Efficiency, Equity, and Sustainability in a Water Quantity-Quality Optimization Model
in the Rio Grande Basin

Frank A. Ward
Professor
Department of Agricultural Economics and Agricultural Business
Campus Box 30003
New Mexico State University
Las Cruces, NM 88003
Email: fward@nmsu.edu

Manuel Pulido-Velázquez
Assistant Professor
Hydraulic and Environmental Engineering Department
Technical University of Valencia (Univ. Politecnica de Valencia)
Cami de Vera, s/n. 46022
Valencia, Spain.
Email: mapuve@hma.upv.es

August, 2007
Forthcoming, in Ecological Economics
Abstract

Integrated hydrologic and economic optimization models at the basin scale provide a framework for policy design, implementation, and evaluation in water-stressed basins. Despite the considerable potential that basin-scale analysis offers, few basin-wide studies have examined tradeoffs among efficiency, equity, and sustainability when analyzing the design of water resource programs. This paper develops a basin scale framework to identify hydrologic and economic impacts of alternative water pricing programs that comply with environmental regulations for protecting water quality. Key issues are examined that confront integrated hydroeconomic basin models: linking water and economics, spatial and temporal scale integration, and quantity-quality relationships. Economic efficiency is defined and measured for each of two urban water pricing arrangements that comply with urban water quality protection regulations. Alternative measures of equity are analyzed in both spatial and temporal dimensions. Sustainability is evaluated physically for protecting the water supply and financially for long-term revenue viability. The approach is illustrated from results of a dynamic nonlinear programming optimization model of water use in North America's Rio Grande basin. The model optimizes the net present value of the basin’s total economic benefits subject to constraints on equity, sustainability, hydrology, and institutions. It is applied to assess impacts of a two-tiered pricing program that complies with recently implemented drinking water quality standards for the basin's two largest U.S. cities: Albuquerque, New Mexico, and El Paso, Texas. Results suggest that two-tiered pricing of urban water supply has considerable potential to perform well in meeting the aims of efficiency, equity, and sustainability. Findings provide a general framework for designing water pricing programs that comply with environmental regulations.

Key Words: Environmental Policy, Welfare Economics, Basin-Scale Analysis
Efficiency, Equity, and Sustainability in a Water Quantity-Quality Optimization Model
in the Rio Grande Basin

1 Background

The typical river basin contains several water-related human activities, including water storage, diversion, pumping, distribution, purification, and pollution. Basin-scale analysis provides a comprehensive framework for informing the design of measures that produce efficient, equitable, and sustainable distribution of economic benefits and costs of water programs. Several basin-scale analyses have been conducted since the mid 1990's. Allan et al (1997) presented a comprehensive and detailed basin scale model for southeastern Michigan; Bockstael et al (1995) integrated ecological and economic modeling for the Patuxent drainage in Maryland; Booker (1995) in a celebrated study, developed and applied an integrated hydrologic-economic-institutions analysis of seven Colorado Basin states. Conway et al (1996) developed a basin scale model of the Nile Basin in Egypt that operated at three scales: global (climate change), regional (land use patterns), and river basin (water management). DeWit (2001) used a basin scale model to conduct policy analysis for the Rhine and Elbe basins in Europe; Rosegrant et al (2000) and Cai and Rosegrant (2004) introduced an integrated economic-hydrologic modeling framework of the Maipo river basin in Chile. Varela-Ortega et al (1998) built a dynamic programming model to examine effects of various water conservation policies in selected Spanish watersheds.

Several papers containing water decision support models have been published: large-scale integrated river basin scale models applied to simulate the economic impacts of policies for managing droughts (e.g., Booker, 1995; Characklis 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., Pulido-Velazquez et al., 2006; Jenkins et al., 2006); optimal system operation (e.g., 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 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 adaptation (e.g., Tanaka et al., 2006).
These examples show considerable advances made in basin scale analysis in recent years. However, few of these studies have explicitly quantified tradeoffs among efficiency, equity, and sustainability in analyzing the design of water programs. The aim of this paper is to present a method for designing and implementing a water pricing program that addresses these three goals. To meet that aim, we present an analysis of water prices that send economically efficient and sustainable signals to water users while also addressing equity, in which subsistence needs for treated water are priced sufficiently low to be accessible to all. The paper describes a two-tiered (lifeline) water pricing system that prices basic subsistence needs cheaply, but charges a price equal to full marginal cost, including environmental cost for any uses in excess of subsistence. It meets that aim by describing a basin-wide optimization model that accounts for efficiency, equity, and financial and physical sustainability for the Rio Grande Basin of North America. The model examines impacts of a pricing program for implementing recently established environmental regulations that limit arsenic levels for drinking water for the basin’s two largest U.S. cities, Albuquerque, New Mexico, and El Paso, Texas.

2 Study Area and Issue

2.1 Rio Grande Basin of North America

The Rio Grande rises in the Weminuche Wilderness, San Juan County, Colorado, on the Continental Divide, as a snow-fed mountain stream at an elevation exceeding 14,000 feet above sea level. The river flows for 170 miles in southern Colorado through the San Luis Valley, then southward for 475 miles splitting New Mexico until it reaches the junction of Chihuahua, Mexico and Texas, USA. There, the Rio Grande becomes the international boundary between the United States and Mexico. Even under normal flow conditions, basin demands exceed supplies; emerging demands for environmental protection in the form of instream flows further increase competition for already scarce water. Overlaid on this is continued population growth, declining ground water levels, and deteriorating water quality. The upper Rio Grande basin (the Basin), is that part of the river that flows from its headwaters to about 70 miles south of the border cities of El Paso - Ciudad Juárez. Surface water from the river meets the primary water needs of three major cities of Albuquerque, New Mexico in addition to El Paso, and Ciudad Juárez. It also serves one million acres of irrigated land in the U.S. and Mexico.
In 1906, the U.S.-Mexico water treaty (the Treaty) provided that the United States deliver to Mexico 60,000 acre feet per year. In 1938, the Rio Grande Compact (the Compact) was approved by the US Congress, dividing annual waters flow among Colorado, New Mexico, and Texas. Environmental demands for and values of water continue to increase. The Rio Grande silvery minnow (the Minnow), was listed as an endangered species by the U.S. Fish and Wildlife Service in 1994.

2.2 A Water Quality Issue: Arsenic Treatment

2.2.1 Introduction

Some of the Basin's soils contain high levels of arsenic, which can increase risks for some types of cancer caused by consuming water originating from its aquifers. While drinking water systems for the basin's two major urban areas, Albuquerque New Mexico and El Paso Texas did meet the previous US EPA’s 50 ppb standard, some of their water sources fail to meet the 2001 10 ppb standard. Both Albuquerque and El Paso will need to secure revenues from its urban water customers to pay for the costs of complying with the new EPA arsenic standards.

