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Economic Costs of Sustaining Water Supplies: Findings from the Rio Grande

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Economic Costs of Sustaining Water Supplies: Findings from the Rio Grande

Abstract

Water claims in many of the world's arid basins exceed reliable supplies. Water demands for irrigation, urban use, the environment, and energy continue to grow, while supplies remain constrained by unsustainable use, drought and impacts of climate change. For example, policymakers in North America's Upper Rio Grande Basin face the challenge of designing plans for allocating the basin's water supplies efficiently and fairly to support current uses and current environments. Managers also seek resilient institutions that can ensure adequate supplies for future generations. This paper addresses those challenges by designing and applying an integrated basin-scale framework that accounts for the basin's most important hydrologic, economic, and institutional constraints. Its unique contribution is a quantitative analysis of three policies for addressing long term goals for the basin's reservoirs and aquifers: (1) no sustainability for water stocks, (2) sustaining water stocks, and (3) renewing water stocks. It identifies water use and allocation trajectories over time that result from each of these three plans. Findings show that it is hydrologically and institutionally feasible to manage the basin's water supplies sustainably. The economic cost of protecting the sustainability of the basin's water stocks can be achieved at 6 - 11 percent of the basin's average annual total economic value of water over a 20 year time horizon.

Economic Costs of Sustaining Water Supplies: Findings from the Rio Grande

1. Background

Twenty-first century decision-makers face an array of challenges in the search for sustainable

environmental policies. In most river basins, actions taken for one use, at one place, or in one period

affect water quantity or quality for another use, at another location, or in another period. For this

reason there is considerable need for integrated water resources management (IWRM) plans that

couple the physics governing water stocks and flows with economic and institutional factors affecting

water's demands and supplies. Decision makers need integrated plans that help them identify the full

range of current and future consequences associated with various management strategies and growing

resource demands in the face of current or altered climate. A water manager may need access to an

integrated framework to evaluate effects of drought on water supply as well as its impacts on other

systems such as key ecological assets, agriculture, urban water use, and economic development.

Effectively managing complex water systems for the benefit of current and future generations is an

ongoing challenge facing contemporary water managers. A single, integrated basin-scale plan presents

several advantages for managers, farmers, and the water-using public in the search for better

performing institutions:

- It offers a clear view of water resources in a river basin, where water goes, how it's used, and
  how much remains available for further use.

- It identifies opportunities for saving water and increasing its economic productivity.

- It pinpoints times and places where water can be transferred from lower- to higher-valued uses.

- It helps identify opportunities to reduce evaporation, pollution, or water flows into non-retrievable sinks.

- It helps conceptualize and test for hydrologic and economic impacts of proposed actions in several time periods for many uses.

- It identifies economically efficient ways to improve the productivity of water and reduce its waste.

- It provides a language and forum for debating water policy choices.

- It can reduce water conflicts by presenting information used to support decisions.

Many researchers have recognized the power of basin scale analysis, and several basin-scale analyses have been developed and applied since the mid 1990's. Booker and Young (1994) and Booker (1995), in two celebrated studies, developed and applied an integrated hydrologic-economic-institutional analysis of the Colorado River Basin covering its seven US states. More recently, several kinds of hydro-economic water resource system management models have been published: large-scale integrated river basin scale models applied to predict economic impacts of policies for managing droughts (e.g., Characlis et al., 1999; Booker et al., 2005; Ward et al., 2006); assessments of the economic value of streamflow by location in a basin (e.g., Brown, 1990; Willis and Whittlesey, 1998; Newlin et al., 2002, Pulido-Velazquez et al., 2006; Jenkins et al., 2006); optimal system operation (e.g., McCarl et al., 1999; Watkins and McKinney, 1999; Pulido-Velazquez et al., 2004); water allocation and policy options (e.g., Letcher et al., 2004); water transfers and water markets (e.g., Rosegrant et al., 2000, Draper et al., 2003; Knapp et al., 2003; Ward et al., 2006; Jenkins et al., 2006), analysis of infrastructure investment (e.g., Cai and Rosengrant, 2004; Ringler et al., 2004, Cai et al., 2006), analysis of trade-offs among competing uses

(Ward and Lynch, 1997; Burke et al., 2004; Watkins and Moser, 2006), and assessments of regional

economic impacts of climate change and its adaptation (e.g., Tanaka et al., 2006).

This *Journal* has blazed new trails in recent years by publishing numerous applications of IWRM to

inform water policy debates on workable measures to promote sustainable water resource systems. For

example, Zarghaami (2006) showed how an IWRM approach could solve irrigation management

problems and as reduce social conflicts in northern Iran. Flugel (2007) developed an integrated basin

scale analysis applied to inform food and environmental policy debates for the Tisza River basin that

rises in Ukraine. Murad et. al (2007) addressed the problem of scarce water in the United Arab Emirates

as limiting sustainable development. The authors found that water scarcity problems there could be

alleviated by implementing an IWRM strategy that including development of non-conventional water

resources. Pascual (2007) found that assessments of social, environmental, and economic impacts, as

advocated by the European Commission could support better administration to IWRM principles.

Schulze (2007) characterized differences between IWRM in Lesser Developed Countries (LDCs) and

Developed Countries (DCs) by outlining characteristics of LDCs and DCs that shape their respective

needs for IWRM. Van der Keur, et. al (2008) characterized uncertainty in the different stages of the

IWRM process with respect to sources, nature and type of uncertainty, and applied their framework to

the IWRM process to inform policy debates in the Rhine Basin. El-Naqa and Al-Shayeb (2009) presented

the status of groundwater resources in Jordan and identified major management challenges from an

IWRM view.

Molina et al (2009) applied IWRM to the water system of the Altiplano region in Murcia, Spain, where

aquifer water extraction exceeds recharge for a highly profitable irrigated region. Prodanovic and

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Simonovic (2011) presented a model for operational support of integrated water resources management in the Upper Thames watershed, Ontario, Canada. Results indicated that water supply will be a limiting factor for future growth and development. As these examples show, considerable advances have been made in basin scale analysis in recent years. Despite these impressive achievements, we have been unable to find any published work that has used a comprehensive basin scale approach to examine the economic cost of reducing current water uses to support more sustainable water supplies. We also have found few if any published works that have identify the kinds of policies that could be implemented to sustain those supplies. Finally, we are also aware of no works that conduct an analysis of how to manage transboundary river basin as a single unified resource that also looks for a management scheme that integrates water needs and economic values of water for the various water-using sectors. The sectors needed for such a comprehensive analysis include economic production of different types, environmental needs, and human direct water consumption demands.

This paper addresses those gaps by designing and applying an integrated basin-scale constrained optimization framework that identifies water allocation and use patterns for the Upper Rio Grande Basin of North America (the Basin). This paper's novel contribution is a comprehensive basin scale analysis of the impact of three policies for achieving sustainability goals for the Basin's most important reservoirs and aquifers. It identifies changes in water use patterns, water allocation, and the level and distribution of economic benefits produced by water that result from each of three policies that address sustainability targets for the basin's water stocks. The approach taken by the paper is practical: it focuses on the costs and benefits to be derived from various management schemes. It is based on the need faced by water managers and political leaders who wish to focus on practical and realistic measures to achieve sustainable water supplies in a complex river basins containing a wide range of interdependent water uses.

2. Study Area

2.1 Rio Grande Basin

The Basin flows from its headwaters in southern Colorado to about 70 miles south of the US-Mexico

border cities of El Paso, Texas - Ciudad Juárez , Mexico (Map). Surface water and groundwater from the

river system meets the primary water needs of three major cities of Albuquerque, New Mexico and El

Paso, Texas in the US in addition to the Mexican city of Ciudad Juárez. 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. Depending on the

year, about 85 percent of the consumptive use of water in the Basin is used for irrigated agriculture.

Only about 47 percent the water applied to crops is consumed under current conditions as ET. The

percentage that is applied but not consumed in the irrigation field where water is applied is an

important water source for groundwater recharge, riparian habitat, and return-flows to downstream

human and environmental uses in current and future generations.

The Basin's water managers face several international, federal, regional, state, and regional institutions

that regulate water flows and allocations. These include an international treaty between Mexico and the

US; the Rio Grande Compact among Colorado, New Mexico and Texas, engagement of a number of US

federal agencies, state statutes, ongoing litigation, and numerous water delivery contracts. While

existing institutions for allocating water have served the basin well in recent decades, there remains

considerable interest in the design and evaluation of alternative potentially more resilient institutions

that could better meet the needs of the Basin's current and future residents.

