

*Forthcoming in the Journal of Water Resources Planning and Management*

Integrated Economic, Hydrologic and Institutional Analysis of Policy Responses to  
Mitigate Drought Impacts in the Rio Grande Basin

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May 2005

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Abstract

In the Rio Grande Basin of North America, water is over-appropriated, and demand for water grows while supplies are constrained by drought and climate change. The Basin is currently in its seventh year of drought, and reservoirs are at historically low levels. Agricultural and municipal river diversions have been sharply curtailed; low flows threaten endangered species. A central policy challenge is the design and implementation of plans that efficiently and fairly allocate the Basin's water supplies. Such plans are complicated by the demands of existing water users, potential new users, three state governments, and two sovereign nations. To address these issues, an integrated basin-wide nonlinear programming model was designed and constructed for the purpose of optimizing water allocations and use levels for the Basin. The model tests whether institutional adjustments can limit damages caused by drought and it identifies changes in water uses and allocations that result from those adjustments. Compared to existing rules governing the river system's water use, future drought damages could be reduced by one-fifth to one-third per year from intrastate and interstate water markets, respectively, that permit water transfers across jurisdictions. Results show hydrologic and economic tradeoffs among water uses, regions, and drought control programs.

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Acknowledgments

The authors are grateful for generous and sustained financial support by the Rio Grande Basin Initiative Project, the U.S. Geological Survey, and by the Agricultural Experiment Stations and Water Resources Research Institutes of Colorado, New Mexico, and Texas. Reviews by two anonymous referees and a co-editor improved this paper considerably.

# Integrated Economic, Hydrologic and Institutional Analysis of Policy Responses to Mitigate Drought Impacts in the Rio Grande Basin

## 1 Background

A global challenge for 21st-century water management is to satisfy growing human demands for water while protecting the aquatic ecosystems upon which economies and life depend. Especially in dry places with rapidly growing populations and economies, this task is daunting. In the western United States most water supply sources are fully claimed and used largely for irrigation, growing cities, and emerging industrial demands. Where water is unappropriated, it is protected for in-stream flows, endangered species, and environmental uses. Most economically accessible groundwater is developed and connected to fully appropriated surface water. Throughout the west, drought and climate change increase the growing competition for water supplies and increase the importance of designing effective water allocation laws and policies.

The upper Rio Grande Basin (See Map) confronts challenges faced by many of the world's rivers that support economies and cultures in dry places. The upper basin extends from southern Colorado to Fort Quitman, Texas. Hereafter we refer to that area as the Rio Grande Basin or simply the Basin. Previous research has described policy challenges in the Sacramento and Colorado river basins of the United States. These include climate change scenarios analyzed by Christensen *et al.* (2004), analysis of the Central Arizona Project by Holland and Moore (2003), sensitivity of a basin's outcomes to changes in policy objectives by Mahmoud and Garcia (2000), and feasibility of water markets by Newlin *et al.* (2002). Challenges faced by the Yangtze and North China Plain, China, also have been examined. They include a comprehensive integrated hydrologic, economic, agricultural, environmental and social/institutional decision support system used for evaluating water resources and the impacts of competing policies and development objectives for the North China Plain, Michelsen and Bargur (1993) and United Nations Development Program (1994), the connection between forest ecosystem processes and economic benefits, which was examined by Guo *et al.* (2000); displacement and resettlement issues, Li *et al.* (2001); land use problems, Liu *et al.* (2003); wetland ecological processes, Liu *et al.* (2004); ecosystem functions, Nakamura (2003); and environmental restoration, Yan and Qian (2004). Policy

analyses of the Jordan River in the Middle East also have received attention. These include political and military control challenges in regions with shared transboundary water sources, as described by Abu Zahra (2001), Haddadin (2002), Jagerskog (2003), Mimi and Sawalhi (2003), and Shuval (2000). Several analyses of the Murray-Darling in Australia have been published. Important issues analyzed include flood plain ecosystem protection (Arthington and Pusey, 2003), improved connections between research and extension (Keogh *et al.*, 2004), environmental improvements (Quiggin, 2001), and improved ecosystem health (Reid and Brooks, 2000). Finally, several scholars have examined opportunities and choices facing the Nile Basin in North Africa. Examples include analyses of water conservation choices by El-Kady and El Shibini (2001), connections between groundwater and surface water by Farah *et al.* (2000); salinity by Kotb *et al.* (2000), and adaptation to climate change by Strzepek (2000).

In most river systems in the world's arid regions, water is over-allocated, supplies are threatened by seasonal or recurrent drought and the effects of climate change, and growing demands for water are placing stress on existing water management institutions. These factors continue to raise the interest of policymakers, scientists, farmers, and water managers for evaluations of existing water institutions and examinations of alternative designs. One challenge in all these regions is the development of system operation rules and policies that complement existing water management institutions and allocate water so as to minimize total economic damages, and to do so in an open and transparent environment. Achieving these aims requires approaches to decision-support that encompass hydrologic boundaries, political and institutional jurisdictions, and account for economic impacts over all important sectors.

This paper focuses on the impacts of transfers resulting from the institution of water markets as one measure for reducing the economic damages from drought. Market-based transfers have been suggested for many years and by many authors as one measure to cope with scarce supplies and limited storage, especially during drought (e.g., Vaux and Howitt, 1984).

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, Howitt, and Mariño, 1993) and incorporated

additional non-consumptive use values (Booker and Young, 1994). Under drought conditions, the impacts of several market institutions were estimated by Booker (1995). At the sub-basin scale, integrated modeling of economic impacts of water transfers for protecting instream flows was developed by Hamilton, Green, and Holland (1999) and by Willis and Whittlesey (1998); impacts of water markets for protecting water quality were examined by Weinberg, Kling, and Wilen (1993).