2.2.2 Drinking Water: Albuquerque and El Paso

Albuquerque is completing its surface water treatment plant now under construction. The arsenic treatment is estimated to raise the typical customer's annual existing bill of $621 by about $252, equal to 40 percent of its current level (Bitner, 2004). El Paso water customers have two main drinking water sources – surface water from the Rio Grande from mid-March through mid-October and groundwater from two aquifers: the Mesilla Bolson and the Hueco Bolson. About half of the water supply comes from the river in normal water years (Lockhart, 2005). Arsenic has been found in the water of 46 of the city's 175 wells. In 2005, El Paso built a 60-million-gallon-per-day (mgd) arsenic removal plant, the largest in the US. The complete cost of the package was $76 million, resulting in a 19 percent rate increase to its customers.

This paper compares two demand management instruments in each of two regulatory environments for urban arsenic treatment in the Rio Grande Basin: (1) marginal cost pricing without arsenic water treatment; (2) marginal cost pricing with urban arsenic water treatment; (3) two-tiered pricing without
urban arsenic water treatment; and (4) two-tiered pricing with urban arsenic water treatment. Each of
these four alternatives are evaluated in terms of both their hydrological and economic performance.

3 Policy Aims

3.1 Efficiency

When water is priced at its real marginal cost, including environmental externalities and other
opportunity costs, it is put to its highest economically-valued uses (Rogers et al., 2002; Young, 1996).
Efficient water use policies are about bringing water’s opportunity costs in line with its correct marginal
value. In principle, if water’s price includes all real marginal costs, an efficient resource allocation can
be reached: marginal net economic benefits of water are equal across different uses, and society’s water-
related welfare is maximized. In the absence of well-functioning water markets, opportunity cost
assessment requires a systems approach combined with a number of assumptions about impacts and
responses to them (Briscoe 1996).

3.2 Equity

Equity has been a policy goal for a long time. Some important human rights documents include the
Magna Charta (Lackland, 1215), Declaration of Independence (Jefferson, 1776) and Declaration of the
Rights of the Man and the Citizen (Sieyès, 1789). More recently, the Universal Declaration of Human
Rights was adopted (United Nations, 1948). The human right to water was slow to come, though its
importance had been recognized for years (e.g., Gleick, 1999). In 2002, the United Nations formally
declared that all have a human right to water. Under that declaration, the right entitles everyone to
sufficient, safe, acceptable, physically accessible and affordable water for personal and domestic uses.
Despite the impressive moral aims of all these documents, the issue of how to finance their
implementation has always been an issue. It is an especially significant challenge for 21st century water
policy.

3.3 Sustainability

3.3.1 Principles

Since the 1987 Brundtland Report was released (Brundtland, 1987) the principle of sustainability has
received widespread attention. By its definition, sustainable development is development that meets the needs of the present without compromising the ability of future generations to meet their own needs. Economists have proposed several implementations, including non-declining consumption per capita, sustaining production opportunities, sustaining use of water resources, a non-declining natural stock of capital and sustained ecosystem stability and resilience.

3.3.2 Application to River Basin Management

For application to water management, the concept of sustainability has been expressed in a variety of ways. While broad guidelines, principles, and procedures have been proposed to assist decision makers (Loucks and Gladwell, 1999; Loucks et al., 2000), they have rarely been translated into operational measures that can be applied to the design and operation of water systems (Biswas, 1994; Cai et al., 2002). Loucks et al. (2000) propose to measure sustainability as the "weighted combination of reliability, resilience, and vulnerability measures of various criteria that contribute to human welfare." Cai et al. (2002) and Schoups et al. (2006) have applied that approach to define global sustainability indexes for water use. However, the method for weighting each criterion for an overall index remains an open question.

Two limited implementations of sustainability are developed for this paper. One is financial: revenues from water supplied must equal or exceed costs in each period at each node in the basin. The other is physical: all the basin’s reservoirs and aquifers must return to first period levels or higher by the last period. Taken together each implementation offers protection if other is ineffective. If financial sustainability produces high revenues while depleting the resource, the physical requirement assures adequate terminal period supplies. If physical sustainability alone would produce wastefully low prices and high use rates in some periods, the revenue requirement raises the price sufficiently high to reduce use and to cover each period’s financial costs.

4 Methods

4.1 Overview of Basin Model

An integrated model of the Basin (See Map) was developed to bring the region's hydrology, 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 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 environmental requirements for endangered species. The model is formulated
as a dynamic nonlinear program, maximizing discounted net present value over water uses and
environments. It sums benefits from water diversions for off-stream uses plus environmental values of
reservoir-recreation as the objective. Constraints are used to characterize basin's hydrology and
institutions. In the model, reservoir contents, pumping, and water uses are optimized over the model's
time horizon, based on measured headwater inflows over the period of record.

The model accounts for decisions made supporting both water use and the water environment. Water use
in irrigated agriculture is defined for the basin’s four major farming regions as well as for urban users in
the two cities. The model simulates irrigation decisions by estimating quadratic benefit functions based
on outcomes of farm income maximization models. In them, irrigators choose a crop mix and a quantity
of surface and groundwater for known crop prices, crop yields, and farm production costs.

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, and return flows), and losses (field, canal,
conveyance, and reservoir evaporation). Booker et al [2005] and Ward et al [2006] present detailed
mathematical documentations. The current paper describes only new equations recently added to support
the current policy analysis.1 While the model and its documentation were developed for the Rio Grande
Basin, it was designed to be easily adaptable to other basins, geographic configurations, cultures, legal
systems, and water allocation rules.

4.2 Existing Institutions

Many existing institutions in the Basin define or limit the allocation of water across political boundaries,

1Model code is posted at http://agecon.nmsu.edu/fward/water/.
time periods, and uses. While these institutions limit the economic efficiency of water allocations, they are important for understanding and predicting current and potential water use patterns in the basin. Four important institutions are described below.

4.2.1 International Treaty
Water allocations and use patterns in many of the world's basins are constrained by international water-sharing agreements. For the Basin, an important trans-boundary agreement is the U.S. Mexico Treaty of 1906. A 60,000 acre-foot annual delivery to Mexico is specified by that treaty. Inspection of the historical data on U.S. deliveries to Mexico shows that a fairly simple linear regression replicates U.S. delivery behavior, as those deliveries vary with Rio Grande project releases from Elephant Butte Reservoir in periods of less than full supply. Our model requires 60,000 acre-feet delivered to Mexico in all periods.

4.2.2 National Law
The U.S. Endangered Species Act (ESA) is an important national law affecting the Basin’s water allocation. The ESA prohibits federal agencies from taking actions that jeopardize the continued existence of any endangered species. A biological opinion issued by the U.S. Fish and Wildlife Service (U.S. Department of Interior, 2001) estimates that bringing the endangered Rio Grande Silvery 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 (See map). Our model 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.

4.2.3 Inter-regional Agreement
River basin compacts have seen widespread application in the American west since the original Colorado River Compact was signed by the Colorado Basin States in 1922. The Rio Grande Compact – signed in 1938 by Colorado, New Mexico, and Texas – divides the annual flow of the Rio Grande so that each state secures more water in wetter years. Articles III and IV of the Compact oblige Colorado to deliver water at the Colorado-New Mexico state line (See Map). Article V and a later resolution oblige New
Mexico to deliver water to Texas. 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 (See Map). The Compact text is web-posted by New Mexico Water Resources Research Institute (2006).