2.2 Sustainability Issues

Basin managers and policymakers confront numerous water issues and choices issues that require a comprehensive sustainable basin scale IWRM view. Examples include:

• third-party impacts of water transfers

• economics of developing and using alternative water sources; for example, desalination, recycling, or reuse for urban and environmental water supplies.

• wastewater reuse for irrigated agriculture

• improved agriculture irrigation efficiencies and shifting to higher value crops or more water-conserving irrigation technologies

• design of resilient institutions to address climate change

• economic and hydrologic impact of climate change on current and potential water decisions

These and other policy debates can be informed more comprehensively with a basin scale view than with analysis conducted for a single sector, location, or period. The Basin's demands for water continue to grow, especially in the urban areas of Albuquerque, El Paso, and Ciudad Juárez. As environmental and urban demands increase in the face of constant or decreasing supplies, various governments, farmers, urban planners, and commercial developers are looking for ways to access and manage increasingly scarce water. Across the Rio Grande from Ciudad Juárez, El Paso water managers continue to examine measures to manage growing demands for water. The present El Paso Texas - Las Cruces New Mexico area population of about 2 million is expected to triple in the next 25 years. The only renewable water source in the lower part of the basin is the Rio Grande itself. These few examples emphasize the importance of the continued search for resilient institutions that would promote sustainable use of the Basin's water. Approaching these issues objectively can be handled more comprehensively with a basin scale approach in which all water uses, use locations, water sources, and time periods are handled simultaneously in a unified analytical framework.

3 Water Institutions

Water institutions are structures and mechanisms of social order governing the behavior of a set of individuals within a group. Often implemented as written or informal rules, they are instruments for defining, constraining, or adjusting individual behavior to improve society's current or future welfare. Four institutions in the Basin stand out from the rest in importance: the U.S. Mexico Treaty of 1906, the U.S. Endangered Species Act of 1973, the Rio Grande Compact of 1938, and the New Mexico-Texas water sharing convention.

3.1 International

Water allocations and use patterns in many of the world's basins are constrained and defined by various trans-boundary water sharing agreements. Finding ways to meet obligations specified by existing water sharing agreements, where they exist, is a major source of political tension in the world's arid basins, and carries with them considerable economic implications. For an upstream political unit to meet its formal or informal water delivery obligations imposes a considerable economic cost. Failure to meet it can impose high economic costs borne by the downstream region or country. For the Basin, a significant trans-boundary agreement is the U.S. Mexico Treaty of 1906, which requires that the U.S. deliver 60,000 acre-feet (1 acre foot = 1233 cubic meters) per year to Mexico, except in times of extraordinary drought. Our framework requires the U.S. to deliver 60,000 acre-feet to Mexico in all years and in all drought conditions.

3.2 National

The U.S. Endangered Species Act (ESA) provides protection for various species of fish, wildlife and plants that are listed in the U.S. as threatened or endangered. Provisions are made for listing species, for

recovery plans, and for designation of critical habitat for listed species. The ESA prohibits federal

agencies from actions that jeopardize the continued existence of any endangered species. It prescribes

measures for federal agencies to follow when taking actions that may jeopardize listed species. Its

purposes are to: provide measures for conserving the ecosystems upon which endangered and

threatened species depend; provide programs for conserving those species; and take steps needed to

achieve the purposes of international treaties and conventions. A biological opinion issued by the U.S.

Fish and Wildlife Service in 2001 estimates that bringing the endangered Rio Grande Silvery Minnow

(the Minnow) back from the brink of extinction requires at least 50 cubic feet per second (cfs) of year-

round streamflow at the San Acacia gauge near Socorro, New Mexico (Map). Our analysis requires

annual flows at that gauge to exceed a critical level required for the minnow's survival, about 240,000

acre-feet per year under recent operating conditions.

3.3 Inter-regional

Many of the world's river basins contain rivers that cross international boundaries. In many cases,

formal or informal transboundary water sharing agreements have been established. In the western U.S.,

twenty two trans-boundary water sharing agreements have been established as interstate compacts.

Typically, under a compact arrangement in this part of the world, two or more states agree to share a

river's natural flow, in which the federal government serves as the referee. The first such agreement was

the Colorado River Compact, signed by the Colorado River Basin states, at Bishop's Lodge, New Mexico,

in 1922.

The Rio Grande Compact (the Compact) – signed in 1938 by Colorado, New Mexico, and Texas – divides

the annual flow of the Rio Grande. The Compact was established so that each state receives more water

in wetter years and less in drier years. Under the Compact, Texas bears the largest percentage of flow

shortages in dry years, but it also has the largest amount of storage to capture high flows in wet years.

Colorado has the least reservoir storage capacity, so it negotiated the highest percentage of natural

runoff in the driest years to compensate for its limited reservoir storage. Articles III and IV of the

Compact oblige Colorado to deliver water at the Colorado-New Mexico state line (Map). Article V of the

Compact and the 1948 resolution of the Compact require New Mexico to deliver water to Texas

measured at the outflow of Elephant Butte Reservoir. 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 (New Mexico Water Resources Research Institute, 2006).

3.4 Intra-regional

Many western U.S. river basins as well as a number of other countries have established informal intra-

basin water sharing agreements, by which historical water use patterns are used as a framework for

sharing water, and for influencing the future course of economic and water use growth. Since the early

1950's, the U.S. states of New Mexico and Texas have agreed to share water delivered by the Rio Grande

Project, for which outflows occur at Caballo Reservoir (Map). Based on historical agricultural land in

production in New Mexico and Texas at the time of the Rio Grande Project's construction, U.S. lands in

New Mexico receive deliveries of up to 57% of any year's allocation, while lands in Texas have received

up to 43%, for a total of up to 100%. In recent years, much of the current Texas allocation actually goes

to urban users serviced by the City of El Paso. Recently west Texas irrigators have found it more

profitable to rent or sell water or water rights to the City of El Paso rather than using it for economically

marginal crops. When total use for any given year is less than 100% of available project storage, the

unused part is held in project storage at either Elephant Butte or Caballo Reservoirs for future use. A

2009 agreement between southern New Mexico and west Texas water users increased the incentive to

hold unused water in those two storage reservoirs for the future rather than using it immediately on low

valued crops.

4 Methods

Our approach for analyzing the economic costs of securing sustainable water supplies is based on the

development of a dynamic constrained optimization framework. An empirical model is developed and

applied that shows results of a policy that allocates stocks and flows of water over time, space, and use.

The objective is to maximize water's discounted net present value subject to various hydrologic and

institutional constraints. In measuring the economic value of water, we account for the fact that the

economic value of water comes from the many uses to which water can be put in satisfying human

wants and needs, including the satisfaction received from water based recreation at the Basin's

reservoirs. The economic value of water is defined as the amount that a rational user of a publicly or

privately supplied source of water is willing to pay. Economic values for different water uses are defined

according to their marginal value in production, consumption, or state of the environment. There is an

extensive literature on valuation of water to determine water demands for its many uses and many

dimensions of quality improvement, recently reviewed and updated by Young (2005). Valuation

approaches for irrigation, urban use, and outdoor recreation are described briefly subsequently.

4.1 Integrated Management of Transboundary Waters

Internationally, numerous communities who share supplies of transboundary waters face a common

challenge: continued population growth and economic development will increase water demands for

energy production, irrigation, industry and domestic use at the regional level while key ecological assets

need to be maintained or restored. Seen in this light, the pressure on freshwater resources in these

transboundary basins will increase unless active measures are taken to secure more economic and

environmental value from existing water resources for all the communities (e.g., states or countries) tied

by the common water. Especially in river basins like the Tigris-Euphrates, Jordan, Nile, and Amu Darya,

integrated transboundary water resource management presents an important mechanism for

promoting the common agenda of peace, trust, stability and economic development.