The *Journal of Water Resources Planning and Management* has published a number of recent papers dealing with modeling and/or policy analysis at the river basin scale. Bouochart and Goulter (1998) developed risk analysis methods for improved reservoir releases for irrigation. Elarabawy *et al.* (1998) developed a basin-wide model for dealing with shortages in Egypt. Ravikumar and Venugopal (1998) developed a stochastic dynamic programming model to analyze optimal reservoir operation for agricultural use in India. Levy and Baecher (1999) developed a policy simulation model of the Nile Basin. Lund and Guzman (1999) derived reservoir operating rules for reservoirs in series or in parallel for optimizing tradeoffs between hydropower, water quality, and water supply. Philbrick and Kitanids (1999) compared the use of stochastic and deterministic reservoir control and operations models. Rangarajan *et al.* (1999) developed a reservoir operations model that optimized Canadian energy production in the face of uncertain future energy demands.

Wagner (1999) developed a decision framework for assessing the value of groundwater sampling for improving groundwater pumping programs. Watkins and McKinney (1999) developed a screening model to support the choice of alternatives for meeting future water demands and protecting sensitive ecosystems in the Edwards aquifer region of central Texas. DeAzevedo *et al.* (2000) integrated surface water quality and quantity objectives for decision-support for the Piracicaba River Basin in Sao Paulo, Brazil. Loaiciga and Leipnik (2000) developed an economic model that maximizes the expected value of net income accruing from the sale of ground water subject to a number of geologic, climatic, and environmental requirements. Shabman (2000) surveyed the literature on measuring values of water in alternative uses. Eschenback *et al.* (2001) described the potential uses, power, and flexibility of River Ware's basin optimization software for application by the Tennessee Valley Authority. Newlin *et al.* (2002) described the potential use of an economic-engineering network flow optimization model for

evaluating market water transfers in southern California. Barros *et al.* (2003) analyzed an optimization model based on a monthly time-step for the management and operations of a Brazilian hydropower system. Cai *et al.* (2003) described the development and use of an integrated hydrology-agronomic-economic model in a river basin in Central Asia, for which irrigation is the dominant use.

In the Rio Grande Basin of the southwestern United States, despite the region's conditions and the extensive contributions of previous work, little comprehensive analysis of the costs of drought and its application to effective policy response has been conducted to date. With growing demands placed on the Basin's water resources, future droughts will result in larger economic and environmental impacts. For this reason, the design of drought-coping policies will take on increasing importance to this region and to other drought-prone basins of the world faced by growing competition for water. This paper's objective is to take a first step toward comprehensive analysis of drought and its impact by contrasting existing institutions that govern the allocation and use of water during drought periods with alternative designs. This objective is accomplished through the development and use of a comprehensive basin-wide nonlinear programming model of the hydrology, economics, and institutions. The model is applied to evaluate the hydrologic and economic effectiveness of selected potential drought-coping policies. The approach could offer considerable potential for more rational institutional design in other drought-prone basins of the world.

One important advantage of the model is its ability to integrate the essential hydrologic, economic, and institutional components of a river basin and to explore both hydrologic and economic consequences of various policy choices. In a similar way as described by Cai *et al.* (2003), all elements are incorporated into a single consistent model. Our model is solved in its entirety by GAMS-MINOS, a widely-used, off-the-shelf non-linear programming solver (GAMS Development Corporation, 1998). The present work is similar to that of Cai *et al.*, who solved a basin-wide optimization model. However, the current model has less detail on irrigation choices and salinity at the farm level, but greater detail on municipal and industrial (M&I) activities and values. In addition, the current model has more detail on institutional constraints governing the transboundary allocation of water, namely interstate compacts and international treaties.

This paper provides an example of reducing economic damages resulting from drought through market-based water transfers in a region with a history of competing water uses, a complex set of institutions, and growing demands on available water supplies for the Rio Grande Basin (See Map). We extend previous work by developing an integrated hydrologic-economic model at the basin scale that incorporates surface and ground water interactions and tracks economic and hydrologic relationships over several time periods. We apply the model to the design of market-based water transfers as a measure for coping with severe and sustained drought.

The remainder of the paper is organized in the following way: First, the physical and institutional environment of the Basin's water use is summarized. Then, we summarize the methods used to develop and use the basin model. Next, the results are presented for which we compare the Law of the River and two institutions that harness the power of market forces. These two drought-coping institutions are (1) water trading within existing political boundaries and (2) water trading across boundaries. Finally, we conclude.

## 2 Physical and Institutional Context

High mountain snowpack is the Rio Grande Basin's primary surface water source. The southern area of the Basin flows through the Chihuahuan desert where annual average precipitation is eight inches (20 cm), most of which comes as widely scattered summer monsoon thunderstorms (Schmandt, 2002). Total annual streamflow in the Basin is variable from year to year and history has recorded several periods of severe and sustained drought. The 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 fall 2004, water storage in Elephant Butte, the largest reservoir in the Basin, was less than five percent of capacity. After an unprecedented 25-year period of full water supplies, water allocations during 2003 were reduced to just one-third of full supply conditions.

The Basin supports a rapidly growing population of more than three million people, extensive irrigated agriculture, and fish and wildlife habitat in Colorado, New Mexico, Texas, and the Mexican state of

Chihuahua. An estimated 80% to 90% of the water in the Upper Basin is used for irrigated agriculture. The main crops are forage, cotton, pecans and vegetables. Only a portion of the water is consumptively used compared to the total water applied to crops. This portion varies 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 downstream users.

While M&I water demands in the basin have historically been met by ground water, this pumping is not sustainable at current use rates, let alone added pumping for growth. El Paso continues to expand its use of surface water, and Albuquerque plans to withdraw and treat surface water. The largest basin city, Ciudad Juárez, is projected to deplete its fresh groundwater reserves in less than a decade and is in need of new sustainable supplies (Paso del Norte Water Task Force, 2001).

Environmental demands for and values of water continue to increase. The Rio Grande silvery minnow (*Hybognathus amarus*) was listed as an endangered species by the U.S. Fish and Wildlife Service in 1994. Despite contentious debate and extensive and costly litigation, minimum river flows have been mandated by the federal courts (e.g., Parker, 2002) and to date 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 adequate instream flows for the minnow in the San Acacia reach of the river near Socorro, New Mexico (See Map). One cubic foot per second (cfs) = 0.028321 m<sup>3</sup>/s.

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 tri-state compact involving Colorado, New Mexico and Texas; involvement of multiple federal agencies; state statutes; ongoing litigation, and numerous water delivery contracts. Collectively, we characterize these as the “Law of the River,” described below.

