcome reflects what actually occurred in the 2003 irrigation season. Resulting damages from loss of crops worth just over $100 per acre-foot are about $16 million annually. For El Paso area agriculture, there was little existing installed groundwater capacity before 2003. Lacking such capacity, consumptive use could fall as low as 31% of full when inflows are at the 50% level, with marginal consumptive use damages above $100 per acre-foot reaching totals of about $10 million annually. As with El Paso municipal use, further damages and water management stresses will likely result from elevated salinity at low-flow levels.

[42] Deliveries to Mexico under severe drought are presumed to be limited to the surface water proportions received by Texas water users. Under the compact, all use below Elephant Butte Reservoir, New Mexico, is considered Texas. While surface water delivered to Mexico is currently used for agricultural purposes, that supply is important for groundwater-dependent Ciudad Juárez. From a treaty allocation of 60,000 acre-feet, Mexico can expect supplies to fall to about 45,000 and 20,000 acre-feet under mean water inflow at the 75% and 50% basin supply levels, respectively.

[43] Albuquerque and El Paso MI water users are unlikely to experience the severe damages suffered by agriculture. Albuquerque is well insulated from drought impacts. Currently Albuquerque satisfies 100% of water use through largely nontributary groundwater pumping. Further, the city will likely supplement those supplies with surface water diversions beginning in about 2007. Our results show that under existing institutions, Albuquerque increases its contracted consumptive use of the river to meet growing demand. Moreover, the city is able to reduce gross groundwater pumping from about 185,000 acre-feet in 2004–2006 to 100,000 acre-feet after beginning surface water diversions, except when basin inflows fall to 50%. When that happens, high levels of groundwater pumping are used to maintain consumptive use.

[44] Our results underestimate drought vulnerability in El Paso: water quality from elevated salinity declines considerably with both lower river flows and with higher pumping levels of marginal wells. El Paso is more likely to suffer short-run drought damages from poorer quality supplies than from an absolute shortage of available supplies. Still,

Table 3. Total Annual Drought Damages of Consumptive Use Relative to Normal Supplies and Existing Institutions, by Institution, Water Supply Condition, State, and Sector, Rio Grande Basin

				New Mexico			Texas		
Baseline Institution and Policy Adjustments to Drought	Drought Condition, Percentage of Average Annual Surface Water Supply	Distribution of Damages[a]	Colorado San Luis Valley (Ag), 1×10^6 \$/yr	Albuquerque (MI), 1×10^6 \$/yr	Middle Rio Grande Conservancy District (Ag), 1×10^6 \$/yr	Eleph Butte Irrigation District (Ag), 1×10^6 \$/yr	El Paso (MI), 1×10^6 \$/yr	El Paso (Ag), 1×10^6 \$/yr	Total Among Trading Partners, 1×10^6 \$/yr
Law of the river	75	drought damages	0.7	0.1	0.0	4.9	2.3	2.1	9.4
Law of the river	50	drought damages	18.2	2.4	0.6	16.0	7.5	9.9	36.4
Intracompact marketing	75	drought damages	0.7	−0.2	0.0	4.9	−7.2	5.3	2.8
Intracompact marketing	75	cash compensation	na	−0.2	0.0	3.4	−7.9	4.7	0.0
Intracompact marketing	75	net damages	0.7	0.0	0.0	1.5	0.7	0.6	2.8
Intracompact marketing	50	drought damages	18.2	−0.2	1.5	25.1	−6.3	8.8	28.9
Intracompact marketing	50	cash compensation	na	−2.1	1.0	12.4	−12.3	0.9	0.0
Intracompact marketing	50	net damages	18.2	1.9	0.5	12.7	6.0	7.9	28.9
Interstate marketing	75	drought damages	0.7	2.4	4.1	−0.1	−7.2	1.3	0.5
Interstate marketing	75	cash compensation	na	2.4	4.1	−0.4	−7.3	1.2	0.0
Interstate marketing	75	net damages	0.7	0.0	0.0	0.3	0.1	0.1	0.5
Interstate marketing	50	drought damages	18.2	3.5	7.8	13.4	−7.2	6.9	24.4
Interstate marketing	50	cash compensation	na	1.9	7.4	2.7	−12.2	0.3	0.0
Interstate marketing	50	net damages	18.2	1.6	0.4	10.7	5.0	6.6	24.4

[a]For drought damages, baseline is 100% of long-term average basin inflows, 1.57 million acre-feet, for which damages are defined as zero. Tabled damages are losses in economic benefits from reduced water availability compared to that baseline. A negative number refers to lower damages than under that baseline. For cash compensation, a positive (negative) number means cash received (paid). Cash compensation is distributed to each user by multiplying its drought damages under law of the river times proportion of basin-wide damages avoided by the transfer. Identical avoided drought damages can produce different cash payments.

results show that with continued population growth in El Paso pumping will soon be insufficient to meet demand at current water prices under very low river flows (e.g., the 50% scenario shows a minor shortage in 2006–2009). However, greater than normal short-run pumping by El Paso also reduces the length of time to depletion of its fresh groundwater resources, an impact not quantified here.