4.2.4 Intra-regional Agreement
An intra-regional water sharing agreement is another measure for sharing water among political jurisdictions. 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. Based on historical irrigated acreage in the states at the time of the Project's construction, U.S. lands in New Mexico receive deliveries up to 57% of any year's allocation, while lands in Texas have received up to 43%, for a total of up to 100%. Much of the current Texas allocation actually goes to El Paso urban users. That proportion is likely to grow in future years, as West Texas irrigators find it is more profitable to rent or sell water or water rights to El Paso. 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 (see Map).

4.3 Economics
4.3.1 Benefits
Water in the Basin produces both use-related benefits and environmental benefits. Each benefit is defined by water users' total willingness to pay (e.g., Young, 2005). For agricultural uses, we follow convention by measuring the willingness to pay for water as its contribution to increased net farm income. For urban nodes, water's value is measured by price per unit water multiplied by the number of units sold to the customer plus any unpriced consumer surplus. For environmental benefits, we measure willingness to pay as the maximum price that could be charged to visitors who visit any of the Basin's six reservoir-based recreation facilities. This simplification ignores several important environmental values. For example we exclude environmental values produced by instream flows at non-reservoir nodes. We also ignore other environmental values, such as option, existence, and bequest values that are affected by variations in reservoir levels or by other water actions.

4.3.1.1 Benefits from Water Use: Concepts
Benefits and costs associated with water use (depletions) were measured for both urban and agricultural uses at the Basin’s most important nodes. For urban uses, the empirical benefits analysis for the current study were measured as the willingness to pay by urban users to consume water associated with various possible quantities and associated prices. Consistent with neoclassical demand and welfare theory, reduced water quantities supplied to urban users increase the price and reduce total urban benefits, equal to the sum of water bills and consumer surplus.

The present study adapted the empirical demand schedule findings from the study of Michelsen et al (1998) to the climatic and demographic conditions of Albuquerque New Mexico and El Paso Texas (Ward et al., 2001). For irrigation uses, income-maximizing farm behavior models were estimated and calibrated to produce optimized cropping patterns consistent with cropping patterns seen historically. 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. Agricultural benefits functions of the same structure were estimated for the Basin's three major downstream irrigated areas in New Mexico and west Texas. The three areas are: (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.

4.3.1.2 Water Use Benefits: Application
We used equations to model the benefits associated with each water use (ag and MI) at each node. Water uses produced by diversions in the t-th period and u-th use, XB_{ut}, produce economic benefits by being applied to this quadratic total benefits function:

\[
XB_{ut} = B_{0u} + B_{1u} X_{ut} + B_{2u} X_{ut}^2
\]

where \(B_{0u}, B_{1u}, \text{ and } B_{2u} \) are parameters for the constant, linear and quadratic terms, respectively, for the beneficial use of surface flow at each u-th node, \(X_{ut}\). Economic theory requires the following interpretation: \(B_{2u} < 0\) says the marginal benefits (demand) schedule for water is downward sloping. For agricultural nodes, marginal benefits from added water use start small (\(B_{1u}\) is small but positive). The
equation above describes use-related benefits per household for urban uses and benefits per acre for irrigation nodes. Alternative futures are accounted for by scaling the equation up by number of households for urban uses and by number of acres in production for agricultural nodes.

4.3.1.3 Benefits from Environmental Quality: Concepts

Water is the limiting resource influencing management of sensitive species in this Basin as well as in many other arid lands. Cowley (2006) summarizes historical human-induced modifications of this Basin's natural aquatic ecosystem and focuses on the challenges it has created, particularly for protecting habitat for the endangered minnow. This study conducts a limited implementation of the value of the aquatic ecosystem and its services. We simplify considerably by measuring water's value in sustaining a quality environment by water's role in supporting fish habitat at the Basin's six mainstem reservoirs. Considerably more research in understanding, measuring, and valuing the Basin’s aquatic ecosystem services is needed to comprehensively incorporate environmental benefits and costs in an overall basin level framework.

4.3.1.4 Environmental Quality Benefits: Application

Economic benefits of environmental quality are measured as the willingness to pay for changes in quantities of water supplied for sport fishing at the basin's six mainstem reservoirs. This method simplifies a complex and growing field of environmental and ecological economics, which has grown immensely since the mid 1980's. Much of that growth in knowledge and method has occurred through publications in *Ecological Economics*. For any given reservoir node in the Basin, economic benefits of an improved water-related environment are measured as:

\[ XBE_{\tau} = B_{oe} + B_{u}Z_{\tau} + B_{u}Z_{\tau}^{2} \]

For this equation, the \( B \) coefficients used are based on the published work by Ward et al (1997), in which a regional travel cost model was used to characterize the demand for and benefits of sport fishing at 133 New Mexico fishing sites. Those earlier results were recently updated by total visitor use counts in 2004-2005. The quadratic functional form for benefits was chosen to reflect the observation that further
volume increases beyond that point at which the quadratic function tops out reduce visitation and total recreation benefits. It also ensures technical consistency for a single model which compares tradeoffs among irrigation and urban benefits versus environmental benefits across a wide hydrology and policy space.

4.3.2 Costs

Each use nodes has a similar pattern of costs. For each node increased water diversions or water depletions typically require the user to incur more costs to make suitable for human use that additional water. The greatest incremental costs for irrigation pumping nodes are those incurred for energy, operation, and maintenance of pumps. For urban pumping nodes there are also considerable additional costs for purification to make the water safe and healthy for human consumption. An important cost considered for this research is the considerable increase in water purification costs at urban nodes associated with arsenic treatment for Albuquerque and El Paso.

4.3.2.1 Use-Related Costs

Albuquerque currently has no surface treatment, with or without arsenic treatment. However, surface treatment currently supplies just under half of El Paso’s supplies in full water years. El Paso's surface water comes directly from upstream reservoir releases, which contains virtually no arsenic. So its surface treatment costs are unaffected by the arsenic treatment scenario. The term used to characterize energy, operation, and maintenance cost per acre foot pumped at a pumping node is $\delta_{peu}$, while treatment costs at the same node is $\delta_{stu}$ per acre foot. Policy scenarios that introduce arsenic treatment result in $\delta_{stu}$ increasing compared to scenarios without arsenic treatment. Energy and treatment costs are also defined for surface diversion nodes by the term $\delta_{duu}$ for energy, operations, and maintenance cost. The term $\delta_{duu}$ is the equivalent cost per acre foot of surface water treatment. Urban delivery cost data were obtained from the two urban water utilities, while agricultural water cost data were obtained from published enterprise cost and return budgets. Based on these use-related costs described above, the total cost of water delivered to any agricultural or urban node is:

$$X_{Ct} = \sum_{p} \left[ \delta_{peu} + \delta_{stu} \right] X_{pt} + \sum_{d} \left[ \delta_{deu} + \delta_{dtu} \right] X_{dt}.$$
where $X_p$ is the number of acre feet pumped from an aquifer and $X_d$ is the number of acre feet diverted from the Rio Grande mainstem in the $t$-th period. Both of these quantities are endogenous (unknown) variables whose values are determined by the model's optimized solution.