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., Middle Rio Grande Water Assembly, 2001; Tidwell *et al.*, 2004) that could better meet the needs of people who live there. The next section describes economic and hydrologic principles underlying the development and application of an integrated model designed to test whether alternative institutions for water management and allocation could significantly reduce damages produced by the inevitable drought.

### 3 Methods of Analysis

#### 3.1 Integrated Basin Model

A framework for estimating future drought impacts and testing alternative policies was developed to account for the Basin's critical hydrologic relationships, institutions, and economic sectors. This integrated model is formulated as a mathematical optimization problem, using the sum of benefits from basin water diversions for off-stream uses and benefits of instream use (recreation) as the objective. Constraints are used to characterize basin hydrology and institutions. This analysis extends similar previous work by Vaux and Howitt (1984) Booker (1995), and Hurd *et al.* (2002, 2004) all of whom developed integrated basin-wide hydrologic models for policy analysis containing an economic objective. In this work, the hydrology identified by Cai *et al.* (2003) as characteristic of integrated models is expanded with the introduction of multiple lagged ground and surface water interactions.

For the present work, the model is formulated and solved on an annual time-step, with reservoir contents and other hydrologic and economic conditions carried forward to the next time period. The actual model code supports dynamic solutions as well, where, for example, reservoir contents could be managed over a predetermined period to achieve the greatest benefits. Such a perfect foresight model could be useful in establishing a benchmark for “perfect” drought management. Additional details and the model's GAMS code are available online and from the authors on request. See <http://wri.NMSU.Edu/publish/techrpt/tr317/cdrom/>. While the model and its documentation were developed for the Rio Grande Basin, it was designed to be easily adaptable to other basins, cultures, and contexts.

#### 3.2 Characterizing Institutions

The allocation and use of water in the Rio Grande Basin is heavily constrained by limited water supplies and by existing institutions. We characterize these institutions as the Law of the River. Among the institutions, the Rio Grande Compact and U.S. Mexico Treaty have the most influence on allocation and use and also are the least flexible to short-run change.

### 3.2.1 Law of the River

In our model, solutions representing water allocations under the Law of the River are obtained through a single optimization, by maximizing basin-wide economic benefits, subject to institutional and hydrologic constraints. Our intent is to create a baseline with existing institutional allocations for comparison to institutional changes. The Law of the River 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 M&I.

### 3.2.2 Intrastate Banking

For intrastate water banking the objective function is the sum of all net benefits in consumptive water uses; institutional constraints previously specifying the allocation between users within each state are removed from the constraint set. By finding water allocations that maximize economic benefits of consumptive use, we approximate allocations resulting from an intrastate water bank.

Within each of the three Compact states, the model maximizes total regional economic benefits by equalizing marginal benefits among users. 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 intrastate water market that facilitates trading water for cash within each state, but not across state 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.

### 3.2.3 Interstate Banking

A more geographically widespread market linking all New Mexico and Texas water users can be imagined. Colorado and Mexico could also be included in an interstate market of even larger geographic scope. This larger market is an important area for future research. The potential for interstate trades between New Mexico and Texas has received considerable recent attention in the Basin. For this case, the objective function includes all monetized benefits, including net benefits of consumptive uses in addition to recreation benefits of reservoir recreation. Reservoir-based recreation benefits were estimated from the regional travel cost model described in Ward et al. (1997). Compact deliveries from Colorado are maintained, but we remove Compact constraints allocating water among the potential water trading partners of New Mexico and Texas. The result is an estimate of allocations under interstate water banking between New Mexico and Texas. Total water supplies are unaffected by this institution, 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 of the trading partners subject only to hydrologic constraints, such as gains and losses as water moves downstream.

### 3.3 Objective

The objective function follows the form

$$V = \sum_v (\beta_{vt}^0 + \beta_{vt}^1 U_{vt} + \beta_{vt}^2 U_{vt}^2 + \beta_{vt}^P P_{vt}) + \sum_u (b_u^0 + b_u^1 Z_{ut} + b_u^2 Z_{ut}^2) \quad (1)$$

where the first summation term is a node's total water-related benefits as a quadratic function of consumptive use,  $U_{vt}$ , at the  $v$ -th diversion node and a negative linear function of that part of that node's consumptive use consisting of pumping,  $P_{vt}$ . This last term in the first summation accounts for the higher cost of pumping compared to simple surface diversion ( $\beta_{vt}^P < 0$ ). The second summation term defines recreation benefits at the  $u$ -th reservoir, as a quadratic function of storage  $Z_{ut}$ .

### 3.4 Basin Hydrology

The basin hydrology is defined in both annual flows  $X_{it}$  and reservoir stocks  $Z_{ut}$ . The fundamental mass balance for flows can be written as

$$X_{rt} = \sum_i \Delta_{ir} X_{it} \quad (2)$$

where  $X_{rt}$  is streamflow at the  $r$ -th river nodes;  $X_{it}$  are flows of type  $i$ , (Table 1) and  $\Delta_{ir}$  are the elements of an  $r \times i$  matrix defining the spatial configuration of the basin that links  $i$  to river node  $r$ . Elements of  $\Delta_{ir}$  can be either +1 (the inflow point is immediately above river node  $r$ ), -1 (the off-stream diversion point is immediately above  $r$ ), or most commonly, 0 (flow  $r$  has no direct effect at river node  $r$ ). Flow types in (2) include headwaters inflows, off-stream diversions, current and lagged return flows, impacts of groundwater pumping, depletion from non-agricultural plants (phreatophytes), net releases from storage, and conveyance functions.

Table 2 shows the geographical and functional relation among the basin's major water sources and uses. Depending on the location patterns of headwaters, river reaches, cities, agricultural users, reservoirs, and endangered species requiring minimum flows, a table like Table 2 would be adapted to the unique conditions surrounding any basin's hydrology, settlement patterns, and demand conditions. The table characterizes the basin's geometry, summarizing locations of water supply and use points. It shows how each of the major functions that influence streamflow at a point are affected by various upstream activities. These functions include use, seepage, pumping, net seepage, net groundwater return flow to the river, surface water return flow to the river, evaporation, reservoir net release. Brief explanations of each function are described in the table's bottom row. Each column is a river basin function described by a block of similar equations. Coefficients are typically equal to 1 (contributing), -1 (reducing), or 0 (no effect). For some equation blocks, coefficients are not equal to 1. An example is the seepage block. Seepage into an aquifer depends positively on total water diverted from the river and applied to beneficial use, as well as on total water pumped and applied. This relationship is shown by the two sets of positive coefficients  $B_{ds}$  (effect of diversions on seepage) and  $B_{ps}$  (effect of pumping on seepage). Each cell in table 2 is an intersection of a row defined as a set of nodes in the basin with a common function and a column defined as a set of nodes with a another common function. For example, the shaded block in the table shows the intersection of all river flow nodes with all other river flow nodes.