The development and application of analytical capacity to inform IWRM helps to identify options to

secure more benefits from water resources development and management in the world's

transboundary basins. While our analysis was limited to the Rio Grande Basin of North America, its

approach has implications for transboundary waters everywhere where there are debates over the

sharing of water or sharing benefits from water. Both water sharing and benefit sharing have the

potential to promote regional cooperation, secure economic and political stability, and opening up

opportunities for cooperative economic development in communities often hydrologically, politically, or

culturally isolated from each other. Results from our IWRM exercise illustrate the common frame of

reference that could provide stakeholders access to a consistent set of basin scale information. This

common frame of reference has the potential to build understanding and seek cooperative solutions on

regional water development challenges.

4.2 Data

4.2.1   Water and Water Use Patterns

The Basin has four major US agricultural producing areas (Map): they include the Rio Grande Water

Conservation District (2011) in the San Luis Valley (SLV) of southern Colorado; the Middle Rio Grande

Conservancy District (2011) in central New Mexico (MRGCD); the Elephant Butte Irrigation District

(2011), in southern New Mexico (EBID); and the El Paso County Water Improvement District#1 (2011) in

far west Texas (EP#1). Each of these areas uses surface water for agricultural production; however, only

SLV and EBID pump significant amounts of groundwater for irrigation. MRGCD and EP#1 have access to groundwater but neither has developed much groundwater pumping infrastructure for irrigation as of 2012. The Basin's two US urban water use areas in the model are the City of Albuquerque, New Mexico (2011) and the El Paso Water Utility (2011).

Modeled flows include headwaters inflows (supplies), impacts of groundwater pumping on streams and aquifers, and net reservoir releases from storage, pumping from aquifers, irrigation and urban diversions, crop water ET, aquifer recharge, groundwater flow to or from the river, surface water return flow to the river, and reservoir evaporation. The model includes major functions that influence streamflow at each node as well as impacts of each important activity upstream of that node. The mass balance for reservoirs is given by starting storage minus reservoir releases plus river inflows to the reservoir minus evaporation. For groundwater storage changes in any period, the stock of groundwater is represented through effects of current and past seepage, water applied to crops, and water pumped for irrigation and urban uses. Work is ongoing to develop of a set of unifying groundwater equations implemented at the basin scale through a US Geological Survey MODFLOW type of mechanism with more precise linkages governing stream-aquifer interactions.

4.2.2   Economic Value of Water in Alternative Uses

The integrated basin analysis is formulated as a mathematical optimization of the Basin's water allocations using the General Algebraic Modeling System (GAMS). The integration of economic, hydrologic, and institutional characteristics provides a mechanism for conducting analyses of various policy choices with complex impacts on the hydrology, agronomy, and economics of a river basin (e.g., Ward and Pulido-Velazquez, 2008; Gürlük and Ward, 2009).

The value of urban water use is measured as revenue collected by the utility water supplier plus any

unpriced consumer surplus (Ward and Pulido-Velazquez, 2008). Urban use produces an economic

benefit by consuming water. Benefits and costs were measured for urban use at the Basin's two

important U.S. cities: Albuquerque, New Mexico, and El Paso, Texas. We adapted the empirical demand

elasticity estimates from the study of Michelsen et al. (1998) to the climatic and demographic conditions

of Albuquerque New Mexico and El Paso Texas. In that previous study, seven study areas were selected

in southern California, Colorado, and Arizona. The absolute value of price elasticities varied from a low

of about 0.05 to a high of about 0.20 for summer outdoor landscape use. For each city, a linear demand

schedule was specified to pass through the water use and price combination for 2010, in which the

slope of that schedule was chosen to be consistent with the above price elasticity at that point. We used

the integral of the marginal benefits of water use to measure total benefits of urban use. A linear

demand function results in a quadratic total benefits function, for which those total benefits are

maximized at the level of water consumption that occurs at a zero price (zero marginal benefit).

The economic value of the water environment is measured by the willingness to pay for water based

recreation in the Basin's six major reservoirs, based on a regional travel cost model (Ward et al., 1997),

updated with visitation data collected in 2003 at several New Mexico State Parks. The economic value of

water in agriculture is measured by its contribution to producer net income. Our economic analysis of

irrigation rests on a foundation of farm level economics. The farm economics is analyzed thorough the

use of enterprise budgets (e.g., Hawkes and Libbin, 2011). They summarize the economics of irrigated

agriculture in the Basin, and are published by the respective three state land grant universities

agricultural extension services: Colorado State University, New Mexico State University, and Texas A&M

University. The budgets contain detailed financial information regarding flood-irrigated crop production,

including crop acreage, equipment, crop production processes, and overall crop cost and return

summaries. The published budgets typically contain detailed financial data for agricultural production,

typically based on flood irrigation, by far the most common irrigation technology used in the Basin.

4.3 Model Development

The Basin's IWRM model was developed to bring the region's hydrology, agronomy, economics, and

institutions within a single framework for policy analysis. The model starts with the basic water supply,

which includes all major tributaries, interbasin transfers, and hydrologically connected groundwater.

Current and projected water demands for the model's 20 year time horizon include agricultural

demands for the basin's major irrigated areas, urban demands for Albuquerque and El Paso, recreation

at all major reservoirs, and streamflow requirements for endangered species. The model is formulated

to maximize discounted net present value over water uses and environments. It sums benefits from

water diversions for off-stream uses plus environmental values of reservoir-based recreation.

Constraints are used to characterize the basin's hydrology and institutions. In the model, reservoir

contents, water applications, water return flows, groundwater pumping, aquifer recharge, and water

uses are optimized over the model's time horizon, based on a stochastic representation of headwater

inflows with means and variances of historical inflows, adjusted for a future of climate change in which

future mean inflows are reduced, while maintaining historical variances.

The model accounts for decisions made by water users that support both water use and the water

environment. Economic benefit functions are defined for the basin's four major farming regions, for

urban users in the two US cities described above,[1] and for water based recreation in the basin's six most

important reservoirs. The model accounts for irrigation decisions by the use of economic data from farm

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[1]The use for urban water is specified as a linear demand functions, calibrated to match recently estimated use levels and price elasticities of demand for each city. Demands are satisfied to meet growing demands in the face of growing populations. Population growth rate projections used for our analysis for the two cities are: Albuquerque at 2.4 percent per year and El Paso at 3.8 percent per year. Costs of urban water supply include costs of pumping, treating, and delivering the water.

enterprise budgets. On farm irrigation decisions are based on irrigators choosing a crop mix and a

quantity of surface and groundwater for known crop prices, crop yields, farm production costs, and the

price of water. Changes in the price or availability of water alter land in production, farm income, and

crop mix.

The integrated framework allows analysis of alternative water management proposals. It accounts for

physical interactions among uses (agricultural, urban, streamflow, and environmental), storage

(reservoirs and aquifers), flows (diversions, pumping, applications, seepage, and return flows), and

losses (field, canal, conveyance, and reservoir evaporation). Booker et al (2005), Ward et al (2006), Ward

and Pulido-Velazquez (2008) present detailed mathematical documentations of earlier versions of the

model applied to the Rio Grande Basin. While the model was originally developed to applied to policy

debates in the Rio Grande Basin, it was designed to be adaptable with minimum structural change to

other basins, geographic configurations, land tenure arrangements, cultures, legal systems, and formal

and informal water allocation rules. To date, the original Rio Grande Basin model has been successfully

adapted several other basins. These include Egypt's use of the Nile (Gohar and Ward, 2010) to the

Nilufer Basin in Turkey with mathematical documentation (Gurluk and Ward, 2009) and to the Balkh

Basin in Afghanistan (Torell and Ward, 2010), with ongoing but as yet unpublished work in the Amu

Darya and Tigris-Euphrates Basins.

4.4 Total Economic Efficiency of a Policy Proposal

A significant question facing water policymakers who wish to analyze impacts of decisions at the basin

scale centers on the measurement of economic efficiency gains produced by a proposed water decision

for a given climate scenario. We use a method that accounts for economic efficiency by computing four

important kinds of benefits and costs for each location in the basin where economically important values of water occur.

For each of the nodes described above, our model calculates (1) use-related benefits, (2) use-related costs, (3) environmental benefits,[2] and (4) environmental costs. For any node, total net benefits in a single period equal total benefits minus total costs. Total benefits equal the sum of (1) and (3), while total costs are the sum (2) and (4). Based on this computation for any node and for any program of measures, we calculate the discounted NPV of use-related net benefits added to environmental net benefits, summed over uses and time periods. Applying this method to calculate and compare use-related net benefits to those net benefits arising from a quality environment, we measure total opportunity costs of any program of measures as the efficiency change it brings about, positive or negative. Compared to a given baseline program of measures, the total economic efficiency change, positive or negative, resulting from a different program is the present value of the total change in net benefits.