4.3.2.2 Environmental Costs

Environmental costs continue to be a large and growing factor influencing outcomes of important water policy decisions. Two concepts were considered for measuring environmental costs: (1) opportunity costs, equal to gross environmental benefits displaced by a decision, and (2) environmental operations costs, equal to the cost of additional resources required to support securing and protecting larger environmental benefits at a given site. We combined both by measuring each reservoir's environmental benefits as gross environmental benefits minus added gross environmental management costs needed to secure a higher quality environment. In this Basin, data are scarce on costs of protecting the water environment. As a first approximation, we measured those costs as marginal costs incurred by site managers to maintain fishing facilities and to accommodate increased numbers of anglers in the face of reservoir volume increases. These environmental operations costs were measured as:

$$\text{(4) } XCe_{et} = \delta_{et} Z_{et}$$

where $\delta_{et}$ is the marginal cost of managing larger volumes of water at any reservoir site in the basin and $Z_{et}$ is the reservoir's storage volume in period $t$. For this study, the term $\delta_{et}$ was measured as the additional monetary cost required to support marginal visitors attracted by larger water quantities held in a reservoir. A more comprehensive treatment of marginal costs of environmental improvements will include any operations costs needed to preserve, protect, or improve a natural environment.

4.3.3 Resource Benefits and Costs

The European Union Water Framework Directive (EU Commission, 2000) requires good quality waters in the EU countries by the year 2015. It has assigned considerable importance to the notion of resource benefits and costs. The WFD calls for the internalization of water service costs, including resource and environmental costs, in accordance with the principle of cost recovery. The definition and practical assessment of resource and environmental costs for the purposes of the Directive remains controversial,
and is likely to produce considerable scientific, intellectual and political challenges in its implementation (WATECO, 2002; Brouwer, 2004; Görlach and Interwies, 2004; Maestu et al., 2004; Brouwer, 2006). Recently, an EC-funded project, AQUAMONEY, brought together 16 universities and research institutes with the aim of developing and testing practical guidelines for the assessment of environmental and resources costs and benefits for application to the WFD (European Commission, 2006). In the WATECO terms developed by a group of EU economists, resource cost (RC) is defined as the "... cost of foregone opportunities which other uses suffer due to the depletion of the resource beyond its natural rate of recharge or recovery..." Other studies have further extended this interpretation of resource cost to also include the opportunity cost of the efficiency losses resulting from a misallocation of scarce resources (Maestu et al., 2004; Brouwer, 2004; Andreu et al., 2005; Pulido-Velazquez et al., in press – this issue).

WATECO’s guidelines are relevant in the sense of avoiding irreversible risks associated with damaging a resource. Economic cost analysis of irreversible risks was originally developed the early 1950s, particularly for species extinction (Ciriacy-Wantrup, 1952). Methods for measuring these costs have been debated many times since then, often using the principle of the safe minimum standard (SMS) as a target of environmental and natural resource policy. The SMS is achieved by avoiding the critical zone, which is the physical conditions, brought about by human action, which would make it uneconomical to halt and reverse depletion.

We account for resource costs in the current analysis by the simple requirement that the critical zone is avoided. We have no data on critical zones for any of the Basin's reservoirs, river reaches, or aquifers. So we simply constrained the model to return all the basin's reservoirs and aquifers to a storage level no lower than they began in the initial period. This method assumes that no basin reservoirs or aquifers occupy the critical zone in the initial period. While our method avoids the important issue of how resource costs should be measured, it is one way to assure that resource costs, however correctly measured will not exceed their initial levels.

4.3.4 Net Benefits
4.3.4.1 Net Use-Related Benefits

For our model, total net use-related benefits are specified as the following conventional algebraic subtraction of use-related costs from use-related benefits:

\[ (5) \ XNBu_{\text{st}} = XBu_{\text{st}} - XCu_{\text{st}} \]

In wet years, net use-related benefits are maximized by the model at each use node, while its sum is maximized over all use nodes, consistent with other constraints. That is, with sufficient system water, the model moves water around the system to maximize each node's net benefits consistent with remaining constraints.

4.3.4.2 Net Environmental Benefits

Net environmental benefits are computed by a similar conventional algebraic expression:

\[ (6) \ XNBe_{\text{st}} = XBe_{\text{st}} - XCe_{\text{st}} \]

With adequate starting reservoir volumes, these net environmental benefits are also maximized by selecting reservoir volumes for which environmental benefits exceed environmental costs by the largest amount, i.e. where marginal benefit at that site equals marginal cost. With heavy restrictions on water supplies, either hydrological or institutional, the model sets reservoir levels so that marginal net environmental benefits exceed zero by a considerable amount.

4.3.5 Net Present Value

Discounted net present value is expressed in its standard algebraic form:

\[ (7) \ XNPV = \sum_{\epsilon} \sum_{t} \frac{XNBu_{\text{st}}}{(1 + r_\epsilon)^t} + \sum_{\epsilon} \sum_{t} \frac{XNBe_{\text{st}}}{(1 + r_\epsilon)^t} \]

The four existing institutions incorporated into this model are described earlier. All four have
considerable influence on the basin's allocation of water and, in the absence of active water markets promoting water trading, are inflexible to change in the short-run. That discounted net present value includes the summed and discounted stream over all periods of net use-related benefits added to net environmental benefits.

4.3.6 Integrating a Policy's Total Economic Efficiency
A significant question facing water policymakers centers on the measurement of economic efficiency effects of a proposed water decision. Our analysis accounts for efficiency impacts, the change in total economic value, by computing four important kinds of benefits and costs for each location where economic benefits from water occur. For each of node, our model calculates (1) use-related benefits, (2) use-related costs, (3) environmental benefits, and (4) environmental costs. Each node’s total net benefit in a single period is its 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, shown in equation (7) above. Using this method to calculate and compare use-related net benefits to net benefits arising from an environmental improvement, we measure total opportunity costs of any program of measures as the efficiency change it brings about, positive or negative.

4.4 Evaluating Institutions

4.4.1 Law of the River
The model constrains water allocations to produce outcomes consistent with the four water institutions described above. We characterize these four institutions as the “Law of the River.” In the model, solutions representing water allocations under this Law of the River are obtained through a single optimization. That optimization maximizes basin-wide economic benefits, subject to these four institutional constraints as well as the hydrologic relations described above. While always respecting the Law of the River, the model compares effects of four proposed policies described below.

4.4.2 Marginal Cost Pricing
What we label marginal cost pricing is implemented in our model by a simple maximization of total basin-wide net benefits with no constraints requiring urban water deliveries to satisfy human rights requirements through subsidized prices. So the term marginal cost pricing strictly correct only if it’s recognized that the Basin’s institutional and hydrologic constraints require that some of the costs included in marginal costs are marginal net benefits displaced from other basin users.

Consider the rare Basin condition of plentiful inflows and full reservoirs, last seen in 1985. Water allocated under a marginal cost pricing arrangement will result in marginal net benefits equal to zero (price - marginal cost = 0). In such a wet period, at the environmental nodes, an economically efficient system operation will set price (marginal benefit) equal to the marginal environmental cost of supplying additional reservoir volume to support the higher quality environment desired by visitors.