Table 3 shows the kind of detail required to fill out the shaded cells of Table 2. The coefficients in Table 3 show how flows at each river node depend on flows from one or more upstream node throughout the basin. Source flows at the gauge at each column originate from flows at the row for which there are one or more coefficients equal to 1. Each cell in table 2 has this kind of detail: node-by-node connections between column headings and row headings.

The mass balance for reservoir stocks,  $Z_{ut}$  is given by

$$Z_{ut} = Z_{u,t-1} + \sum_w \Delta_{iw} X_{wt} \quad (3)$$

where  $\Delta_{iw}$  are matrix elements linking annual changes in storage to the flow types directly causing storage changes. These flows consist of evaporation, calculated as a quadratic function of storage, and net releases, calculated as reservoir outflow from storage minus inflow; all nonzero elements of  $\Delta_{iw}$  equal -1. Mass balance for off-stream consumptive use  $U_{vt}$  and diversions  $X_{vt}$  is given by

$$U_{vt} = X_{vt} + P_{vt} - S_{vt} - \sum_n \Delta_{nw} X_{nt} \quad (4)$$

where  $P_{vt}$  is withdrawal of pumped groundwater,  $S_{vt}$  is seepage into groundwater from canal leakage and field infiltration exceeding use by plants, and  $X_{nt}$  is the return flow to the river within the current time period. The return flows are given as a proportion  $D_n$  of diversions and pumping.

$$X_{nt} = \rho_n \left( \sum_v \Delta_{vn} (X_{vt} + P_{vt}) \right) \quad (5)$$

where  $\Delta_{nv}$  is the matrix of 1s and 0s that configure the basin by linking diversion and return flow at relevant locations. The interaction of flow elements shown in figure 2 shows that infiltration to groundwater from the river itself is treated as a negative return flow (lagged or current period). Where such infiltration is not directly modeled, conveyance functions, as shown in the figure, allow for river

losses.

Total seepage into groundwater from diversion  $v$ , equal to  $S_{vt}$ , is given by

$$S_{vt} = \sigma_v (X_{vt} + P_{vt}) \quad (6)$$

where  $F_v$  is the proportion of diversion  $v$  infiltrating into groundwater rather than contributing directly to return flows. The effect of this infiltration is to contribute to the net seepage  $N_{vt}$  to groundwater, defined as

$$N_{vt} = S_{vt} - P_{vt} \quad (7)$$

where  $P_{vt}$  is the direct withdrawal of groundwater by pumping. Equation (8) can then be used to find return flows from groundwater  $X_{gt}$  calculated as a lagged function of net seepage:

$$X_{gt} = \bar{G}_g + \sum_{t'=0}^t \gamma_{g,t-t'} \left( \sum_v \Delta_{vg} S_{v,t-t'} \right) \quad (8)$$

where  $\gamma_{g,t-t'}$  gives the contribution to groundwater return flows from net seepage in each previous time period  $t-t'$ , and  $\bar{G}_g$  is a the contribution to groundwater flows in each period independent of net see page.

The model has a yearly time step; however lagged seepage produced in any given year is carried forward to the following year. The parameters  $\gamma_{g,t-t'}$  are unique to each groundwater basin and represent our best judgement from the literature and from local expertise on the magnitude of and lag between ground and surface water impacts. There is no explicit representation of groundwater storage; rather, changes in any period's stock of groundwater is represented through past seepage and pumping activities.

Groundwater pumping limits are specified that reflect both available infrastructure and the short-term possibility of significant drawdown or depletion of shallow aquifers during drought. The latter effect is captured through a pumping limit which 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:

$$P_{vt} < P_{base} + (P_0 - P_{base})(1 - \exp(-\lambda_v \bar{X}_{rt})) \quad (9)$$

where  $P_{base}$  defines the pumping capacity from flow independent, large deep groundwater reserves, and the second term,  $P_0 - P_{base}$ , defines the pumping capacity from the shallow aquifer. Lagged flows  $\bar{X}_{rt}$  are a simple average of recent (typically three years) river flows. Pumping depth (lift) increases with reduced lagged river flows for aquifers connected to the river. So long periods of low flow indirectly reduce pumping capacity by increasing the cost of pumping through greater lift required to access groundwater. Important future research needs to connect current and lagged river flows, pumping lift, the change in cost of pumping groundwater, and the reduced economic attractiveness of that pumping.

Depletions by phreatophytes are similarly defined by a lagged function of past river flows. Conveyance functions representing non-modeled gains and losses  $X_{ct}$  (e.g., un-gauged inflows) are linear functions of headwaters flows.

### 3.5 Institutional Constraints

#### 3.5.1 Rio Grande Compact

The Compact – signed in 1938 by Colorado, New Mexico, and Texas – divides the annual flow of the Rio Grande. Under the Compact each state receives more water in wetter years. Articles III and IV of the Compact oblige Colorado to deliver water at the Colorado-New Mexico state line. These flows, measured at the Lobatos stream gauge (see Map), must be at least:

$$X_{Lobatos,t} \geq \sum_h \theta_{0h} + \theta_{1h} X_{ch,t} + \theta_{2h} X_{ch,t}^2 \quad (10)$$

This additive 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  $X_{ch,t}$ . The **2** terms are constant coefficients for the intercept, linear, and quadratic terms, respectively, for headwater gauge flows. The delivery schedule defines Colorado's water

rights to be senior to those of New Mexico, hence,

$$\frac{\partial^2 X_{Lobatos,t}}{\partial X_{Ch,t}^2} > 0 \quad (11)$$

which says that Colorado's delivery obligation to New Mexico increases at an increasing rate with increases in Colorado's gauged runoff,  $X_{ch,t}$ . The effective seniority of Colorado's water right compared to New Mexico comes from the historical fact that prior to 1929, Colorado water users took a higher percentage of Colorado's native runoff in dry years. Each state's right to use water, as well as its requirements to deliver to the downstream state under the Compact, are based on historical use patterns and responses to drought that occurred prior to 1929. So, the desirable position occupied by water users located farther upstream, still common throughout the world, is reaffirmed by the terms of the Compact.