4.5 Analysis of Three Policies

The model constrains water allocations to produce outcomes consistent with the four water institutions described above. These institutions include: (1) International Treaty, (2) Federal Law; (3) Interstate Compact, and (4) Instrastate Agreement. We characterize these four institutions as the "Law of the River." In the model, solutions representing water allocations under the Law of the River combined with any of the three programs described below are obtained through a one shot optimization. For each policy the model maximizes basin-wide discounted net present value at a two percent discount rate, subject to constraints defined by the Law of the River in addition to requirements of the basin's

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[2]Environmental recreation benefits at each reservoir are specified as a quadratic function of reservoir area.

hydrologic continuity for surface water and groundwater. These four institutions place limits on storing, moving, pumping, evaporating, and applying water, while allowing the model to compare three alternative programs: unsustainable natural capital, sustaining natural capital, and renewing natural capital, all of which are described below.

4.5.1 Unsustainable Natural Capital

A policy of unsustainable natural capital promotes natural capital (water) being used up faster than it can be replenished. Sustainability requires that human activity uses only nature's water resources at a rate at which it can be replenished naturally. For purposes of this paper we define unsustainable institutions as those that reduce the Basin's long-run water supply stocks. This concept is implemented by the simple method of placing no requirement whatsoever on terminal reservoir storage volumes or aquifer stocks. Reservoirs and/or aquifers can be run down as low as desired in the terminal year with no regard for future generations. The only current economic cost that direct groundwater users confront when pumping aquifers unsustainably is the increased pumping costs incurred by that pumping. Additional pumping takes place as long as the economic value of the pumped water exceeds the additional cost of the pumping and as long as the current installed pumping capacity is enforced.

Beyond these marginal costs, there are no special incentives to conserve water for the future or to internalize the external pumping costs. External impacts in groundwater use are pervasive (National Research Council, 1997; Livingston and Garrido, 2004). When resource users do not bear the full costs of their actions, private and social costs diverge. In addition the individual pumper is unable to capture the future value of the resource, and there is a perverse incentive to develop and use the resource more intensively than is economically efficient from the view of social costs and benefits (Brown et al., 2000; Livingston and Garrido, 2004; Koudouri, 2004).

This Basin is for the most part currently managed with more emphasis on current flows and uses than on future reservoir and aquifer stocks. So this description of unsustainable management approximately replicates the way water is currently managed in the Basin, in which little thought is given to water stocks available for future generations.[3] No part of the current Law of the River described above explicitly calls for maintaining or increasing storage of the basin's water stocks.

4.5.2   Sustaining Natural Capital

Freshwater supplies in most watersheds fluctuate considerably from period to period. Even without human intervention, streamflows and aquifers can experience considerable fluctuations over the short, medium, and long term. For our purposes, we characterize the sustaining long term natural capital as occurring when any water management program succeeds in returning each Basin reservoirs to at least 80 percent of maximum storage capacity[4] and also returns all aquifers to their starting (2010) levels by then end of the 20 year planning period. The Basin's total reservoir storage at the beginning of 2010 was about 1.1 million acre feet, 22 percent of its maximum storage capacity. So the requirement of sustaining natural capital would raise terminal period reservoir storage levels by about 3 million acre feet compared to 2010 conditions.

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[3]However, the City of Albuquerque in 2008 completed a surface water treatment plant in which the City's reliance on the local depletable aquifer was greatly reduced.

[4]The baseline policy of 'Unsustainable Natural Capital,' desribed above, sets no requirement whasoever for returning any of the basin's reservoirs to any level at the end of the planning horizon. However for a policy of 'Sustaining Natural Capital,' described here, a requirement of returning reservoirs 80 pecent of maximum storage capacity might be too demanding, too artificial, or both. Historically, many reservoirs in the basin almost never reached 80 percent of maximum capacity. Reservoirs in many of the world's dry regions are designed to be oversized to deal with short wet periods in addition to capturing intra- and inter-year carryover storage; One way to define reservoir sustainability that's common in the reservoir optimization literature is to require that they return to their starting levels. Yet, this, too is artificial: starting levels may be unusually low because of recent droughts, so they are hardly a target for sustainability. They may also be too high because of recent floods, so they, too, are unrealistic as a sustainability target. Any reservoir sustainability target raises hard questions.

4.5.3 Renewing Natural Capital

Both the principle and implementation of sustainable water institutions are subjects of intense debate. One dimension of that debate focuses on the substitutability between the economy and the environment or between natural capital and manufactured capital, a debate often couched in terms of weak versus strong sustainability (e.g., Tietenberg, 2009). For purposes of this paper, we view a policy that renews the basin's natural capital in water in terms of the basin's water stocks. Our approach recognizes that the existing stock of water must be maintained and enhanced because the functions it performs cannot be duplicated by other resources.[5] We consider capital stock renewal as requiring the basin's terminal period reservoir storage to reach 90 percent of their maximum capacity, about half a million acre feet more terminal storage than achieved under the sustainable policy.[6] In addition the four major regional aquifers under this scenario must return to at least as high a level as occurred under the policy that sustains natural capital described above.

For all three policies, water inflows produce stochastic supply levels to the basin for twenty consecutive future years, 2010-2029. That is, the model starts out with very low reservoir levels in 2010 produced by several sequential dry years. These current starting conditions are combined with the assumption that inflow conditions over the next ten consecutive years will equal to long term mean inflows at each of the headwater (inflow) nodes for the period of record. Inflow variation from one year to the next matches historical variance for the period of record. Climate change is addressed simplistically by reducing mean inflows in the last ten years of the model to 95% of their historical mean while

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[5]This ignores the possibility of importing water from other basins, but recognizes that these imports, if carried out, would impose considerable environmental, economic, and political cost.

[6]The standard of 90 percent of maximum capacity poses all the problems of using 80 percent. However one justification is the recognition that 90 percent would provide an additional 500,000 acre feet of storage compared to 80 percent. That addition could be a cushion for dealing with future climate change that produces significantly less inflow to the Basin than produced under historical inflow patterns.

maintaining historical year to year inflow variance. Many other approaches could be used to examine

potential impacts of climate change.

4.6 Institutions v. Policies

The four existing institutions described above are quite important and are not trivialized by any of the

three US states involved. The four institutions amount to constraints that define or limit the basin's

water use patterns. Those four institutions (Law of the River) are required to be followed for all three

policies we analyze, also described above. These four institutions are absolute requirements that are

maintained throughout our policy analysis. All four are respected and enforced throughout the basin,

regardless of cost or consequence. All four are constraints that are satisfied for the entire period of our

analysis, reflecting the recent historical administration of water in the basin. These institutions are

required to be enforced and are independent of which people, nations, or water users have more

political strength or influence. By contrast, we describe three water sustainability policies as three

competing water resource management aims. No more than one can of the three policies can occur at

any one time. Each of those three policies respects all four existing institutions described above.   These

policies reflect three competing targets that could influence the long-term management of the basin's

water. Each has an economic cost of its implementation that we present in the results.

4.7 Measures to Implement Policies

4.7.1   Water Rights Adjudication

Clear definition of the property right to use water can be an important foundation for a range of policies

that can could support and sustain a river basin's future water supplies. Water rights adjudications are

important because they can clarify property rights to use water as well as simplify administration of

programs to limit current water uses to sustain future supplies. A stream adjudication settles all claims

of water right holders with respect to each other within a particular water system, such as a river basin.

For example, in the US, a stream adjudication is typically a legal process conducted through the courts used to determine the extent and validity of existing water rights. It can determine rights to either surface water or groundwater. It creates no new wet water. It merely establishes existing water rights, often in terms of priorities among the competing users who claim the right to use water from a stream-aquifer system. An adjudicated water rights for any user is defined as the right to take water from the system. That right can vary according to the basin's water supply level. An adjudication is a mechanism to provide legal certainty for water right holders. When a court adjudication confirms a water right, that right becomes enforceable against other water users and can be protected from impairment by illegal non-adjudicated users.