In a dry years there is inadequate water to enable price to equal marginal cost at all nodes. In these dry conditions, if there were neither institutional constraints nor conveyance losses, price minus marginal cost is equal everywhere. However, institutional constraints such as the Compact, federal environmental laws, and Treaty, complete economic optimization cannot occur, so price minus marginal cost varies by node. As a consequence of all these issues, what term ‘marginal cost pricing’ is a hydrologically- and institutionally-constrained marginal cost pricing.

4.4.3 Two-Tiered Pricing

Two-tiered pricing combines elements of efficiency, equity, and sustainability. Debates on tradeoffs between equity and efficiency have long surrounded water pricing proposals. Economic efficiency in water use requires that the price charged on the last unit used equals the marginal cost of supply, including all environmental costs. In some heavily-industrialized river basins, environmental externality costs can be the largest element of cost associated with urban use, and efficient environmental taxes could be quite significant on discretionary use (Garcia and Reynaud, 2004).

We implement two tiered pricing by adding two constraints to marginal cost pricing described above. (1) subsistence requirements of 22 gallons (83 liters) per person per day are priced at a politically negotiated
price of $1/1000 gallons for all urban households; (2) discretionary urban use exceeding subsistence
demands are priced sufficiently high to permit recovery of total urban costs. That outcome raises price
above marginal cost on discretionary uses, which has the advantage of sending nearly efficient price
signals to urban users. Pricing water at a low or zero price, which may be attractive on equity grounds,
makes it difficult for the utility to pay for its operation costs, and therefore puts at risk the long run
sustainable water supply.

Two-tiered pricing presents one way to deal with conflicts between equity, efficiency, and sustainability.
Here, the price on all water use in excess of the subsistence level is raised to a level higher than average
cost. The price will be high enough to offset losses on the subsidized water, if long run financial
viability is important. The price that ensures the financial viability of the water utility is that price that
produces revenues in excess of average costs on discretionary use. The constraint characterizing
implementation of two-tiered pricing is set up below in three steps:

Step one defines total revenue:

\[ (8a) \ XRu_{ut} = P_{ut} (X_{ut} - \bar{X}_{ut} ) + \bar{P}_{ut} \bar{X}_{ut} \]

which says total revenue, \( XRu_{ut} \), at the two urban nodes, equals revenue from unsubsidized discretionary
use plus the same from subsidized use. Revenue from unsubsidized use is the equilibrium price, \( P_{ut} \),
times the difference between total water use, \( X_{ut} \), and the politically set subsistence use rate per
household, \( \bar{X}_{ut} \). Revenue from the subsidized use is the politically set price, \( \bar{P}_{ut} \), times subsidized
use, \( \bar{X}_{ut} \). The equilibrium price at each urban node, is the partial derivative (slope) of the total use
benefits function, \( XB_{ut} \), with respect to additional use.

Step two defines net revenue as total revenue minus total costs:

\[ (8b) \ XNRu_{ut} = XRu_{ut} - XCu_{ut} \]
Defining net revenue as total revenue minus total costs allows setting a constraint that requires financial sustainability in each period. The model implements this requirement through a constrained optimization: it raises price just enough on unsubsidized use to make up for losses on subsidized use. Only urban nodes are affected. Step three defines equity on subsidized use as the difference between average cost and the subsidized price times total subsistence use:

\[ (8c) \quad X_E Q u_{st} = \left[ \frac{X C u_{st}}{X u_{st}} - \bar{P}_{st} \right] \overline{X}_{st} \]

While this equation presents a simplistic and limited concept of equity, it permits the model to measure and implement a politically important constraint in the conduct of water policy. For subsistence use, a more politically attractive water price is one that produces a larger value for \( (8c) \), i.e., average cost of supply minus price to those users multiplied by the total quantity of subsistence use.

This two-tiered water pricing system presents three advantages: (1) It achieves equity by supporting human rights for urban water consumers; (2) it is nearly economic efficient: By charging a price approximately equal to the marginal cost for all use levels exceeding basic needs, price signals the real scarcity of expanding system capacity; (3) it is financially sustainable. By securing each period’s revenues adequate to cover costs, the utility and its water supply can last.

When two-tiered pricing is combined with arsenic treatment, the cost of supplying arsenic treated water is higher. So the second tier price is much higher with arsenic treatment than without. When water treatment costs increases with stricter environmental regulations, a self-financing utility must charge a much higher price on discretionary uses to make up for the fact that the higher costs of supply cannot be recovered by charging for subsistence use.

5 Results

5.1 Overview

Results show impacts starting from the severely depleted reservoir conditions existing in late 2005. We focus on four scenarios representing a combination of two pricing institutions and two water treatment
programs, all of which affect the hydrologic and economic results. The hydrologic conditions produce constant inflow levels to the basin for twenty consecutive future years, 2006-2025. While this assumption is simplistic, it’s used to permit a clear viewing of economic impacts of water pricing and water quality improvements to be distinguished from varying hydrologic conditions. We developed the model using GAMS (GAMS, 2007). Water flows and stocks are allocated simultaneously over all years and nodes in the model, reflecting the assumption that the Basin's planners believe that each future year's inflows at the headwater gauges will match that gauge's long run average over the period of record. We hope to conduct future work in which we find out more about the length Basin managers' planning horizons and their expectation of future Basin inflows.

5.2 Existing Urban Water Prices

Albuquerque’s current water price on its lowest residential use level is $1.80 per thousand gallons for the first 16,000 gallons per household per month. El Paso’s equivalent rate is $1.63 for the first 2992 gallons. Neither city practices pure marginal cost pricing, because of the undesirable equity properties described in this paper. Both cities use a water rate structure consisting of increasing block pricing in which higher use levels are charged a higher marginal price. Rate structures are summarized by Albuquerque (2007) [http://abcwua.org/customerservices/waterbill.html](http://abcwua.org/customerservices/waterbill.html) and El Paso (2007) [http://www.epwu.org/services/water_rates.html](http://www.epwu.org/services/water_rates.html).

One way to know if price on discretionary use is close to marginal cost is to see if that price increases in a drought. During drought, when scarce supplies result in capacity falling below demand, the marginal cost of any one household’s use is the opportunity cost of displacing another’s use. We could find no special drought-pricing program for either utility, in which water’s price automatically increases in drought to reflect a rising marginal cost. By comparison, the Los Angeles Department of Water and Power, one celebrated practitioner of two-tiered pricing, structures rates to increase during drought (Hall, 2000 and Los Angeles (2006)). So we conclude that for Albuquerque and El Paso, prices on discretionary use are closer to average cost than to marginal cost. That is, neither city practices two-tiered pricing as described in this paper. Still, a policy in which subsistence uses are priced affordably for all while remaining uses are priced at marginal cost provides a well-defined set of principles for
designing rates that nearly meet efficiency, equity, and sustainability goals, as summarized in the results below.

5.3 Performance of Four Water Programs

5.3.1 Marginal Cost Pricing without Arsenic Treatment

Hydrologic impacts are shown in the top part of Table 1. These impacts reflect the net-benefit maximizing combination of storage, release, and use patterns consistent with the Law of the River combined with a marginal cost pricing policy without arsenic treatment. About 10 percent of the water applied to non-environmental uses is for urban customers, with the remaining 90 percent going to agriculture. Part of the low storage at the two lower reservoirs occurs under the model’s optimization goal because of the considerably lower evaporation per acre of water exposed in the upper reservoirs. El Paso delivers just over 160,000 acre-feet per year averaged over the next 20 years, about 40 percent from its surface treatment capacity. The rest is made up by groundwater pumping. West Texas agriculture applies just over 300,000 acre feet per year, all from surface supplies. All Basin reservoirs and aquifers’ ending levels are constrained to be at least as high as their starting levels, so this policy produces zero resource costs (WATECO, 2002).