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 map). 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

$$X_{EB,t} - X_{EBR-r,t} \geq \delta_0 + \delta_1 X_{Otowi,t} + \delta_2 (X_{Otowi,t})^2 \quad (12)$$

where the \* terms are constant coefficients,  $X_{EB,t}$  is annual outflow from Elephant Butte Reservoir,

the location at which New Mexico must deliver to Texas under the Compact, and  $X_{Otowi,t}$  indicates

annual flow past the Otowi gauge. Under the Compact, annual flow at that gauge 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 ( $X_{EB,t}$ ) and net releases  $X_{EBR-r,t}$ , respectively. The algebraic

difference of those two terms, when added to reservoir evaporation, is mathematically equivalent to the

Elephant Butte Reservoir outflow plus the net change in reservoir storage, which is New Mexico's delivery obligation to Texas. The original Rio Grande Compact defined New Mexico's delivery obligation to Texas as inflows to Elephant Butte. However that measurement proved unreliable, so a more accurate measurement was moved to the gauge immediately downstream of the reservoir. Measuring what New Mexico's delivery into the reservoir with no reliable inflow measurement is accomplished by measuring outflow, change in reservoir storage, and evaporation.

### 3.5.2 U.S. Mexico Treaty of 1906

A constant 60,000 acre-feet annual delivery to Mexico is assumed in the absence of severe drought, as required by the U.S. Mexico Treaty of 1906. Historically, in times of severe drought, U.S. deliveries to Mexico have been reduced considerably below 60,000 acre-feet in approximate proportion to the reduction of deliveries from Elephant Butte Reservoir to U.S. lands, consistent with the language of the Treaty. Thus, following that language, U.S. deliveries to Mexico are described as:

$$X_{MX,t} = 60,000 \left( \frac{\sum_{LB} X_{LB,t}}{\sum_{LB} \bar{X}_{LB,t}} \right) \quad (13)$$

where  $X_{MX,t}$  = annual deliveries to Mexico,  $X_{LB,t}$  = actual deliveries to U.S. lands from the Rio Grande Project, and  $\bar{X}_{LB,t}$  is the delivery to U.S. lands in a full supply condition, defined as water outflows from project storage, equal to 790,000 acre feet.

### 3.5.3 Minimum Flows to Protect Endangered Species

A biological opinion issued by the U.S. Fish and Wildlife Service (U.S. Department of Interior, 2001) estimates that the endangered Rio Grande Silvery Minnow requires at least 50 cubic feet per second (cfs) of year-round streamflow between the river at approximately Socorro, New Mexico, and the inflow to Elephant Butte Reservoir (see Map). 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:

$$X_{Mt} \geq \varepsilon_{0v} . \tag{14}$$

That is, annual flows at the San Acacia gauge (see map),  $X_{Mt}$ , must exceed a critical level required for the minnow's survival, about 240,000 acre-feet per year under current operating conditions.

### 3.5.4 Demand, Infrastructure, and Custom

Current water users in the basin have typical maximum levels of surface diversions and pumping. In the case of agricultural uses, these may be limited by land and irrigation infrastructure and are fairly stable over time, as long as the Basin's reservoir's are suitably full. For regional municipal uses with rapidly growing populations, the maximum use increases as population increases. The combination of existing and future water demand, limited infrastructure, and both customary and legal restraints puts a practical maximum on consumptive use at each off-stream locations. Thus, while economic demand functions with known elasticities are used for approximating market allocations, the demand function is capped at an upper limit. The institutional constraint limits actual consumptive use,  $U_{vt}$ , to be no more than anticipated future demands in the case of municipalities,  $\bar{U}_{vt}$ ,

$$U_{vt} \geq \bar{U}_{vt} . \tag{15}$$

### 3.6 Water Allocation Efficiency

Water allocations or water policy designs can be judged from the view of economic efficiency, where water allocations are seen as a series of investment projects. Water is the limiting resource, and the economic sectors use the resource and produce economic returns. In an economically efficient water allocation, the marginal benefit from the use of the water is equal across uses in order to maximize total benefits produced by the water. Economically efficient water use in a river basin requires that the equi-marginal condition be satisfied to the extent possible consistent with hydrologic and institutional constraints. That is, the benefit from using one additional acre-foot of water (MB) by one user is equal to the incremental benefit from an acre-foot for every other user. Where this condition fails to occur, society benefits economically by allocating more water to the sector where the incremental benefits are highest.

The economic efficiency challenge posed by water scarcity is to allocate a known supply of water among all competing users to maximize the economic beneficial use of that water. Economic efficiency is achieved if this equi-marginal rule is followed,

$$MB_1 = MB_2 = \dots = MB_n . \quad (16)$$

Any policy or institution that effectively transfers the water to users who value the marginal water more also increases total net benefits produced by the water's use. People who lose use of the water lose a smaller economic benefit than water gainers gain in benefit. Finally, when enough water is transferred so that marginal benefits are equalized among all users within each state, it is not possible to increase overall total net benefits by more transfers.

### 3.7 Valuing Water in Alternative Uses

The economic value of water comes from the many uses to which water can be put in satisfying human needs. The economic value of water is defined as the amount that a rational user of a publicly or privately supplied water resource is willing to pay. Willingness to pay for water reflects the water user's willingness to forego other consumption and is measured by a demand schedule relating the quantity of water used at each of a series of different prices. For any potential quantity that could be supplied, demand is limited. So the economic value of an *added* unit of water supplied decreases as greater quantities are offered to water users. For example, most people will use water only for irrigating their lawns or for low-valued crops if the price of water is suitably cheap. At a high price, those economic values are too low to justify purchasing the water.