Adjudicated rights are regulated in favor of senior water right holders during times of water shortage induced by drought or climate change. Adjudication provides a foundation for managing the use of water in an orderly way, especially important when water supplies vary from one period to the next. Adjudicated stream systems greatly simplify the process of water right transfers to support sustaining aquifers and reservoirs of the kind described in this paper. In fact, water right transfers in all three of the Basin's US states are both legal and common. The Cities of Albuquerque and Las Cruces, New Mexico have both entered the market for land/and or water several times since the 1980s to purchase farms and/or farm water to firm up their future supplies to meet their urban demands. A considerable amount of West Texas farm water use has also been transferred to the rapidly growing City of El Paso Texas since the 1980s. So in this Basin, market-based water transfers from farms to cities have been for many years a common and ongoing institution for adapting to growing urban demands in the face of limited supplies.

When the legal clarity of water rights suffers from a cloud of uncertainty, common in non-adjudicated streams that typically occur outside the western world, it's difficult to assure that a water right purchase for aquifer recharge actually achieve its mission by reducing current uses. Without reducing current uses, an aquifer will see little additional recharge, so the water right purchase will have little effect. A recently published paper shows how to calculate the impacts and economic benefits of adjudicating a stream system in the case where adjudicated water rights do not currently exist (Torell and Ward, 2010).

4.7.2   Payment for Sustainability Services

We introduce the label Payment for Sustainability Services (PSS) as a broad label for any kind of market-based mechanism used to redirect current water depletions for urban or agricultural back into recharge of aquifers or filling reservoirs. For the purposes of this paper, we define PSS as a voluntary transaction where a well-defined water right buyer retires[7] an existing use of water, and uses that water to recharge an aquifer or refill a reservoir by more than the recharge that would have otherwise occurred. Where a water rights system currently exists through a formal adjudication or other culturally compatible mechanism that recognizes property rights, PSS could offer an efficient policy instrument for recharging water systems for sustainability. In the Rio Grande Basin, the two largest water users are farms and cities. A PSS buyer could be the state, an environmental organization, a city, or a group of farmers, any of whom is willing to pay to sustain or renew the basin's aquifers and/or reservoirs.

PSS buyers could retire surface water or groundwater use rights.[8] With surface water rights retired, the hydrologic effect of a PSS is to reduce the use of surface diversions, for which water savings from

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[7]Sometimes short term "contract water" can be purchased without buying the water right. A water right is the right to continue using water for the indefinite future, while a contract to use water carries no such right.

[8]When a groundwater right is bought, groundwater extractions (abstractions) are reduced. So if the PSS buyer bought a groundwater right, there is no need to recharge the aquifer with the purchased water, since the reduced pumping would effectively do the recharging.

reduced use could be re-injected into a regional aquifer. The retirement would reduce overall surface

diversions. Since the PSS as described here would not be used for current (beneficial) use, it would likely

need a legislative authority to define PSS as a beneficial use. In regions of the world where water law is

based on the prior appropriation system, such as most of the American west, lacking the label of

beneficial use presents a problem for sustaining water stocks. Lacking the tag of beneficial use, aquifer

recharge through PSS purchases risks presenting a similar legal challenge as seen by instream flow rights

when instream flow is not defined as a beneficial use of water.

4.7.3   Cap and Trade

Cap and trade arrangements are becoming increasingly common in water resources management as a

market trading mechanism to move water to sustainable uses. Cap and trade is a potentially workable

policy instrument to move water into more sustainable uses in communities where formal water rights

systems do not currently exist. A recent paper by Speed (2009) described efforts in China by water

planners who are beginning to take steps down this path. Cap and trade could be especially attractive in

many developing countries that currently have no legal foundation supporting well-defined, secure, and

transferable water rights assigned to water users.

In conditions where formal water rights do not exist, a cap and trade program could be used as a policy

measure to sustain regional aquifers. If established in places where formal water rights do not currently

exist, a cap and trade arrangement could have several features that promote the movement of water

into sustainable uses. It could be a culturally acceptable way to reduce water use by sending the right

water price signals to irrigators and to urban water suppliers. Under the program, all farmers could be

assigned a water entitlement per unit land irrigated, namely the cap. Urban water suppliers could be

assigned an equivalent cap, based on a politically negotiated level of water need for basic subsistence

needs per household.

The cap could be established for both agriculture and urban users based on a presumed right to a base

level of subsistence water use. For example, in agriculture, something like 1.2 meters depth per unit

land per year could be assigned as a base water use right for an amount of land required for a

subsistence level of food security. That base right could be assigned to every farmer that demonstrated

historical irrigation for a set amount of recent years. While important details obviously need to be

worked out with considerable care, the amount chosen for the cap in agriculture could be based on the

full yield surface irrigation requirements of all but the most water-intensive crops, like sugar cane, rice,

or alfalfa. A higher cap could be assigned to farmers or urban utilities in areas where higher

temperatures produced higher evaporation and greater crop or landscape evapotranspiration (ET).

Under a cap and trade arrangement, any water use in excess of the cap would be legal, but would also

require a purchase of water from a willing seller at a price reflecting the opportunity cost of water taken

from that use. For example, Gohar and Ward (2010) describe in detail some of the challenges

surrounding trades of water for cash for irrigated agriculture in Egypt. A cap and trade program avoids

the most undesirable effects of government-administered prices, namely that administered prices can

be unjust as well as rarely signaling the real scarcity of water.

Under a cap and trade arrangement, market forces rather than government edict would establish the

price of water. The market price of tradable water to be purchased for aquifer recharge would vary from

time to time, as the scarcity of water or its economic value changed. These changes could be brought

about from any adjustments that affected any crop's price, yield, or production costs. It could also fall

with advances in plant genetics or irrigation engineering that reduced any crop's water use or

application requirements.

5   Results

5.1 Reservoir Storage

Table 1 shows reservoir storage patterns across the basin associated with each of the three water

management policies considered. The first policy is the unsustainable institution described above. The

second policy returns each reservoir to 80 percent of its maximum storage in the last period combined

with requiring each regional aquifer's storage in the last period meeting or exceeding starting 2010

values. The third policy returns all reservoirs to 90 percent of maximum storage with each regional

aquifer's last period storage at least as high as terminal period storage under the second policy.

Each of the two alternative policies for promoting sustainability is achieved to minimize the cost of

economic benefits lost required to achieve that sustainability while being consistent with the Law of the

River described earlier. Table 1 shows how to meet each of the three policy's sustainability objectives in

such a way that altered water uses from policy goals 2 and 3 are achieved at the lowest economic cost in

discounted net present value reduced. Notice that for the base policy, no reservoir is constrained to

meet any terminal period storage constraint. So it's no surprise that results show that most reservoir

storage levels falls to zero or nearly so in the last period.

For each of the two alternative policies, the table shows that sustainability targets are met on a

basinwide level by sharing responsibilities for achieving policy goals across reservoirs, but not requiring

any particular performance for any single reservoir. Like many other shortage sharing rules, the table

shows that for each of the two alternative sustainability policies, the optimal strategy for ensuring

sustainability is to avoid equal sharing of responsibilities among reservoirs. This occurs because different

reservoirs have different characteristics. Some are high elevation reservoirs in steep deep canyons,

while others are shallower low elevation reservoirs with higher evaporation rates. Managers use each

reservoir to bear the responsibility of contributing to current use and future sustainability by specializing

in its unique comparative advantage.

Results show that the hottest (lowest elevation) reservoir in the upper part of the basin (Cochiti) bears

the least responsibility for storing water under the policy of sustaining natural capital (policy alternative

1) among the four upper Basin reservoirs: Heron, El Vado, Abiquiu, and Cochiti. Those top four

reservoirs store water for delivery to New Mexico under the Rio Grande Compact. Among the four,

Cochiti has the highest evaporation rate. So if those four New Mexico reservoirs as a group do not all

need to return to their maximum capacity, unused storage is largest at Cochiti Reservoir, while the other

three use the largest part of their capacity to store water, because of their lower evaporation losses.