5.3.2 Two-Tiered Pricing without Arsenic Treatment

Table 2 shows hydrologic and economic outcomes associated with a two-tiered pricing system without arsenic treatment. Two tiered pricing is expected to be less desirable on pure efficiency grounds because a higher price charged for discretionary urban uses is required to finance subsistence uses. That higher price for discretionary consumption restricts urban uses slightly compared to a scenario of pure marginal cost pricing. Total net efficiency benefits are $782.8 million per year, a modest one tenth of one percent reduction from Basin total net benefits of $783.6 million produced under pure marginal cost pricing.

The table shows the distribution of total benefits, total costs, and total net benefits to three classes of beneficiaries: (1) urban uses, (2) agricultural uses, and (3) water environments. It also shows marginal benefits (prices), marginal costs, and marginal net benefits to the same uses. Notice that marginal benefits are considerably higher than marginal costs for urban uses because of the two tiered pricing
arrangement. The excess of marginal benefits over marginal cost occurs because marginal (discretionary) uses are priced at a level exceeding marginal cost by an amount needed to offset financial losses on water subsidies for subsistence needs. A similar water pricing program has been practiced by the Metropolitan Water District of southern California since the early 1990s (Los Angeles Department of Water and Power, 2006).

5.3.3 Marginal Cost Pricing with Arsenic Treatment
Table 3 shows annual water use falling in both cities, from 143,000 to 132,000 acre feet in Albuquerque and from 162,000 to about 155,000 for El Paso. The reduction is larger for Albuquerque because of its considerably higher arsenic treatment cost. Demand price elasticities for both cities are about -0.10. Most of the effects of arsenic treatment costs passed onto water customers are concentrated in reduced urban water use. There is a small effect of increased basin water supplies made available for agriculture brought on by reduced urban use due to arsenic treatment. Most of the reduced urban use reduces groundwater pumping, and associated reduced depletion of the basin’s aquifers. As of 2007, Albuquerque relies exclusively on groundwater pumping, and any reductions in El Paso’s water use will come from changes in groundwater pumping, because its surface treatment capacity is at its upper bound. The table shows that the arsenic treatment programs make for higher quality drinking water as well as a longer-lasting aquifer.²

5.3.4 Two-Tiered Pricing with Arsenic Treatment
Compared to two-tiered pricing without arsenic treatment, table 4 shows water use falling in both cities, from about 139,000 to about 122,000 acre feet per year in Albuquerque and from about 156,000 to about 145,000 for El Paso. This water use reduction is due exclusively to the higher prices charged to water customers to pay for arsenic treatment. But the impact of arsenic treatment on use is larger for the case of two-tiered pricing than for marginal cost pricing. This occurs because subsistence needs are independent of the cost of treating water. This table reminds us that securing human rights for urban

---

²We should point out that our analysis makes no attempt to measure the human health benefits produced by arsenic treatment, an amount we would certainly expect to exceed the annual efficiency losses of $68.5 million = $783.6 million - $715.1 million, compared to the no-treatment scenario.
water when natural water quality is poor or health requirements are strict is a more expensive proposition than when natural water quality is good or health requirements are lax or poorly-enforced. Not surprisingly, total basin-wide benefits under this arrangement are the lowest, at a total of $712.8 million per year.

5.4 Tradeoffs among Policy Goals
Meeting human rights goals by charging a fee on discretionary use becomes more difficult as the required quantity of water increases or as the cost increases of supplying environmentally acceptable drinking water (Table 5). A small increase in the cost of treating water to acceptable levels can lead to a much larger increase in the overall price charged on discretionary use. In fact, high prices charged on discretionary use can reduce that discretionary use by so much that there is too little total revenue from high charges on that use left to pay for the subsidy. The problem becomes more severe with a higher price elasticity of demand for discretionary uses. In fact, many poor countries have discovered that charges on high volume users simply cannot finance sufficient accessible water for all. Financing the human right to water may require intervention by the central government or by donor nations. The search for self-financing measures for delivering affordable clean water to the world’s 1 billion who lack it is likely to remain high on the international agenda.

6 Conclusions
This paper has examined the policy-informing role that can be played by the development and use of basin scale models. By combining and integrating elements of hydrology, economics, and law, use of these models has considerable potential to support the design of better-performing policies. Improved access to subsistence demands for safe water is a major challenge everywhere, especially in the developing world, due to its widespread impacts on human health and economic growth and its close connection to the well-being of poor people.

The framework developed in this paper was applied to assess impacts of two policy instruments under each of two regulatory frameworks that address recently implemented drinking water quality standards for the Rio Grande Basin’s two largest U.S. cities: Albuquerque, New Mexico, and El Paso, Texas. Both
marginal cost pricing and two-tiered pricing are examined under weak versus strong environmental regulations for treating arsenic in urban water supply.

Economic theory predicts that a two-tiered pricing scheme will lead to some efficiency losses to secure more equitable water allocations, but the size of this tradeoff is an empirical question. Our empirical results conclude that the efficiency losses are negligible in comparison to the gains in fairness. This result has significant implications for the design of water pricing programs that could promote nearly efficient and sustainable water use patterns while attracting political support by being seen as fair to low income urban water users.

Implementing a two-tiered water pricing program incurs a low cost of economic benefits foregone. Without environmental protection of water quality (weak arsenic treatment standards), two-tiered pricing secures an affordable human right to urban water with only a 0.1 percent loss in basin-wide total economic benefits. Even with environmental protection of water quality (stringent arsenic treatment standards), basin scale efficiency losses are only 0.3 percent when two-tiered pricing is implemented compared to pure marginal cost pricing.

Declaring a universal human right to water is on solid moral ground. However, implementing that right can be an expensive proposition. So an important policy question in development circles centers around the economic cost of implementing the human right to water and how that cost varies by community, culture, hydrologic conditions, and economic system. One way to answer that question is to calculate the economic benefits displaced by implementing a two-tiered pricing arrangement under various conditions. Results of our basin scale analysis predict that efficiency losses produced by two-tiered pricing will vary. Costs increase with (1) an increased quantity of subsistence water per household that defines an acceptable human right, (2) a lower price charged on that subsistence requirement, (3) a larger percentage of people currently lacking access to safe water, and (4) higher safety standards for defining acceptable water quality.

Two-tiered pricing has been used successfully for many of the world’s urban water utilities. But
stakeholders will have a say in defining its two important dimensions: the amount of water use defining subsistence needs, and the price charged for that use. Compared to more conventional rate structures, such as average cost pricing, water customers may resist a two-tiered pricing system unless most see reduced bills (Hall, 2000). Moreover, two-tiered pricing for urban water supply can challenge the recovery of costs where most water customers are poor, which occurs often in places where the human right to water is lacking.