4.1.2. Intracompact Marketing

[45] While existing water policy in the Upper Rio Grande Basin is based largely on maintaining historical patterns of water use, there are increased calls for water allocation based more on current needs and demands. One alternative within the basin would allow expanded water markets to operate within each state. Such markets would allow water transfers between willing buyers and sellers. Two market areas are considered: (1) New Mexico, between MRGCD agriculture and Albuquerque, and (2) Texas, among El Paso MI, El Paso agriculture, and EBID agriculture. Deliveries to Mexico are assumed unaffected by either market. Economic impacts, summarized in Table 3, include the sum of changes in drought damages from the value of water and offsetting cash transfers in which water is traded for cash. All parties are shown to gain under this institution in comparison to losses produced by drought under the law of the river. Whenever a water user reduces use (sells water) under this institution cash income is larger than the reduction in value of water used. Water users who increase their usage gain a value of water in use larger than the amount of cash paid for the right to use the additional water. The additional water is not an absolute gain, but reflects only a smaller loss than is produced by a drought under the law of the river.

[46] Introducing intracompact marketing has a modest effect inside New Mexico at higher basin inflow levels, but considerably increases Albuquerque's ability to use surface water under the lowest inflow levels of 50%. This is accomplished through transfers of 28% of the consumptive use otherwise used by MRGCD agriculture. The net benefit of the transfer is shown in Table 3 by the reduced drought damages incurred by agricultural users above and below Albuquerque as well reduced damages incurred by Albuquerque MI use. For the Texas intrastate market at the 75% and 100% inflow levels, reductions in El Paso area agricultural use support reduced groundwater pumping by El Paso. EBID use is for the most part slightly affected compared to the law of the river. Table 3 shows that total use throughout the basin varies by institution because of compensating groundwater pumping resulting from transferred water.

4.1.3. Interstate Marketing

[47] A more geographically widespread market linking all New Mexico and Texas water users can be imagined, such as including Colorado and Mexico as part of the trading group. We term this an interstate marketing option and assume that such a market arrangement will leave long-term compact allocations and long-term property rights unaffected, but actual water use temporarily changes as water is traded for cash both within and across compact state lines. That is, interstate marketing will not affect long-term compact delivery obligations, but will create a short-term spot market that moves water to higher-valued uses on a short-term basis.

[48] If an interstate market is established in which water is traded for cash, water buyers will be users who pay out cash and receive water put to a higher-valued incremental economic use; sellers receive cash and forego lower incremental economic benefits produced by some existing uses. The buyer gains a value of water greater than the cash paid, and the price received by the seller is higher than the economic value of water foregone. Establishing an interstate market will cause the difference to narrow (sometimes to zero) in incremental economic benefits of water use between buyers and sellers. Water buyers will see falling incremental benefits of water use compared to use patterns under law of the river and therefore pay sellers to forego water use. Water sellers lose some benefits of existing water use, keeping only enough water for higher marginal valued uses. Compensation by buyers for sellers to forego use results in a net benefit to both the buyer and seller (Table 3).

[49] One important result of such a market is to transfer consumptive use from MRGCD agricultural uses to downstream agricultural and municipal uses compared to the law of the river. At the smallest inflow level Albuquerque surface diversions are also transferred downstream, as Albuquerque substitutes pumped groundwater for surface water. However, limited pumping capacity precludes Albuquerque from pumping significant amounts of groundwater and selling it at market prices.

[50] Impacts of interstate marketing in Texas are more complex. At the 100% inflow level (full supply of water), there is no transfer from MRGCD agriculture, but El Paso agriculture transfers nearly 50,000 acre-feet of consumptive use to reduce El Paso's municipal pumping. Under a full supply situation the marginal cost (but not average cost) of El Paso's pumping is higher than its surface water delivery. However, in periods of surface water shortfall, greater water-related net benefits for El Paso ratepayers are achieved by pumping from the city's higher-cost groundwater sources than by reducing demand. Only when the drought is so extreme that surface supplies are nearly depleted is there a greater net benefit from demand side measures, such as conservation pricing, than from complete groundwater substitution for surface water shortfalls. Simply put, the city has inadequate pumping capacity to deliver all its MI demand from groundwater sources.