However, the second alternative policy of renewing natural capital requires a larger amount of terminal

period storage in the reservoir system as a whole. So Cochiti sees its average storage increase from

119,000 acre feet under alternative policy 1 (sustaining natural capital) to 556,000 acre feet stored

under alternative policy 2 (renewing natural capital). Results shown in table 1 affirm widely-held

knowledge of experienced water managers and water users who are aware of the important role of

specialization. Each reservoir should be managed to make its best contribution to achieving overall

Basin's mission of sustainability. Assigning a different responsibility across reservoirs occurs for two

reasons:

First, considerably lower evaporation occurs at the three upper basin reservoirs. That allows them to

contribute to achieving more terminal period storage, losing the least water to evaporation. This

allocation of responsibility can be seen as putting water in the reservoir (bank) while minimizing the

negative evaporation (interest) rate. Requiring lower elevation reservoirs to share responsibility by

increasing their storage volume would have incurred a cost of greater evaporation losses, i.e., a more

negative interest rate. Rather than losing much of the lower basin reservoir storage to evaporation, that

potential evaporation could be put to beneficial use for cities, irrigation, and the environment. Viewing

the complete system of reservoirs as a system of banks, it makes hydrologic, economic, and political

sense to put water in those banks that pay the lowest negative interest rate.

The second reason that it's economically efficient to use upper basin reservoirs to support sustainability

goals is the considerably greater opportunity for water reuse that occurs at the upper elevation

reservoirs. Their higher reuse occurs because many downstream users rely on the multiple uses of their

releases through cascading return flows. For both reasons, operation of a system of reservoirs in series

is often driven by a practical rule of thumb: fill upstream reservoirs first, in order to minimize spill losses,

since the spills from upstream reservoirs can then be collected by the downstream ones (Lund and

Guzman, 1998).

5.2 Aquifer Storage

Table 2 shows parallel results for the basin's four major aquifers that were shown in Table 1 for

reservoirs. Reservoirs and aquifers have different hydrologic and economic properties, so managers can

operate reservoirs and aquifers to contribute water management goals in different ways. The four

regional aquifers shown are (1) the San Luis Valley, Colorado, aquifer, (2) Central New Mexico Aquifer

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near Albuquerque, (3) Mesilla Bolson including the Las Cruces area, and (4) Hueco Bolson in west Texas

and southern New Mexico. Both these last two aquifers dip into to northern Mexico.

Aquifer locations with large levels of high economic valued pumping for urban water use occur in and

near Albuquerque (Central New Mexico Aquifer) and El Paso (Hueco Bolson). Lower valued pumping

occurs in irrigated agriculture at the San Luis Valley, Colorado and also by irrigators at the Elephant

Butte Irrigation District, New Mexico (Mesilla Bolson). Little to no pumping capacity is currently

developed at either the Middle Rio Grande Conservancy, New Mexico, or for west Texas agriculture.

Constraints that require sustainable aquifer use for the basin as a whole will be borne less by urban than

by irrigation water users. This occurs because a much lower price elasticity of demand for urban use

than for irrigation gives rise to higher urban benefits lost from water not pumped. For all four regional

aquifers, ending period storage levels are constrained to be at least as high as 2010 levels. That is, no

additional pumping for the twenty year period of analysis is permitted under either of the two

alternative policies than pumping that would reduce terminal period storage lower than 2010 starting

levels. Without this requirement, a policy that raises the terminal period reservoir storage levels would

produce greater groundwater pumping as a compensation for reduced opportunities to use reservoir

water.

Table 2 shows that a regional policy requiring greater levels of sustainable water stocks results in

irrigated agriculture using less surface water. This result occurs for both irrigated areas near the urban

centers of Albuquerque and El Paso. Both of those irrigated areas are primarily surface irrigated. So,

much of the aquifer recharge that would occur with heavier reservoir depletion under the base policy

falls off as sustainability targets increase. Reduced irrigation associated with less reservoir water

available for use means that aquifer recharge no longer takes place compared to recharge that would

have occurred. Since agriculture contributes less to aquifer recharge as land is taken out of production,

that aquifer recharge must be made up by reduced pumping by the two major cities as sustainability

targets become more ambitious. This happens. Raising the terminal period storage volume for the

basin's reservoirs requires both urban areas to pump less to compensate for the reduced aquifer

recharge from irrigated agriculture.

For the policy requiring sustained natural capital, agricultural recharge of the aquifer falls by 284,000

acre feet near Albuquerque and by 319,000 acre feet near El Paso by the end of the twenty year period

of analysis. For the case of renewing natural capital, irrigation recharge falls by 517,000 acre feet near

Albuquerque and by 319,000 acre feet again near El Paso compared to a policy of no sustainability. For

both these urban areas, urban water prices increase in the face of greater sustainability requirements by

enough to take the pressure off these two aquifers, as tables 3-5 show in more detail.

5.3 Unsustainable Natural Capital

Table 3 presents results that reflect the basin's current management institutions, in which no policy

requires a sustained performance for any water stocks anywhere in the Basin. There are no terminal

period storage requirements for any reservoir or aquifer. Compared to the two alternative policies, it

shows the highest water depletions over the 20 year planning period, producing about 1.40 million acre

feet depleted per year on average summed over the basin. Because it shows the highest quantity of

water used, it also shows the greatest discounted net present value of those benefits, about $608

million per year summed over uses and averaged over years.[9] These results are based on a simple

maximization of the present value of total basinwide net benefits. The only background constraints

required are defined by the Law of the River described earlier while subjecting the basin to the required

hydrologic physical water balance.

The table also shows that the bulk of water depletion is contributed by irrigated agriculture, consuming

about 86 percent of the basin's total use. Nevertheless the lion's share of the basin's economic benefits

accrue to urban users, about three quarters of the total. That total includes a considerable economic

productivity of reservoir-based recreation. This large share of benefits calculated for urban uses occurs

because of the very low price elasticity of demand for urban uses and its associated high consumer

surplus. That high consumer surplus produced by urban water consumption reflects a high willingness to

pay for urban water compared to actual payments made for water bills to the Albuquerque and El Paso

water utilities. Marginal net economic values of water for urban uses are low because both utilities

supply water at a price close to their marginal cost of supply, and they deliver all demands at those

prices. Still, total net economic benefits from urban water use are considerably higher than equivalent

benefits of water used in irrigated agriculture.

Another interesting observation regarding urban and agricultural uses is that both marginal benefits

(price) and marginal costs are much higher in urban than agricultural uses. However marginal net

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[9]Only benefits of water use and water environments over the 20 year time horizon are measured. So the model treats as zero all future benefits outside the 20 year time horizon. There is zero scrap value for unused water. Without constraints requiring sustainable future water stocks, the model tends to drain reservoirs and pump aquifers to the point of zero discounted marginal net benefit. For these reasons, greater sustainability constraints are achieved at the cost of reduced benefits over the 20 year time horizon. Another way to account for sustainability not used for this paper is to specify an infinite time horizon model driven by a zero discount rate in which discounted net present value is made as high as possible.

benefits for the two classes of use are more nearly equal (not shown). In fact, with sufficiently large

headwater flows and sufficiently few institutional constraints to interstate water allocations, marginal

net benefits will be zero for all urban, agricultural, and even environmental locations. In that case,

marginal benefits of all uses and all environments are equal to marginal costs. These conditions have

rarely occurred in the Rio Grande Basin, but may have nearly occurred in the mid 1980's when all

reservoirs were full, aquifers were well-recharged, and snowpack runoff was above average for several

years running.

5.4 Sustaining Natural Capital

Table 4 presents the current economic cost incurred by enacting policies that would sustain the basin's

natural capital in water. The table shows a lower value of discounted net present value of benefits over

the 20 year planning period by requiring the basin's reservoirs to return to 80 percent of their capacities

with aquifers suffering no net depletions compared to 2010 levels.

Results show that a modest loss in present value of net benefits from water use and water

environments are required to support a sustainable natural capital of water. That loss can be computed

by comparing $608 billion per year under the base policy to $571 billion under the policy of sustaining

natural capital in water, resulting in a basinwide loss of $37 billion per average year in discounted net

present value. That loss in economic benefits is about six percent of total water-related benefits under

the base policy. Total annual average depletions for the basin equal 1.20 million acre feet per year for

the 20 years when sustainable aquifer and reservoir management is practiced. By comparison to table 3

in which there is 'no management' to secure a sustainable future, total ET is 1.40 million acre feet per

year. This means that sustainable management of water stocks results in about 14 percent less water

depleted each year over the 20 year horizon. The much smaller percentage loss in economic benefits compared to the percent reduction in the basin's ET indicates that the lion's share of water consumptive use reduction is borne by irrigated agriculture. This finding is expected: total economic costs of required adjustments are minimized when a given level of total use reduction is borne by irrigated agriculture than by urban uses. The larger value of water in urban areas than for irrigated agriculture is a signal that water trading could benefit both farms and cities in the search for policies that sustain natural capital.