Quantity supplied is only one dimension of water's use. Time utility of water use can be improved by building dams and developing groundwater reserves, while location utility can be improved by building water transport systems such as aqueducts to move water to places far from the natural watercourse. Moreover, location utility itself is measured in three dimensions, since ground water is increasingly expensive to put to beneficial use with increasing depth and increased energy prices. The model described in this paper does not consider quality effects on water's value nor does it consider increasing pumping

costs with depth. Finally, water may be of varying qualities depending upon the soils through which it moves or depending on how people affect the water in supplying or using it.

### 3.7.1 Water Values in Agriculture

For the Colorado region, the economic value of water is determined using an optimization model that maximizes annual agricultural income in the San Luis Valley (SLV) 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 distributes 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 then optimized based on crop production functions and costs of production for the major crops produced in the study area (Dalsted, *et al.*, 1996; Sperow, 1998).

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 No. 1 (EP#1) near El Paso, Texas. For each of these three farming areas, agricultural prices, yields, and production costs are 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, linear programming models were 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 models are calibrated to produce optimized cropping patterns consistent with historical cropping patterns, in the spirit of the positive mathematical programming approach described by Howitt, 1995; Martinez, *et. al*, 1999; and Heckeley and Britz, 2000.

Results of these income-maximizing models are based on constraints on available land in each major cropping area and by crop-water production technologies (Ward, et. al, 2001).

Table 4 summarizes the benefit functions for these four irrigation regions. These agricultural benefit functions were developed in a previous analysis using the methods described above. After that previous analysis was completed, the functional forms and coefficients summarizing the benefit functions were used for the current model.

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: ground water 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, the table 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.

### 3.7.2 Water Values for Municipal and Industrial

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 is based on earlier work by Michelsen *et al.* (1998). That impact is measured as the willingness to pay to avoid drought damages. 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, and revenues from water sold and non-price conservation programs covering the period from 1980 through mid-1994. Across seven cities, water's demand was found to be price inelastic. A price inelastic demand means that a large percentage increases in price are required to induce small percentage decreases in water use. 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 the basin's two major U.S. cities, Albuquerque (ALB) and El Paso (EP). For each city, a linear demand schedule was defined to pass through the water use and price combination for 2003 (Ward *et al.*, 2001). 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. Table 4 shows that for each city the marginal benefits of groundwater use are lower than for surface water, because of higher pumping costs for obtaining groundwater.

### 3.7.3 Interpretation of Benefit Functions

The last column of Table 4 provides a key to interpreting the benefit functions by showing the quantity of water at which incremental benefits of additional water use is zero. That quantity of water represents the point at which the quadratic total benefits function reaches a maximum for both agricultural and M&I uses. Note that for the typical household, maximum total benefits occurs at a point of about 0.5 acre feet per household per year. For agriculture, maximum total benefits per acre occur at a much larger amount, typically larger than 4 acre feet per acre. This larger quantity of water reflects the fact that in the face of plentiful water supplies, irrigators have shown that they substitute large amounts of comparatively low-

valued water for land, labor, and other resources.

#### 4 Results

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.

Basin supply and demands for the years 1998-2003 are used for model calibration. Historic Elephant Butte reservoir volumes and actual deliveries to users downstream from the reservoir were targeted, with unmeasured groundwater return flows in the reach between Cochiti Lake and Elephant Butte Reservoir the primary calibration factor. Typical model dimensions are 112 variables, 153 equations, and 380 nonzero elements for the first year of what is typically a multiple year sequentially solved problem. Solving for the Law of the River with a 12 year time period using MINOS solver requires approximately 15 seconds of actual clock time, on a 1.8 GHZ PC with 512 MB memory running GAMS version 20.7; solutions estimating intrastate and interstate market allocations require similar total run times.

A benchmark from which to gauge future drought damages is provided by the same 1998-2003 time period. 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 2004-09 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.

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 six-year period.

#### 4.1 Impacts of Alternative Water Supplies

Table 5 shows hydrologic 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 2004-06, Albuquerque relies entirely on groundwater for its M&I use. For 2007-09, 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. The table shows total consumptive use in each sector, including use derived from surface water and pumped groundwater. Growth in M&I water use from growing demand occurs each year from 2004-2009 for both Albuquerque and El Paso.

##### 4.1.1 Law of the River

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 six-year model projections here, as they rely more heavily than agriculture on non-tributary groundwater.

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 damages occur under the largest supply reductions we consider. For MRGCD, table 6 shows that economic impacts of drought are typically 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. The Rio Grande Compact treats all use downstream of the reservoir as Texas, even though there are more than 100 miles of New Mexico left before the river reaches the Texas state line. With reduced deliveries under the Compact, Texas water users suffer considerable drought impacts. For the 2004-09 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 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.

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.

Albuquerque and El Paso M&I 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 non-tributary 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 2004-06 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.

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, 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 2006-09). 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 Intrastate Marketing

While existing water policy in the 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 M&I, El Paso agriculture, and EBID agriculture. Deliveries to Mexico are assumed unaffected by

either market. Economic impacts, summarized in table 6, 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 only a smaller loss than is produced by a drought under the Law of the River.

Introducing intrastate 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 6 by the reduced drought damages incurred by agricultural users above and below Albuquerque as well as reduced damages incurred by Albuquerque M&I 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 5 shows that total use throughout the basin varies by institution, because of compensating groundwater pumping resulting from transferred water.

#### 4.1.3 Interstate Marketing

A more geographically widespread market linking all New Mexico and Texas water users can be imagined. Colorado and Mexico could also be included in an interstate market of even larger geographic scope. This larger market is an important area for future research. New Mexico and Texas are currently the most likely trading partners. 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 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.

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 6).

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. At the 75% inflow level, 45% reductions in MRGCD consumptive use support reduced pumping by both Albuquerque and El Paso. That is, 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. 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 high-valued agricultural and M&I uses in that part of the basin.

#### 4.2 Discussion

Modeling the hydrology, economics, and policy for a complex river basin is still in the experimental stages, and will need to see considerable future development before it is in widespread use to support the design of improved policies. Model structure, simplifying assumptions, and limited data all introduce the potential for errors.

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 re-allocated 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, they should be accounted for in any comprehensive analysis of drought policy.