[51] At the 75% inflow level, 45% reductions in MRGCD consumptive use support reduced pumping by both Albuquerque and El Paso. That it, it is cheaper for both cities to rent surface water from MRGCD agriculture than to deal with shortages through constant or increased pumping. Under this marketing arrangement, EBID use is increased through increased surface water use, compared to its loss of 43,000 acre-feet under the law of the river. EBID's absolute use does not increase when the basin's supplies fall from 100% to 75% of normal. However, when the basin's supplies are 75% of normal, EBID's use does increase under an interstate market compared to the Law of the River. This occurs because EBID's high-valued agriculture can afford to buy imported surface water from lower-valued MRGCD agriculture. All parties gain from the trade.

[52] At the 50% inflow level, MRGCD consumptive use reductions are limited only by a model constraint: even the highest-valued MRGCD use produces a lower economic value than other surface water uses in the basin. Use reductions by MRGCD support consumptive use increases by EBID and El Paso area agriculture, and groundwater pumping reductions by El Paso. At all inflow levels there is an increase in surface water diversions below Elephant Butte Reservoir under the interstate marketing institution compared to the law of the river because of high-valued agricultural and MI uses in that part of the basin.

4.2. Discussion

[53] Modeling the hydrology, economics, and policy for a complex river basin is still in the experimental stages. Model structure, simplifying assumptions, and limited data all introduce the potential for errors.

[54] This analysis measures only primary economic damages to water users resulting from drought and from institutional alternatives for coping with drought. Secondary impacts, such as reduced trading with local business by water users who lose water in a drought, are not counted. As described by *Howe* [1997], not counting these impacts amounts to assuming there are no real costs of displaced resources faced by local economies when water is reallocated at a significant scale, either by drought itself or by mitigating actions taken to cope with drought. In fact, these additional losses are often politically and economically important. To the extent these indirect impacts can be measured and valued in a way that is consistent with direct impacts, an anonymous referee reminded us that they should be accounted for in any comprehensive analysis of drought policy. Methods for valuing secondary impacts in a way that can be expressed in a common denominator with primary impacts (willingness to pay by water users) are the subject of long standing and lively debates.

[55] Our results depend on the choice of drought scenarios and existing water supply conditions. Other drought scenarios and water supply conditions are possible. For this study, an important assumption is the initial condition of a nearly depleted Elephant Butte Reservoir (a reality in 2004). If we designed drought-coping measures beginning with a full reservoir, an important result of this study is reversed: central and northern New Mexico are immediately more vulnerable to drought flows through compact limits on use, while Texas uses are protected for a number of years by carryover storage.

[56] Northern and central New Mexico also may be considerably more vulnerable than model results presented here suggest. First, when Elephant Butte storage falls below 0.4 million acre-feet, as is the case in 2004, increased storage in post-1929 reservoirs above most New Mexico agricultural regions is prohibited by the compact. Such storage captures snowmelt for use throughout the irrigation season. With this compact limit on storage in New Mexico, much spring runoff is likely to pass unused to Elephant Butte Reservoir. Second, MRGCD has historically diverted flows many times the level of consumptive use, leading to high aquifer recharge and return flow levels. While the model fully represents these diversion-groundwater-river interactions, the parameterization may not accurately reflect actual losses which would occur under extended low-flow conditions. Similarly, a major consumptive use component, of similar magnitude to MRGCD consumptive use and Elephant Butte Reservoir evaporation under full supply conditions, is the bosque, or riverside vegetation; again,

the parameterization of both maximum use and changes to consumptive use with evolving river flows and groundwater conditions is potentially inaccurate.

[57] Our modeling approach only approximates the operation of water markets. We do not explicitly include transaction costs associated with the design and operation of a water market. Important transactions costs of markets include the fixed costs of establishing a water marketing system and the variable costs of expanding the scope of the market in the face of increasing drought severity. Market institutions are modeled using an objective maximizing the total benefits of water use. As such, the model internalizes externalities, defined as impacts on third parties resulting from cash-for-water trades. Designing a water market institution to protect third parties to water trades may require additional policy instruments. Indeed, many existing prohibitions or strict limitations on market transfers are motivated by concern for return flows which might be lost (an externality) when water is transferred. While optimization models such as ours easily include such reduced return flows in designing efficient allocations, implementing actual markets to appropriately internalize externalities is a major challenge facing water researchers and policy analysts.