A comparison of table 3 and table 4 shows that 203,000 acre feet per year of the basin's overall reduction in water consumptive use from a sustainability requirement is achieved by ET reductions in irrigated agriculture. A much smaller 25,000 acre feet per year of consumptive use reduced by urban users. In fact, reservoir evaporation under the sustained policy actually increased by 31,000 acre feet per year, reflecting higher reservoir levels on average required to carry out a policy to sustain water's natural capital.

5.5 Renewing Natural Capital

Table 5 shows the economic costs incurred by enacting policies that would renew the basin's natural capital in water. The table shows that water use reductions are larger when those reductions are used to renew the basin's natural capital rather than merely sustain it. The table shows a larger loss in discounted net present value of benefits over the 20 year planning period when the basin's reservoirs are required to return to 90 percent of their storage capacities while each aquifer must produce terminal period levels at least as high as levels under a sustained policy. That loss is computed in the following way: $608 billion per year with no sustainability required compared to $540 billion when

renewed capital stocks are required, for a basinwide difference of $68 billion, for a total loss equal to

about 11 percent of the baseline average annual total economic value of water.

Results shown in Table 5 reveal the economic price to pay for filling the basin's reservoirs by an

additional 524,000 acre feet of storage and requiring aquifers to return to an equal level as levels

achieved by a policy of sustaining the basin's water stocks. Total average water consumption per year

for the basin is 1.18 million acre feet when renewed natural capital in water is set as the target. Under

the base policy of no management, total consumption for the basin is 1.40 million acre feet. This

comparison across policies means that renewing the natural capital in water stocks requires an average

of about 22,000 acre feet reduced water use each year over the 20 year horizon than merely sustaining

that capital. Like Table 4, Table 5 shows a much smaller reduction in economic benefits (11 percent)

than reduced water use (16 percent) to renew stocks than when no sustainability is required. Again this

result occurs because the economic costs of renewing the capital stock are minimized when more water

is retired from agriculture than from urban use.

6   Discussion

Our findings show that economically efficient policies provide no guarantee of being sustainable. That is,

ensuring economic efficiency in the sense of maximizing discounted net present value of uses and

environments provides no guarantee of sustainability. In addition, sustainability of natural capital can be

achieved with an economically inefficient use pattern over the period of analysis. So merely designing a

sustainable policy provides no guarantee of conventionally defined economically efficiency in water

management over the period of analysis. This paper has described an economically efficient allocation

of current water uses for sustaining reservoirs and aquifers over a 20 year period in North America's

upper Rio Grande Basin. That allocation is efficient in the sense that it minimizes the economic sacrifice required to sustain or renew the basin's water stocks while being consistent with the basin's four most important existing water institutions. However an important and unanswered question centers on what institutions or policies could bring about these two kinds of sustainability.

One way to achieve the sustainability objectives described here is a cap and trade arrangement. Water rights in this basin are typically held as private property. These rights need to be adjudicated to be effective in recharging the basin's water stocks. Under a cap and trade program, future transfers of water or water rights to new uses could be accompanied by a requirement to take some specified percentage of that transfer out of production. For example, with a 20 percent transactions cost imposed on all transfers, a transfer of 10 acre feet of water from an existing use will only allow 8 acre feet of new use. The cost of this arrangement that shrinks overall use is shared by the seller and buyer, with little expense borne by the taxpayer. Such an arrangement could be implemented for either groundwater or surface water right transfers.

Another implementation of sustainability policy is through direct state intervention into the market. For example a reservoir or aquifer conservation fund could be established in which water or water rights are purchased by the state from existing right holders. The purchased water would be retired from existing uses and, then recharged into the aquifer or held in reservoirs. The cost of this plan would be borne by the taxpayer, which avoids a loss in asset value incurred by the buyer.

Finally, economic incentive policies can enhance sustainability and efficiency in river basin management. Getting the water prices right can lead to full cost recovery, reflecting both externalities and user costs.

Other economic instruments can be applied, like subsidizing water conservation measures. Examples include subsidizing the purchase price of things like low flow showerheads, low flush toilets, water-efficient appliances, desert landscapes, and drip irrigation. Regardless of which institution is used to renew the basin's water stocks, there is a light at the end of the tunnel. After the basin's stocks are recharged, future water uses and environments can rely exclusively on renewable sources of water, with no need to continue reducing use to raise the basin's water stocks.

7   Conclusions

Integrated river basin management is high on the international political agenda. World-wide, sustainable water management and reductions in water and related food poverty have become top priorities. Hydroeconomic models offer one resource for the design sustainable water management plans. This paper has addressed that challenge by describing the design and application of an integrated basin-scale constrained optimization analysis for water allocation and use patterns for the Rio Grande Basin of North America.

The principle of designing resilient institutions to support sustainable river basin management continues to receive widespread international attention. Despite that considerable support, the thorny issue of costs associated with that management nearly always receives scrutiny when current water uses are reduced to support implementation of sustainability goals. Understandably managers and stakeholders who benefit from heavy water use in irrigated agriculture in addition to ratepayers in large urban areas resist proposals to have their current water uses reduced for which the main beneficiaries are water users of future generations who pay no current taxes. When sustainable management of water resources is implemented by policies that would incur a high cost of current water uses displaced, water

managers and consumers have a natural interest in seeing reliable information on the size of those

costs. This paper has provided that information, in a limited way, for one basin.

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table

Table 1: Reservoir Storage by Policy, Upper Rio Grande Basin, USA, 2010-2029 (1000 a-f)											
		Policy Alternative									Reservoir Storage Capacity
Reservoir	State	Base Policy: Unsustainable Institutions			Alternative 1: Sustaining Natural Capital			Alternative 2: Renewing Natural Capital			
		Start	End	Change	Start	End	Change	Start	End	Change	
		(1000 ac-ft)									
Heron	NM	252	4	-248	252	400	148	252	400	148	400
El Vado	NM	60	0	-60	60	185	125	60	186	126	186
Abiquiu	NM	181	4	-177	181	1535	1354	181	1535	1354	1535
Cochiti	NM	53	0	-53	53	119	66	53	556	503	719
Elephant Butte	NM	500	0	-500	500	1810	1310	500	1895	1395	2065
Caballo	NM	140	0	-140	140	140	0	140	140	0	331
Total, Basinwide		1186	8	-1178	1186	4189	3003	1186	4712	3526	5236

Table 2: End-of-Period Aquifer Storage Compared to Starting Conditions, by Location, State, and Policy, Upper Rio Grande Basin, USA, 2029 (1000 a-f)					
Regional Aquifer	State	Primary Use	Base Policy: Unsustainable Institutions	Alternative 1: Sustaining Natural Capital	Alternative 2: Renewing Natural Capital
1. San Luis Valley Aquifer	**CO**	agriculture	0	0	0
2. Central New Mexico Aquifer Total	**CO**		2650	2650	2650
Central NM Aquifer - Albuquerque Metro	NM	urban	-405	-121	111
Central NM Aquifer - MRG Conservancy	NM	agriculture	3055	2771	2539
3. Mesilla Bolson Total	**NM**	agriculture	1790	1790	1790
4. Hueco Bolson Total	**TX**		-60	0	0
Hueco Bolson - El Paso Metro	TX	urban	-602	-223	-223
Hueco Bolson - El Paso Water District #1	TX	agriculture	541	223	223
Total, Basinwide			4380	4440	4440

Table 3: Hydrologic, Agronomic, and Economic Outcomes, Base Policy: Unsustainable Institutions, Upper Rio Grande Basin, USA, 2010-29