Several important assumptions influence our results: The model assumes the presence of market-like arrangements, such as water rentals or transfers, by which scarce water moves to its highest-valued uses, constrained only by hydrologic relations and by existing water allocation rules. This paper has presented only two policy alternatives in each of two regulatory environments. We hope to consider more policy choices and a larger number of regulatory environments in future work. Our analysis assumes a zero discount rate. It ignores impacts of heavy real-world discounting of future benefits and costs by water users. Many in the Basin avoid undertaking efficient water actions because their high discount rates favor current use over future supplies. The model is currently limited to a yearly time step. A shorter time step would permit a more precise analysis for addressing important current policy debates like climate change, intraseasonal water allocation, and temporary water banks. The model also has a limited treatment of environmental values of water, currently addressing only anglers’ use values from reservoir level fluctuations. Ignored are important non-use values such as option, existence, and bequest values of the complete water environment. The model is deterministic. A better model will account for stochastic inflows, prices, and water demands as well as for risks of any of these factors failing to measure up to water users’ and managers’ expectations. All these limits point to avenues by which future research could improve the model’s capacity to support water policy design at the basin scale.

Despite the limits of our model, the importance and complexity of 21st century water policy debates assigns considerable importance to the use of basin scale analysis for informing debates, such as the one conducted for this paper. Basin-scale analysis provides a comprehensive framework for informing the design of measures that produce efficient, equitable, and sustainable distribution of economic benefits and costs of water programs.
Acknowledgments

The authors are grateful for generous and sustained financial support by the New Mexico Agricultural Experiment Station and Rio Grande Basin Initiative Program. Remaining errors are the responsibility of the authors.


Ward, F.A., J.F. Booker, and A. Michelsen. 2006. Integrated Economic, Hydrologic, and


### Table 1: Hydrologic and Economic Performance, Marginal Cost Pricing without Urban Arsenic Water Treatment, Rio Grande Basin

<table>
<thead>
<tr>
<th>Sector</th>
<th>CO</th>
<th>NM</th>
<th>TX</th>
<th>Basin Total</th>
</tr>
</thead>
<tbody>
<tr>
<td>Hydrologic Performance</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Water Applied (1000 ac-ft/yr)</td>
<td>1,777.3</td>
<td>143.3</td>
<td>98.8</td>
<td>513.4</td>
</tr>
<tr>
<td>Surface water</td>
<td>660.5</td>
<td>0.0</td>
<td>92.8</td>
<td>513.4</td>
</tr>
<tr>
<td>Groundwater</td>
<td>1,116.8</td>
<td>143.3</td>
<td>0.0</td>
<td>0.0</td>
</tr>
<tr>
<td>Economic Performance</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Benefits ($US million/yr)</td>
<td>207.6</td>
<td>401.1</td>
<td>2.9</td>
<td>32.9</td>
</tr>
<tr>
<td>Use</td>
<td>207.6</td>
<td>401.1</td>
<td>2.9</td>
<td>32.9</td>
</tr>
<tr>
<td>Environmental Costs ($US million/yr)</td>
<td>51.3</td>
<td>116.8</td>
<td>1.0</td>
<td>5.1</td>
</tr>
<tr>
<td>Environmental Use</td>
<td>51.3</td>
<td>116.8</td>
<td>1.0</td>
<td>5.1</td>
</tr>
<tr>
<td>Environmental Net Economic Benefits</td>
<td>156.3</td>
<td>284.3</td>
<td>1.9</td>
<td>27.7</td>
</tr>
<tr>
<td>Marginal Benefit ($)</td>
<td>80.0</td>
<td>1,849.4</td>
<td>60.3</td>
<td>80.8</td>
</tr>
<tr>
<td>Marginal Cost ($)</td>
<td>57.7</td>
<td>1,848.1</td>
<td>36.0</td>
<td>21.7</td>
</tr>
<tr>
<td>Marginal Net Benefit ($)</td>
<td>22.3</td>
<td>1.4</td>
<td>24.5</td>
<td>59.0</td>
</tr>
</tbody>
</table>
### Table 2: Hydrologic and Economic Performance, Two-Tiered Pricing without Urban Arsenic Water Treatment, Rio Grande Basin

<table>
<thead>
<tr>
<th>State</th>
<th>CO</th>
<th>NM</th>
<th>TX</th>
<th>Basin</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sector</td>
<td>SLV Ag</td>
<td>Albuquerque Ml</td>
<td>MRGCD Ag</td>
<td>EBID Ag</td>
</tr>
<tr>
<td>Hydrologic Performance</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Water Applied (1000 ac-ft/yr)</td>
<td>1,777.3</td>
<td>138.3</td>
<td>98.9</td>
<td>513.5</td>
</tr>
<tr>
<td>Surface water</td>
<td>660.5</td>
<td>0.0</td>
<td>98.9</td>
<td>513.5</td>
</tr>
<tr>
<td>Groundwater</td>
<td>1,116.8</td>
<td>138.3</td>
<td>0.0</td>
<td>0.0</td>
</tr>
<tr>
<td>Economic Performance</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Benefits ($US million/yr)</td>
<td>207.6</td>
<td>396.6</td>
<td>2.9</td>
<td>32.9</td>
</tr>
<tr>
<td>Use</td>
<td>207.6</td>
<td>396.6</td>
<td>2.9</td>
<td>32.9</td>
</tr>
<tr>
<td>Environmental</td>
<td>0.0</td>
<td>0.0</td>
<td>0.0</td>
<td>0.0</td>
</tr>
<tr>
<td>Costs ($US million/yr)</td>
<td>51.3</td>
<td>112.7</td>
<td>1.0</td>
<td>5.1</td>
</tr>
<tr>
<td>Use</td>
<td>51.3</td>
<td>112.7</td>
<td>1.0</td>
<td>5.1</td>
</tr>
<tr>
<td>Environmental</td>
<td>0.0</td>
<td>0.0</td>
<td>0.0</td>
<td>0.0</td>
</tr>
<tr>
<td>Net Economic Benefits</td>
<td>156.3</td>
<td>282.9</td>
<td>1.9</td>
<td>27.7</td>
</tr>
<tr>
<td>Marginal Benefit ($)</td>
<td>30.0</td>
<td>2,164.0</td>
<td>60.5</td>
<td>80.8</td>
</tr>
<tr>
<td>Marginal Cost ($)</td>
<td>57.7</td>
<td>1,848.1</td>
<td>36.0</td>
<td>21.7</td>
</tr>
<tr>
<td>Marginal Net Benefit ($)</td>
<td>22.3</td>
<td>315.9</td>
<td>24.5</td>
<td>59.0</td>
</tr>
</tbody>
</table>

T-2
Table 3: Hydrologic and Economic Performance of Marginal Cost Pricing with Urban Arsenic Water Treatment, Rio Grande Basin