[58] Total river depletions due to bosque vegetation and the relationship of these depletions to river flows are poorly understood. Finally, minimum flow levels in reaches of the river impacted by MRGCD diversions are required to support the endangered silvery minnow. While these minimum flow levels are also incorporated in the model, biological research has not yet established the timing or quantity of flow levels in the river required for the minnow's survival. Because MRGCD's consumptive use allowed under the compact depends on a number of large and potentially poorly understood depletions and interactions, model results of its use levels must be interpreted with caution.

5. Conclusions

[59] Given the present path of population growth, agricultural use levels and institutions, we find that multimillion dollar drought damages are likely when inflows fall to between 50 and 75% of long term averages. Under these conditions, but using current and future water demands, instream flows are severely diminished and reservoir storage is depleted. The average economic damage is about $100 per acre-foot of water supply reduction, reflecting damages to agricultural, municipal and recreational users.

[60] Using an integrated hydrologic, economic and institutional model to examine a range of alternative policy responses, we find some reductions in drought damages result from policies such as intracompact market water transfers. Larger reductions in drought damages are produced by interstate market policies that reallocate scarce supplies to the highest-valued uses. However, that kind of policy requires additional institutional flexibility to allow water exchanges across state lines. There are rarely public policy changes that do not involve costs, and any introduction of water marketing across state lines will be subject to considerable debate and scrutiny.

[61] Water uses in headwater areas and in downstream jurisdictions of the Rio Grande Compact are least protected from drought impacts, given an initial condition of a depleted Elephant Butte Reservoir. Central and northern New Mexico water users are best able to withstand drought. Second, maintaining municipal consumptive uses during drought requires groundwater pumping at levels much above current or projected levels. Such pumping is likely not sustainable for periods greatly longer than the 6-year period of this study. Third, unless pumped water is marketed, such pumping may be significantly limited if a water market allowed transfers of agricultural surface diversions to municipal uses. Overall, compared to existing water allocation institutions, we find that future drought damages could be reduced by 20% to 33% per year under the most serious drought through intracompact and interstate water markets, respectively, that would extend across current water management jurisdictions.

Appendix A: Mathematical Documentation

[62] This appendix documents the essential elements of the Rio Grande Basin model described in the text. Additional details and the model's GAMS code are available from *Ward et al.* [2001], via the Web (http://wrri.NMSU.Edu/publish/techrpt/tr317/cdrom/), and from the authors on request. While this model and its documentation was developed for the Rio Grande Basin, it was designed to be adaptable elsewhere.

A1. Inflow

[63] Total inflows into the basin are defined as total annual flows at six headwater stream gauges. Inflow at each hth headwater gauges in year t, X_{ht}, equals total source supplies:

$$X_{ht} = Source_{ht}. \tag{A1}$$

A2. Streamflow

[64] Streamflow at each river gauge in period t, X_{vt}, equals the sum of flows over six kinds of upstream locations in the basin at which water's supply or demand is affected (nodes) whose activities influence that flow: (1) upstream river gauges; (2) headwater inflows; (3) upstream diversions; (4) upstream surface return flows; (5) upstream recharge from groundwater interactions with the river; (6) upstream reservoir releases. Total flows, which cannot be negative, are defined for each of those six types of nodes, respectively, as:

$$X_{vt} = \sum_{v} B_{vv} X_{vt} + \sum_{h} B_{hv} X_{ht} + \sum_{d} B_{dv} X_{dt} + \sum_{r} B_{rv} X_{rt} + \sum_{g} B_{gv} X_{gt} + \sum_{L} B_{Lv} X_{Lt}. \tag{A2}$$

where the set v defines all river gages, and X_{vt} is the streamflow at any river gauge node (set element). Streamflow at any jth river gage node is X^{j}_{vt}, but the j superscript is deleted for economy of presentation unless required. Each of the six vectors of B coefficients takes on values of 0 for noncontributing sources, 1 for sources that add flow, and -1 for sources that subtract flow. So, while positive signs in an equation (+) suggest adding flows, subtractions ($-$) occur whenever a B coefficient is negative. For example, the first right-hand-side term, $\sum_{v} B_{vv} X_{vt}$, sums contributions over the set (v) of river gauge elements. The vector B_{vv} typically contains a single 1, and the rest zeros. The second term, $\sum_h B_{hv}X_{ht}$, sums contributions over the set (h) of headwater nodes. The vector B_{hv} contains 1s for all immediately upstream headwater gages that contribute to a river's flow and 0 otherwise, where X_{ht} are flows at all headwater gages. For the Rio Grande Basin we used published flows at six headwater gages, whose periods of record were sometimes more than 100 years. In some parts of the world, few published headwater flow records exist, so for this kind of modeling exercise, these data have to be estimated indirectly. The third term, $\sum_d B_{dv}X_{dt}$, sums streamflow reductions over the set (d) of diversion nodes. By accounting for upstream diversions, the B_{dv} vector's coefficients are 0 for nondiverting locations and for diversions that do not affect the given river node's flow, but -1 where upstream diversions affect that flow. The last three terms similarly account for: upstream return flows in the set (r), net change in streamflow at nodes influenced by groundwater flows in the set (g), and upstream reservoir releases that affect streamflows in the set (L).