State		CO	NM					TX		Basin
Demand Region	Units	SLV	Albuquerque	MRGCD	EBID	4 Upper Reservoirs	2 Lower Reservoirs	El Paso	El Paso	Total
Sector		Agr	Urban	Agr	Agr	Recreation	Recreation	Agr	Urban	
Hydrologic Performance										
Water Consumed -- ET		612	56	288	199	64	17	102	62	1,401
Water Applied	1000 ac-ft/yr	1,225	188	670	393	-	-	237	207	2,920
Surface water		612	100	670	327	-	-	237	15	1,962
Groundwater		612	88	0	66	-	-	0	192	959
Agronomic Performance										
Cropland in Production	1000 ac	205	-	63	91	-	-	47	-	405
Crop Water Use Rate - ET	ac-ft/ac/yr	3.0	-	4.6	2.2	-	-	2.2	-	3.5
Crop Water Application Rate	ac-ft/ac/yr	6.0	-	10.6	4.3	-	-	5.1	-	7.2
Urban Supply Performance										
Water Price	$US/1000 gal	-	2.55	-	-	-	-	-	2.58	-
Per Household Use	gal/hshld/day	-	377	-	-	-	-	-	321	-
Economic Performance										
Total Net Benefits	$US 1000/yr	45,099	246,191	22,890	36,613	19,250	934	26,432	210,769	608,179
From Water Use		45,099	246,191	22,890	36,613	0	0	26,432	210,769	587,994
From Water Environment		0	0	0	0	19,250	934	0	0	20,184

Table 4 : Hydrologic, Agronomic, and Economic Outcomes, Policy Alternative 1: Sustaining Natural Capital, Upper Rio Grande Basin, USA, 2010-29									
State		CO	NM					TX		Basin
Demand Region	Units	SLV	Albuquerque	MRGCD	EBID	4 Upper Reservoirs	2 Lower Reservoirs	El Paso	El Paso	Total
Sector		Agr	Urban	Agr	Agr	Recreation	Recreation	Agr	Urban	
Hydrologic Performance										
Water Consumed -- ET		591	43	261	103	26	86	42	50	1,203
Water Applied	1000 ac-ft/yr	1,183	144	608	231	-	-	98	168	2,431
Surface water		591	100	608	231	-	-	98	78	1,706
Groundwater		591	44	0	0	-	-	0	89	724
Agronomic Performance										
Cropland in Production	1000 ac	198	-	50	50	-	-	19	-	318
Crop Water Use Rate - ET	ac-ft/ac/yr	3.0	-	5.2	2.0	-	-	2.2	-	3.8
Crop Water Application Rate	ac-ft/ac/yr	6.0	-	12.1	4.6	-	-	5.1	-	7.6
Urban Supply Performance										
Water Price	$US/1000 gal	-	4.25	-	-	-	-	-	2.58	-
Per Household Use	gal/hshld/day	-	289	-	-	-	-	-	261	-
Economic Performance										
Total Net Benefits	$US 1000/yr	43,553	233,450	24,532	26,248	15,271	1,420	18,133	208,368	570,975
From Water Use		43,553	233,450	24,532	26,248	0	0	18,133	208,368	554,284
From Water Environment		0	0	0	0	15,271	1,420	0	0	16,691

Table 5 : Hydrologic, Agronomic, and Economic Outcomes, Policy Alternative 2: Renewing Natural Capital, Upper Rio Grande Basin USA, 2010-29										
State		CO	NM					TX		Basin
Demand Region	Units	SLV	Albuquerque	MRGCD	EBID	4 Upper Reservoirs	2 Lower Reservoirs	El Paso	El Paso	Total
Sector		Agr	Urban	Agr	Agr	Recreation	Recreation	Agr	Urban	
Hydrologic Performance										
Water Consumed - ET		591	32	239	98	37	94	42	48	1,182
Water Applied	1000 ac-ft/yr	1,183	108	557	226	-	-	98	161	2,332
Surface water		591	100	557	226	-	-	98	73	1,645
Groundwater		591	8	0	0	-	-	0	88	687
Agronomic Performance										
Cropland in Production	1000 ac	198	-	45	49	-	-	19	-	311
Crop Water Use Rate - ET	ac-ft/ac/yr	3.0	-	5.3	2.0	-	-	2.2	-	3.8
Crop Water Application Rate	ac-ft/ac/yr	6.0	-	12.4	4.7	-	-	5.1	-	7.5
Urban Supply Performance										
Water Price	$US/1000 gal	-	5.64	-	-	-	-	-	3.90	-
Per Household Use	gal/hshld/day	-	218	-	-	-	-	-	251	-
Economic Performance										
Total Net Benefits	$US 1000/yr	43,553	203,902	23,599	29,038	15,900	1,465	18,109	204,926	540,491
From Water Use		43,553	203,902	23,599	29,038	0	0	18,109	204,926	523,127
From Water Environment		0	0	0	0	15,900	1,465	0	0	17,365

colour figure
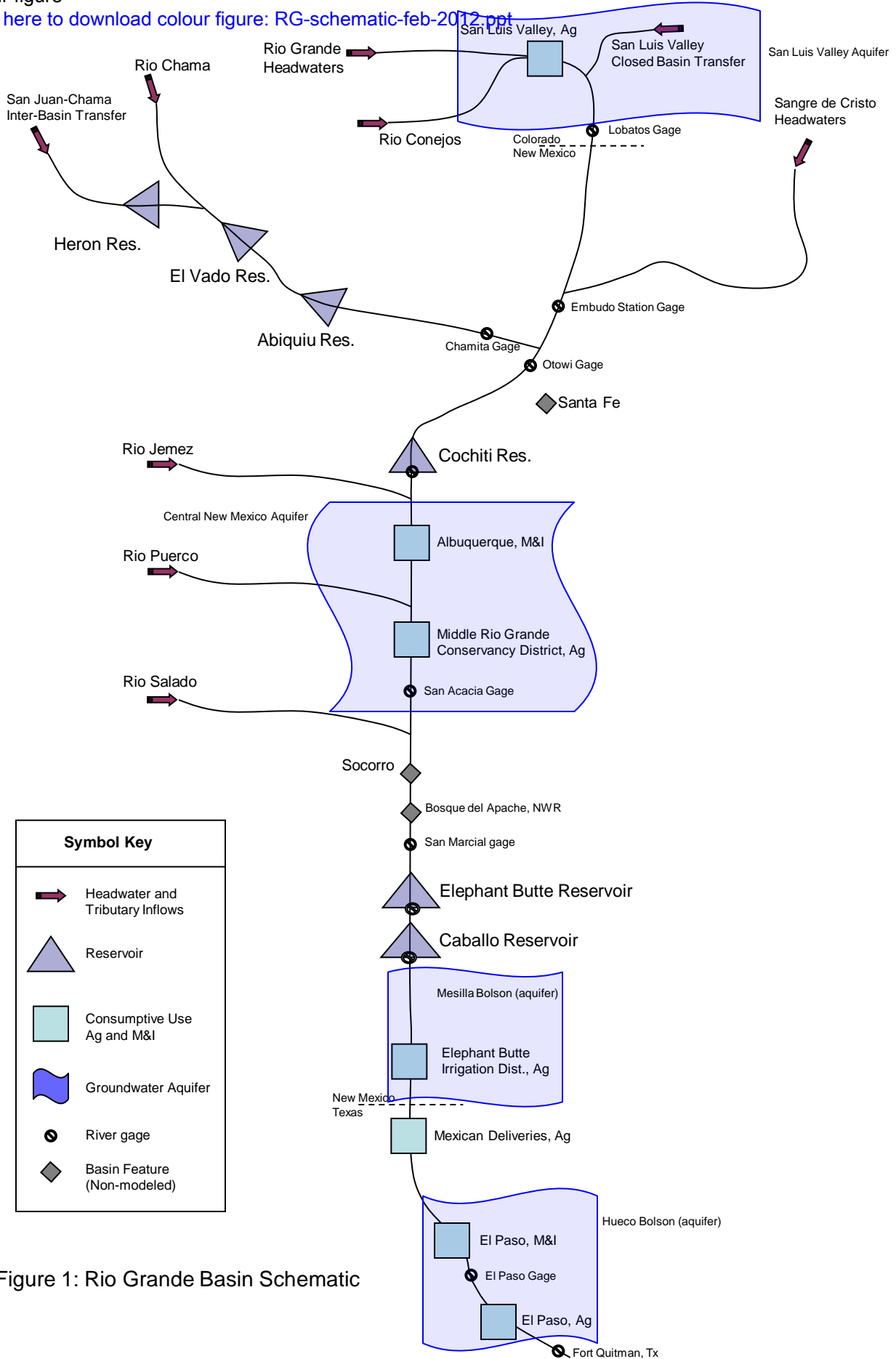Click here to download colour figure: RG-schematic-feb-2012.ppt

Figure 1: Rio Grande Basin Schematic