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, which actually occurred 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.

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 (Hanak, 2003). Designing a water market institution to protect third parties to water trades may require additional policy instruments. Conditioning water trades on a lack of objections after the seller makes a public

announcements in a local newspaper may be one way to protect third parties while promoting economic efficiency in water markets. 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.

Another important limit of our approach is the fact that only long-term average flows were considered in the model. The use of average flows sharpens our ability to simplify impacts of complex water supply patterns, but it also masks important impacts of year to year fluctuations around those long-term averages. Where streamflows fluctuate widely from year-to-year, the presence of water markets produce a larger benefit in the driest of years compared to benefits in more normal years. So the market institution takes on the role of a powerful institution for coping with risks produced by unpredictable and uncertain year-to-year supply fluctuations. The impact of lagged flows on the effectiveness of the market trading institutions are more pronounced with an increase in the number of sequential dry years.

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

In light of the emerging trends of population growth, agricultural use levels and institutions in the Rio Grande Basin, we conclude that multimillion dollar direct economic damages to water users are likely to occur when inflows to the Basin fall to between 50% and 75% of their long run averages. Under these conditions, streamflows and reservoir storage volumes are dramatically reduced. The average economic damage can be as high as \$100 per acre foot of reduced inflows to the basin, but is more often in the

range of \$25 to \$50 per acre foot, reflecting damages to agricultural, municipal and recreational users.

The development and use of an integrated hydrologic, economic and institutional model to examine a range of alternative policy responses finds considerable mitigation in drought damages result from policies such as intrastate market water transfers. Impressive reductions in drought damages compared to those that would occur under the existing Law of the River are possible if an interstate market program is enacted. This market would effectively reallocate drought-induced water losses from higher valued uses of water to lower valued uses. These larger reductions in drought damages under an interstate market program would occur as agricultural water users discover they can reduce their drought losses by trading water for money whenever the income from rented water is larger than the income produced by using the same water in agriculture. In the face of intrastate markets, the cities of Albuquerque New Mexico and El Paso Texas would lose less water to drought than they could expect to lose under the Law of the River. In much the same way as occurred with the California Water Bank established in the early 1990s, the presence of an intrastate water market in the Rio Grande Basin would considerably soften the economic blow to the region produced by drought. The institution of a water market has the effect of making the marginal benefits of water use more nearly equal among trading partners than would occur under the Law of the River.

Even larger reductions in drought damages are possible if the institution of an interstate water market can be established. However, the Rio Grande Compact precisely allocates the share of drought-induced water shortages among the three states in law, in water managers' minds, and in popular culture. Combined with a long-standing mutual suspicion among water users in the Basin, the difficulty of trading drought shortages across state lines will make an interstate water market more difficult to establish and harder to implement than an intrastate water market. That is, because of the importance of the Compact considerably more institutional flexibility will be allowed to allow water trades across state lines than within any single state. In this Basin as in most others in dry places, 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.

The model and corresponding results assume sophisticated perfectly competitive markets that internalize or include third party effects such as changes in return flows from water transfers. However, real markets are not perfect and rarely incorporate the third party effects of transactions, either hydrologic or economic. Real markets are also influenced by other factors such as transaction costs, market power and negotiating party personalities. Because of this, real markets are not able to achieve the complete benefits of transfers assumed under perfect markets and that the benefits reported above will require adjustments to reflect imperfect or real market conditions. This is an important area for future study and policy implementation.

Despite the institutional challenges of introducing water markets as a drought-coping measure, their potential economic gains are considerable. Compared to existing water allocation institutions, we find that future drought damages could be reduced by one-fifth to one-third per year under the most serious drought through intrastate and interstate water markets, respectively, that would extend across current water management jurisdictions.

6 References

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Table 1. Classification of nodes in the Rio Grande Basin Model

Set hierarchy and labels		Description	Sign of )	# elements
set	type of node			
<i>i</i>		set of all flows, occurring over a one year period	na	48
	<i>r</i>	river nodes	na	10
	<i>h</i>	headwater inflows, above all modeled diversions	+	6
	<i>v</i>	diversions for off-stream use	-	8
	<i>n</i>	return flows in current period	+	8
	<i>g</i>	lagged return flows net of impacts of groundwater depletion from pumping	+	8
	<i>b</i>	depletion by phreatophytes	-	2
	<i>c</i>	conveyance functions for unmeasured gains and losses	+	5
	<i>w</i>	set of flows linked to stocks (reservoir storage)		
	<i>e</i>	evaporation from basin reservoirs	na	3
	<i>s</i>	net contribution to flows from reservoir releases	+	3
<i>u</i>		set of reservoir stocks, measured at each year's beginning	na	4

Table 2. Hydrologic Balance, Rio Grande Basin

Item	Inflow	Diversions	Use	Seepage	Pumping	Net Seepage	Net Gw. Flow to River	Surface Return Flow to River	Evap.	Reservoir Net Release	River Flow	Reservoirs
----- Flows -----											--- Stocks ---	
Inflow	1	1									1	
Diversions			1	\$ <sub>ds</sub>				\$ <sub>dr</sub>			-1	
Use												
Seepage			-1			1						
Pumping			1	\$ <sub>ps</sub>		-1		\$ <sub>pr</sub>				
Net Seepage							\$ <sub>ng</sub>					
Net Groundwater Flow to River		1									1	
Surface Return Flow to River		1	-1								1	
Evaporation												-1
Reservoir Net Release											1	-1
River Flow		1									1	
Reservoirs									\$ <sub>e</sub>			1
Explanation	Inflow = source flows	Diversions < upstream contrib. flows (wet river)	Use = diversions - surface returns + pumping - seepage	Seepage increases with (diversions + pumping)	Pumping makes up for surface flow shortages	Net seepage = seepage - pumping	Gw flow to river increases with net seepage	Surface return flows to riv. increase with (diversions + pumping)	Evap. increases with reservoir volume	Reservoir Net Releases for Use	Gauged flow = sum of upstream contrib. flows	Reservoir level = previous level - net release