A3. Diversions

[65] Both agricultural uses and MI uses can be met by diversions from a stream. However, in dry periods, streamflow can be low or even zero. The following equation, a "wet water" condition, requires that no diversion exceeds available streamflow at the point of diversion. A diversion, which cannot be negative, is:

$$X_{dt} \leq \sum_v B_{vd}\, X_{vt} + \sum_h B_{hd}\, X_{ht} + \sum_r B_{rd}\, X_{rt} + \sum_g B_{gd}\, X_{gt}. \tag{A3}$$

where the right hand side terms are the sum of all contributions to flow from upstream sources at the point of diversion. The various B terms, which indicate presence (1) or absence (0) of upstream flow sources for a given node, are used to configure the basin. For example, diversions by MRGCD farmers downstream of Albuquerque cannot exceed the river's flow at that node. The river's flow at that node is found by adding the river's flow at the closest upstream river gage, the Otowi gage, X_{vt}^{O}, surface return flows from Albuquerque, X_{rt}^{Alb}, and groundwater inflows to the river from Albuquerque, X_{gt}^{Alb}.

A4. Use

[66] Consumptive use (X_{ut}) is defined as surface diversions (X_{dt}) plus pumped groundwater (X_{pt}) minus surface return flows (X_{rt}) minus seepage to deep percolation (X_{st}). It measures the quantity of flows lost through evapotranspiration or evaporation to any future use in the system. Hydrologic balance requires that evaporation ultimately returns to some system at some time, but for small systems, evaporation is a net loss. The parameters B are vector elements indicating presence (1) or absence (0) of effect. Consumptive use, which cannot be negative, is:

$$X_{ut} = \sum_d B_{du}\, X_{dt} + \sum_p B_{pu}\, X_{pt} - \sum_r B_{ru}\, X_{rt} - \sum_s B_{su}\, X_{st}. \tag{A4}$$

A5. Seepage

[67] Total seepage to the aquifer at a node, X_{st}, which cannot be negative, is a proportion of the sum of total water applied. Total water applied is the sum of diversions (X_{dt}) and groundwater pumping (X_{pt}). The seepage proportion, B_s, varies from 0 to about 0.35 depending on location. B_{ds} and B_{ps} are coefficients indicating presence (1) or absence (0) of effect. Total seepage is:

$$X_{st} = B_s \left[\sum_d B_{ds}\, X_{dt} + \sum_p B_{ps}\, X_{pt} \right]. \tag{A5}$$

Seepage can be reduced by actions such as lining irrigation ditches with concrete or by substituting sprinkler or drip for flood or furrow irrigation. Typically these actions, which reduce the value of B_s, reduce the quantity of water diverted from the stream, but also reduce groundwater recharge from the aquifer to the river. Whether the overall benefits of any one of those actions exceed its costs depends on whose benefits and costs are counted, how the action influences the economic productivity of water (e.g., increased crop yield), as well as on the cost of the action (e.g., lining ditches).

A6. Net Seepage

[68] Net seepage, X_{nt}, is the difference between seepage to aquifers in a given time period produced by seepage, X_{st}, and pumping from the aquifers, X_{pt}. It can be positive or negative. It is:

$$X_{nt} = \sum_s B_{sn}\, X_{st} - \sum_p B_{pn}\, X_{pt}. \tag{A6}$$

where the Bs are coefficients indicating presence (1) or absence (0) of effects on net seepage.

A7. Return Flow

[69] Surface return flow to a stream, X_{rt}, results from both surface diversions and groundwater pumping. At each return flow node, the return flow coefficient per unit diverted, B_{dr}, is the proportion of the diversion (X_{dt}) returning to the stream in the same period. B_{pr} is the proportion of groundwater pumping (X_{pt}) returning to the stream. Total return flows are:

$$X_{rt} = \sum_d B_{dr}\, X_{dt} + \sum_p B_{pr}\, X_{pt}. \tag{A7}$$

A8. Groundwater Flow

[70] Groundwater can flow from an aquifer to a river, making the river a gaining reach, or it can flow from the river to the aquifer, making it a losing reach. Human activity is a major factor influencing which of the two outcomes occurs. Other things equal, increased levels of pumping increase groundwater flows from the river to the aquifer, while increased quantities of water from upstream surface diversions applied to lands near the river, through increased net seepage, increase groundwater flows from the aquifer to the river.