<table>
<thead>
<tr>
<th>State</th>
<th>CO</th>
<th>NM</th>
<th>TX</th>
<th>Basin</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>SLV Ag</td>
<td>Albuquerque M</td>
<td>MR3CD Ag</td>
<td>EBID Ag</td>
</tr>
<tr>
<td>Hydrologic Performance</td>
<td>1,777.3</td>
<td>131.5</td>
<td>98.9</td>
<td>513.8</td>
</tr>
<tr>
<td>Water Applied (1000 ac ft/yr)</td>
<td>660.5</td>
<td>0.0</td>
<td>98.9</td>
<td>513.8</td>
</tr>
<tr>
<td>Surface water</td>
<td>1,116.8</td>
<td>131.5</td>
<td>0.0</td>
<td>0.0</td>
</tr>
<tr>
<td>Groundwater</td>
<td>0.0</td>
<td>0.0</td>
<td>0.0</td>
<td>0.0</td>
</tr>
<tr>
<td>Economic Performance</td>
<td>0.0</td>
<td>0.0</td>
<td>0.0</td>
<td>0.0</td>
</tr>
<tr>
<td>Benefits ($US million/yr)</td>
<td>207.6</td>
<td>389.5</td>
<td>2.9</td>
<td>32.9</td>
</tr>
<tr>
<td>Use</td>
<td>207.6</td>
<td>389.5</td>
<td>2.9</td>
<td>32.9</td>
</tr>
<tr>
<td>Environmental</td>
<td>0.0</td>
<td>0.0</td>
<td>0.0</td>
<td>0.0</td>
</tr>
<tr>
<td>Costs ($US million/yr)</td>
<td>51.3</td>
<td>150.1</td>
<td>1.0</td>
<td>5.1</td>
</tr>
<tr>
<td>Use</td>
<td>51.3</td>
<td>150.1</td>
<td>1.0</td>
<td>5.1</td>
</tr>
<tr>
<td>Environmental</td>
<td>0.0</td>
<td>0.0</td>
<td>0.0</td>
<td>0.0</td>
</tr>
<tr>
<td>Net Economic Benefits</td>
<td>156.3</td>
<td>239.5</td>
<td>1.9</td>
<td>27.7</td>
</tr>
<tr>
<td>Marginal Benefit ($)</td>
<td>80.0</td>
<td>2,588.8</td>
<td>60.5</td>
<td>80.3</td>
</tr>
<tr>
<td>Marginal Cost ($)</td>
<td>57.7</td>
<td>2,587.3</td>
<td>60.0</td>
<td>21.7</td>
</tr>
<tr>
<td>Marginal Net Benefit ($)</td>
<td>22.3</td>
<td>1.5</td>
<td>24.5</td>
<td>59.0</td>
</tr>
</tbody>
</table>
10.4 Table 4: Hydrologic and Economic Performance, Two-Tiered Pricing with Urban Arsenic Water Treatment, Rio Grande Basin

<table>
<thead>
<tr>
<th>State</th>
<th>Sector</th>
<th>CO</th>
<th>NM</th>
<th>TX</th>
<th>Basin</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Hydrologic Performance</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Water Applied (1000 ac-ft/yr)</td>
<td>1,777.3</td>
<td>121.6</td>
<td>99.1</td>
<td>514.1</td>
</tr>
<tr>
<td></td>
<td>Surface water</td>
<td>660.5</td>
<td>0.0</td>
<td>99.1</td>
<td>514.1</td>
</tr>
<tr>
<td></td>
<td>Groundwater</td>
<td>1,116.8</td>
<td>121.6</td>
<td>0.0</td>
<td>0.0</td>
</tr>
<tr>
<td></td>
<td>Economic Performance</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Benefits ($US million/yr)</td>
<td>207.6</td>
<td>376.9</td>
<td>2.9</td>
<td>32.9</td>
</tr>
<tr>
<td></td>
<td>Use</td>
<td>207.6</td>
<td>376.9</td>
<td>2.9</td>
<td>32.9</td>
</tr>
<tr>
<td></td>
<td>Environmental</td>
<td>0.0</td>
<td>0.0</td>
<td>0.0</td>
<td>0.0</td>
</tr>
<tr>
<td></td>
<td>Costs ($US million/yr)</td>
<td>51.3</td>
<td>138.8</td>
<td>1.0</td>
<td>5.1</td>
</tr>
<tr>
<td></td>
<td>Use</td>
<td>51.3</td>
<td>138.8</td>
<td>1.0</td>
<td>5.1</td>
</tr>
<tr>
<td></td>
<td>Environmental</td>
<td>0.0</td>
<td>0.0</td>
<td>0.0</td>
<td>0.0</td>
</tr>
<tr>
<td></td>
<td>Net Economic Benefits</td>
<td>156.3</td>
<td>238.1</td>
<td>1.9</td>
<td>27.8</td>
</tr>
<tr>
<td></td>
<td>Marginal Benefit ($)</td>
<td>80.0</td>
<td>3210.5</td>
<td>60.5</td>
<td>30.8</td>
</tr>
<tr>
<td></td>
<td>Marginal Cost ($)</td>
<td>57.7</td>
<td>2587.3</td>
<td>36.0</td>
<td>21.7</td>
</tr>
<tr>
<td></td>
<td>Marginal Net Benefit ($)</td>
<td>22.3</td>
<td>623.2</td>
<td>24.5</td>
<td>59.0</td>
</tr>
</tbody>
</table>
10.5 Table 5: Efficiency, Equity, and Sustainability of Four Water Pricing and Allocation Programs, Rio Grande Basin

<table>
<thead>
<tr>
<th>Water Allocation and Pricing Measure</th>
<th>Economic Efficiency (Total Net Benefits) $million/yr</th>
<th>Equity [(AC - P) x Wn] $1000/yr</th>
<th>Sustainability pct of costs recovered</th>
</tr>
</thead>
<tbody>
<tr>
<td>Marginal Cost Pricing for urban without arsenic water treatment⁴</td>
<td>783.6</td>
<td>0</td>
<td>102</td>
</tr>
<tr>
<td>Two-tiered pricing for urban without arsenic water treatment⁵</td>
<td>782.8</td>
<td>110.8</td>
<td>100</td>
</tr>
<tr>
<td>Marginal Cost Pricing for urban with Arsenic Water Treatment⁶</td>
<td>715.1</td>
<td>0</td>
<td>102</td>
</tr>
<tr>
<td>Two-tiered pricing for urban with arsenic water treatment⁷</td>
<td>712.8</td>
<td>184.7</td>
<td>100</td>
</tr>
</tbody>
</table>

⁴Defined as average cost of supply minus a subsidized water price set at $US 0.26/1000 liters ($ 1/1000 gal) for urban basic needs. That need is defined as 83 liters (22 gallons) /day/person/household.

⁵Achieved by maximizing regional economic benefits subject to 4 institutional constraints: (1) US Mexico Treaty of 1906, (2) Endangered Species Act of 1973, (3) Rio Grande Compact, and (4) New Mexico Texas water allocation convention; Excludes urban water arsenic treatment while pricing all water at its full marginal cost.

⁶Maximizes regional economic benefits constrained by four institutions above. Excludes urban water arsenic treatment, while subsidizing required urban water uses.

⁷Maximizes regional economic benefits constrained by four institutions above. Includes a higher cost and price to pay for urban water arsenic treatment while pricing all water uses at full marginal cost.

⁸Maximizes regional economic benefits constrained by four institutions above. Includes a higher cost and price to pay for urban water arsenic treatment while subsidizing required urban uses.