Table 3. Geographic Configuration of River-to-River Nodes, Rio Grande Basin

Node	Lobatos	Embudo	Chamita	Otowi	CO_gauge	Acacia	Marcial	EB_gauge	El Paso	Ft. Quitman
Lobatos		1								
Embudo				1						
Chamita				1						
Otowi					1					
CO_gauge						1				
Acacia							1			
Marcial								1		
EB_gauge									1	
El Paso										1
Ft. Quitman										

Table 4. Total Benefits of Consumptive use for Agricultural and M&I Uses of Water Per Acre (or per household) per year, Rio Grande Basin, Colorado, New Mexico, Texas.<sup>a</sup>

Location	Label	State	Sector	<b>\$<sup>0</sup></b>	<b>\$<sup>1</sup></b>	<b>\$<sup>2</sup></b>	<b>\$<sup>p</sup></b>	use at which MB = 0
				(\$)	(\$/acre-foot)	(\$/acre-foot <sup>2</sup> )	(\$/acre-foot pumped)	(acre feet per acre or per household, surface water)
San Luis Valley	SLV	CO	Ag	195	145	-14.0	na	5.18
Albuquerque	ALB	NM	M&I	0	10843	-9627	-10	0.56
Middle Valley	MRGCD	NM	Ag	-30	67	-5.9	na	5.68
Mesilla Valley	EBID	NM	Ag	137	94	-2.5	-76	18.80 <sup>b</sup>
El Paso	EP	TX	M&I	0	9507	-9392	-100	0.51
El Paso	EP#1	TX	Ag	0	193	-21.5	na	4.49

<sup>a</sup>The functional form for economic benefits at these nodes are: Total benefits = **\$<sup>0</sup>** + **\$<sup>1</sup>** (acre-feet consumed) + **\$<sup>2</sup>** (acre-feet consumed)<sup>2</sup> + **\$<sup>p</sup>** (acre-feet pumped).

<sup>b</sup>For EBID, incremental benefits from added water use fall slowly over the observed data range. However maximum observed use was 6 acre feet / acre, so 18.80 is a considerable extrapolation beyond observed use patterns..

Table 5. Average Annual Consumptive Use, by Institution, Drought Condition, State, and Sector, Rio Grande Basin (1000s a-f / yr),<sup>a</sup> 2004-2009

Baseline Institution and policy adjustments to drought	Drought Condition, percentage of average annual surface water supply	Colorado		New Mexico		Texas		Mexico	Total
		SLV	ALB	MRGCD	EBID	EP <sup>b</sup>	EP#1	Ciudad Juarez	
		Ag	M&I	Ag	Ag	M&I	Ag	Ag	
Law of the River <sup>c</sup>	100% (Baseline)	758 (147)	101 (75)	195 (0)	277 (68)	89 (59)	133 (0)	56 (0)	1609
	75%	625 (118)	101 (75)	195 (0)	234 (69)	89 (66)	105 (0)	44 (0)	1393 <sup>d</sup>
	50%	445 (73)	101 (75)	177 (0)	146 (69)	88 (77)	49 (0)	20 (0)	1026
Intrastate Water Marketing <sup>e</sup>	75%	625 (118)	101 (75)	195 (0)	235 (69)	89 (39)	77 (0)	44 (0)	1366
	50%	445 (73)	101 (75)	153 (0)	81 (69)	89 (41)	55 (0)	20 (0)	944
Interstate Water Marketing <sup>f</sup>	75%	625 (118)	101 (94)	96 (0)	279 (67)	89 (44)	113 (0)	44 (0)	1347
	50%	445 (73)	101 (101)	39 (0)	166 (67)	89 (45)	66 (0)	20 (0)	926

<sup>a</sup> Average annual surface supply produced by the headwater gauges is 1.57 million acre feet. Bracketed numbers are consumption from pumping.

<sup>b</sup> Annual growth in M&I demand functions are based on historical population growth of 2.4% per year for Albuquerque and 3.7% for El Paso.

<sup>c</sup>Current system operation rules maintained in the face of drought. No trading of water for cash is permitted.

<sup>d</sup>The distinction between water consumption from pumping versus surface water use is shown in the table.

<sup>e</sup>Trading water for cash is permitted within each state.

<sup>f</sup>Water can be traded for cash both within a single state and across state lines.

Table 6. 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

Baseline Institution and policy adjustments to drought	Drought Condition, percentage of average annual surface water supply	Distribution of Damages	Colorado		New Mexico		Texas		Total among Trading Partners
			SLV	ALB	MRGCD	EBID	EP	EP#1	
			Ag	M&I	Ag	Ag	M&I	Ag	
----- dollars, millions per year -----									
Law of the River	75%	drought damages <sup>a</sup>	0.7	0.1	0.0	4.9	2.3	2.1	9.4
	50%	drought damages	18.2	2.4	0.6	16.0	7.5	9.9	36.4
Intrastate Marketing	75%	drought damages	0.7	-0.2	0.0	4.9	-7.2	5.3	2.8
		cash compensation <sup>b</sup>	na	-0.2	0.0	3.4	-7.9	4.7	0.0
	50%	net damages	0.7	0.0	0.0	1.5	0.7	0.6	2.8
		drought damages	18.2	-0.2	1.5	25.1	-6.3	8.8	28.9
Interstate Marketing	75%	cash compensation.	na	-2.1	1.0	12.4	-12.3	0.9	0.0
		net damages	18.2	1.9	0.5	12.7	6.0	7.9	28.9
		drought damages	0.7	2.4	4.1	-0.1	-7.2	1.3	0.5
	50%	cash compensation	na	2.4	4.1	-0.4	-7.3	1.2	0.0
		net damages	0.7	0.0	0.0	0.3	0.1	0.1	0.5
		drought damages	18.2	3.5	7.8	13.4	-7.2	6.9	24.4
		cash compensation.	na	1.9	7.4	2.7	-12.2	0.3	0.0
		net damages	18.2	1.6	0.4	10.7	5.0	6.6	24.4

<sup>a</sup> Baseline means 100 percent 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. Because of the difficulty of assigning recreation benefits to state of visitor origin, recreation benefits are not included in drought damages.

<sup>b</sup> 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.

7 Figures

7.1 Figure 1: Upper Rio Grande Basin Map



7.2 Figure 2: Interaction of Flow Elements for Rio Grande Basin Model