[71] The net impact of groundwater flow on the river (gain or loss) at the groundwater nodes is a function of the lagged net seepage to or from the river influenced by the aquifer. It is used together with its lag structure to calculate the net effect on river flows in each period. *Cook and Balleau* [1998] analyze some of the basin's groundwater relationships. *Kernodle et al.* [1995] analyze the connection between pumping by the city of Albuquerque and the flow of the Rio Grande.

[72] The lag is a simple linearly declining function of net seepage. The lag time may vary from the current year only (no lag) to the full number of years in the model. Depending on the aquifer, the proportion of net seepage impacting river flows, summed over the full lag period, ranges from zero to one. Groundwater inflows to or outflows from the river at any time, t, X_{gt}, is:

$$X_{gt} = \sum_n B_{ng1} X_{nt} + \ldots + \sum_n B_{ngk} X_{n\,t-k}, \quad \text{(A8)}$$

where the B_{ng} terms are the impact on river flow in period t from net seepage in the same and earlier periods; and k is the maximum number of previous periods for which groundwater flows affect the river. An example of this hydrologic process is illustrated by an ongoing study showing that seepage from acequia (community ditch associations) canals in northern New Mexico serves several functions. It replenishes aquifers, contributes to riparian vegetation growth and helps maintain surface water levels downstream. Historically, the New Mexico State Engineer's Office has administered the river in New Mexico as if all pumping reduces the flow of the river by the amount of that pumping in the same period.

A9. Reservoir Contents and Releases

[73] Each reservoir's stock of water is tracked for the tth year. The vth reservoir's contents in year t, Z_{vt}, equals its contents in the previous year, minus the net release (outflow minus inflow) from the reservoir, X_{Lt}, that contributes to added flow at the downstream node in that period. A second term subtracts a period's evaporation from a reservoir's contents. The evaporation coefficient, B_e, accounts for the fact that a reservoir's exposed surface area typically depends on its contents. A (0-1) vector of coefficients. B_{Lv} keeps track of each vth reservoir location in the basin, assuring that streamflow into it adds to the reservoir's contents, while outflows from it reduce the reservoir's contents and also add to streamflow in the downstream reach. Reservoir contents are

$$Z_{vt} = Z_{vt-1} - B_e Z_{vt-1} - \sum_L B_{Lv} X_{Lt} \quad \text{(A9)}$$

Contents of the vth reservoir in the initial period (0), Z_{v0}, are defined by beginning watershed conditions, B_{ro}:

$$Z_{v0} = B_{r0}. \quad \text{(A10)}$$

Each reservoir's maximum contents are defined as

$$Z_{vt}^{\max} = C_v. \quad \text{(A11)}$$

This equation guarantees that the vth reservoir's level cannot exceed its capacity. Policies that would change a reservoir's capacity, such as dredging or adding to a dam's height, are simulated by altering the value of C_v.

A10. Institutional Constraint

A10.1. Rio Grande Compact

[74] The compact (signed in 1938 by Colorado, New Mexico, and Texas) divides the annual flow of the Rio Grande [*Hill*, 1974]. Under the compact, each state receives more water in years with higher basin inflows. Articles III and IV of the compact oblige Colorado to deliver water at the Colorado-New Mexico state line (see Figure 1). These flows, X_{vt}^L must be at least:

$$X_{vt}^L \geq \theta_{0h} + \theta_{1h} X_{ht}^c + \theta_{2h} \left(X_{ht}^c\right)^2. \quad \text{(A12)}$$

This quadratic equation approximates Colorado's total delivery requirements to New Mexico defined by compact Articles III and IV, and is based on annual source runoff measured at Colorado's relevant headwater gauges, X_{ht}^c.

[75] Article V of the compact and the February 1948 resolution of the compact oblige New Mexico to deliver water to Texas measured at the outflow of Elephant Butte Reservoir (see Figure 1). New Mexico's delivery requirement to Texas is based on New Mexico's annual supply, defined as total flows at the Otowi stream gauge, north of Santa Fe, New Mexico. It is approximated in the model by

$$X_t^E - X_{Lt}^E \geq \delta_{0h} + \delta_{1h} X_{vt}^O + \delta_{2h} \left(X_{vt}^O\right)^2 \quad \text{(A13)}$$

where X_t^E is annual flow from Elephant Butte Reservoir, the location at which New Mexico must deliver to Texas under the compact, and X_{vt}^O indicates annual flow at the Otowi gauge, which, under the compact, is defined as New Mexico's total supply from which a proportion must be delivered to Texas. The two left-hand-side terms are Elephant Butte Reservoir outflows (X_t^E) and net releases (X_{Lt}^E), respectively. The algebraic difference, $X_t^E - X_{Lt}^E$, when added to reservoir evaporation is equivalent to the Elephant Butte Reservoir outflow, plus net change in reservoir storage, New Mexico's annual delivery requirement to Texas.

A10.2. The 1906 U.S.-Mexico Treaty

[76] A 60,000 acre-foot annual delivery to Mexico is specified by the U.S.-Mexico Treaty of 1906. Historically, in times of severe drought, Mexican deliveries have in fact been reduced considerably below 60,000 acre-feet. Inspection of the historical data on U.S. deliveries to Mexico shows that a fairly simple linear regression replicates U.S. delivery behavior, as those deliveries vary with Rio Grande project releases from Elephant Butte Reservoir in periods of less than full supply: Our model, replicates that behavior by requiring that 60,000 acre-feet be delivered to Mexico except under extreme drought conditions:

$$X_{vt}^M = 60{,}000 - X^M \quad \text{(A14)}$$

where X_{vt}^M = annual deliveries to Mexico, and X^M is an adjustment factor that subtracts off an amount proportional

Table A1. Total Benefits of Consumptive Use for Agricultural and MI Uses of Water Per Acre (or Per Household) Per Year, Rio Grande Basin, Colorado, New Mexico, and Texas[a]

Location	Label	State	Sector	β_0, \$	β_1, \$/acre-foot	β_2, \$/acre-foot^2	β_3, \$/acre-foot
San Luis Valley	SLV	Colorado	Ag	195	145	−14	na
Albuquerque	ALB	New Mexico	MI	0	10843	−9627	−10
Middle Valley	MRGCD	New Mexico	Ag	−30	67	−6	na
Mesilla Valley	EBID	New Mexico	Ag	137	94	−2	−76
El Paso	EP	Texas	MI	0	9507	−9392	−100
El Paso	EP1	Texas	Ag	0	193	−21	na

[a]Functional form is Total benefits = β_0 + β_1 (acre-feet) + β_2 (acre-feet)^2 + β_3 (acre-feet pumped). Here acre-feet refers to total consumptive use, X_{ut}, in (A4), while acre-feet pumped is pumped groundwater, X_{pt}, also defined in (A4). The zero coefficient for Colorado groundwater reflects the widespread practice of conjunctive management at the farm level that continually recharges and pumps from shallow groundwater. Groundwater extraction costs are essentially zero.

to drought-induced shortfalls on U.S. Rio Grande Project lands.

A10.3. Minimum Flows for Endangered Species

[77] In 1994, the U.S. Fish and Wildlife Service listed the Rio Grande Silvery Minnow (*Hybognathus amarus*) as an Endangered Species under the ESA. The Bureau of Reclamation maintains a Web page devoted to the silvery minnow (see http://www.usbr.gov/uc/albuq/library/eis/pdfs/ba_mrg_jan_2003.pdf). A biological opinion issued by the U.S. Fish and Wildlife Service [*U.S. Department of Interior*, 2001] estimates that the minnow requires at least 50 cubic feet per second (cfs) of year-round streamflow in the San Acacia reach. A regression analysis showed that total annual deficits, defined as the total additional acre-feet of water needed to overcome all shortages in streamflow below 50 cfs, takes the following form:

$$X_{Mt} \geq \varepsilon_{0v}\,. \tag{A15}$$

That is, annual flows in the San Acacia reach of the Rio Grande, must exceed a critical level required for the minnow's survival, about 240,000 acre-feet per year under recent operating conditions.

A11. Economic Benefits

[78] Economic benefits from all water used in the basin are defined in the model as total net income, plus consumer surplus summed over uses and time periods, defined as X_B. Diversions in the *t*th period and *s*th use, X_{st}, create economic benefits by being applied to the following quadratic total benefits function:

$$X_B = B_{ou} + \sum_u \sum_t B_{1u} X_{ut} + \sum_u \sum_t B_{2u} X_{ut}^2 + \sum_u \sum_t B_{3u} X_{pt}, \tag{A16}$$

where B_{ou}, B_{1u} and B_{2u} are parameters for the constant, linear and quadratic terms, respectively, for the beneficial use of surface flow at each of the u nodes (X_{ut}) and groundwater pumped at each of the p nodes (X_{pt}). The term B_{3u} is a parameter reflecting the benefit reduction (added cost) of pumping (X_{pt}) compared to surface water use (X_{ut}). Equation (A4) shows that X_{ut}, total consumptive use, includes groundwater pumping, X_{pt}. So the negative benefits coefficient on additional pumping means that pumping is more expensive than surface water use, not that additional pumping produces a negative benefit. The authors thank an anonymous referee for raising this question. $\beta_2 < 0$ reflects a downward sloping demand schedule. Reservoir recreation benefits vary with reservoir levels (stocks), and only depend upon streamflows to the extent that streamflows affect reservoir levels. Table A1 shows model parameters by sector and location for agriculture and MI uses.

[79] For agricultural nodes, incremental benefits from added water use begin small (i.e., B_{1s} is small but positive), then fall gradually with higher water use per acre as farm producers shift into water-intensive labor-saving crops, such as cattle feed (i.e., B_2 is small but negative). For MI use nodes, incremental benefits from added use begin high as basic human requirements, such as drinking and sanitation, are met (i.e., B_1 is large and positive). Incremental MI benefits fall rapidly as household water is applied to lower-valued uses, such as outdoor landscapes, in the face of greater supplies and lower prices (B_2 large and negative). Similarly, displaced incremental MI benefits rise rapidly as droughts or other urban shortages become more severe and opportunities are reduced for painless conservation.

[80] Total and marginal benefits for MI water uses are based on estimated price elasticities of demand for El Paso and Albuquerque. Total benefits for agricultural uses are based on linear programming income maximization models. Data for these models come from published farm cost and return budgets for Colorado, New Mexico, and Texas. The income maximization models allow producers to shift from water-using labor-saving activities into water-saving labor-using activities as water scarcity increases. Increased water scarcity reduces water use, and increases the marginal value of remaining water as producers move back along their water demand functions, substituting land, labor, and capital for water.

A12. Objective

[81] Water use in the upper Rio Grande Basin is heavily constrained by scarce water supplies and by existing institutions. We characterize these institutions as the law of the river, of which the Rio Grande Compact and U.S.-Mexico Treaty have the most influence and are the least flexible to short-run change. The objective function chosen for this analysis was a simple maximization of total economic benefits defined in equation (A16). That is, total regional economic benefits are maximized subject to the constraints defined by equations (A1)–(A15) describing the basin's hydrology and institutions. The objective and water alloca-

tions that maximize that objective are based on standard neoclassical microeconomic welfare economic theory.

A12.1. Law of the River

[82] This institution is simulated by constraining water allocations to produce outcomes consistent with historical water use patterns. These are water use patterns consistent with the compact and Mexican Treaty, as well as patterns characterized by large amounts of water used in agriculture that produce low marginal economic values compared to use by MI.

A12.2. Intracompact Water Market

[83] Within each of the three compact states the model is designed to maximize total regional economic benefits by equalizing marginal benefits. This maximization occurs to the extent permitted by the constraints of hydrology, compact allocations, and Treaty deliveries. This regional objective is consistent with the institution of an intracompact water market that facilitates trading water for cash within each state but not across compact boundaries. The recently published New Mexico State Water Plan emphasizes markets as an institution to make a given amount of water perform more economic work (increase economic efficiency), as long as they are implemented to protect third parties by accounting for hydrologic impacts of water trades.

[84] Both the intracompact market and interstate markets are assumed to be operated under special conditions compared to law of the river. Under those conditions, water is allocated to maximize total regional benefits taking full account of hydrologic interdependencies among upstream and downstream users. It assumes that any economic benefits lost produced by reduced water use is more than fully compensated by cash from users who gain water. By accounting for hydrologic interdependencies of water reallocation, it shows where water comes from, where water goes, and whose uses are affected. This kind of basin-wide model could be an important tool for showing water marketers which third parties need to be charged or compensated to be kept whole after a proposed water reallocation. Failure to account for these impacts risks producing a market failure, in which third parties to market trades are uncompensated for gains or losses. We thank an anonymous referee for providing this insight.

A12.3. Interstate Market

[85] This institution is simulated by relaxing the Rio Grande Compact rules for allocating water among the trading partners, New Mexico and Texas. Total water supplies are unaffected, but instead of water allocations among the states being governed by the compact, water flows to its highest-valued uses. Marginal benefits of each use are equalized both within and across state lines subject only to hydrologic constraints, such as gains and losses as water moves downstream.

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Figure 1. Map of study region.