Rio Grande Basin Policy Model

Mathematical Documentation

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1 Overview

This report documents mathematically a decision support system of the Upper Rio Grande Basin of Colorado, New Mexico, and West Texas, USA. The system was developed to support analysis of policy options affecting the use of the water resources of the Upper Rio Grande Basin (the Basin) for multiple uses, including urban water supply, irrigated agriculture, and the environment. A related objective was to assemble a comprehensive database for the Basin informing policy debates on the development, conservation, use, and management of water resources. It was designed to analyze and assess various policy options based on their cost, water demands, affects on water supply, and long-term sustainability.

The river basin is a natural unit for integrated water resources planning and management.
Policy instruments designed to promote economically efficient use of water resources can be applied more comprehensively at the basin scale. This model integrates hydrology, land use, economics, and water resources institutions to support improved policy design, implementation, and evaluation. Additional model details and the several versions of the model's GAMS code are posted on the web[1] and are available from the authors on request. An older version of the model has been published.[2] While this model and its documentation was developed for application to the Rio Grande Basin, it was designed to be adaptable to the hydrology, land use patterns, economics, and institutions of any basin.

2 Hydrology

The essential principle of the hydrology model is mass balance, both for surface flows, reservoir levels, and aquifer levels, and aquifer-stream interactions. The hydrology model described below uses mass balance principles to account for headwater flows, streamflows, reservoir levels, water from surface or groundwater sources applied to various uses, groundwater pumping, and the impact of pumping and surface flows on current and future storage levels of reservoirs and aquifers.

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[1] URL is http://agecon.nmsu.edu/fward/water/

[2] Ward, F.A. and M. Pulido Velazquez, "Pricing and Cost Recovery at the Basin Scale," *Journal of Environmental Management*, forthcoming, 2008.

2.1 Headwater Runoff

Total inflows into the basin are defined as total annual flows at nine headwater stream gauges. Inflow at each *h-th* headwater gauges in year *t*, X_{ht}, equals total source supplies:

$$(A1) \quad X_{ht} = Source_{ht}.$$

2.2 Streamflow

Streamflow at each river gauge in period t, X_{vt}, equals the sum of flows over six kinds of upstream nodes[3] whose activities influence that flow: (1) headwater inflows; (2) upstream river gauges; (3) upstream diversions; (4) upstream surface return flows; (5) upstream groundwater-to-stream recharge; (6) upstream reservoir releases. Total flows, which cannot be negative, are defined for each of those six types of nodes, respectively, as:

$$(A2)\ X_{vt} = \sum_h B_{hv} X_{ht} + \sum_v B_{vv} X_{vt} + \sum_d B_{dv} X_{dt} + \sum_r B_{rv} X_{rt} + \sum_g B_{gv} X_{gt} + \sum_L B_{Lv} X_{Lt}.$$

where the set v defines all river gauges, and X_{vt} is the streamflow at any river gauge node (element of the set v). Each of the six vectors of B coefficients takes on values of 0 for non-contributing upstream sources, 1 for sources that add flow, and -1 for sources that reduce flow. So, positive signs in an equation (+) require adding flows, and subtractions (-) occur whenever a B coefficient is negative. For example, the first term, $\sum_h B_{hv} X_{ht}$, sums contributions over the set (h) of headwater nodes. The vector B_{hv} contains 1s for all immediately upstream headwater gauges that contribute to a river's flow and 0 otherwise, where X_{ht} are flows at all headwater gauges. The second right-hand side term, $\sum_v B_{vv} X_{vt}$, sums contributions over the set (v) of relevant upstream river gauge elements. The vector B_{vv} typically contains a single 1, and the rest zeros. The third term, $\sum_d B_{dv} X_{dt}$, sums streamflow reductions over the set (d) of upstream diversion nodes. By accounting for upstream diversions, the B_{dv} vector's coefficients are 0 for non-diverting locations and for diversions that do not affect the given node's flow, but -1 where upstream diversions directly reduce that flow. The last three terms similarly account for:

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[3] A node is a location in the basin at which water's supply or demand is affected.

upstream surface return flows in the set (*r*), net change in streamflow at nodes influenced by groundwater flows to the river in the set (*g*), and upstream reservoir releases in the set (*L*) that affect streamflows.

2.3 Water Diverted

Both agricultural and urban uses can be met by stream diversions. However, in many of the world's dry places, historical record show many periods of zero flow in periods of high demand and low runoff. The following equation, a "wet water" condition, requires that no diversion exceeds available streamflow at the point of diversion. So each diversion must be less than the sum of all six classes of upstream sources: (1) headwater inflows; (2) upstream river gauges; (3) upstream diversions; (4) upstream surface return flows; (5) upstream recharge from groundwater interactions with the river; (6) upstream reservoir releases. A diversion, which cannot be negative, is:

$$(A3)\ X_{dt} \leq \sum_{h} B_{hd} X_{ht} + \sum_{v} B_{vd} X_{vt} + \sum_{d} B_{dd} X_{dt} + \sum_{r} B_{rd} X_{rt} + \sum_{g} B_{gd} X_{gt} + \sum_{L} B_{Ld} X_{Lt}.$$

where the right hand side terms are the sum of all contributions to flow at the point of diversion from upstream sources. The various *B* terms, which indicate presence (1) or absence (0) of upstream flow sources for a given node, are used to configure the basin.[4]

2.4 Water Applied

Like water diverted, total water applied to a use at any node in period *t*, X_{at}, is a choice variable. Water applied can come from two sources: a stream diversion, X_{dt} or from groundwater pumping, X_{pt}. Total water applied is:

$$(A4)\quad X_{at} = \sum_{d} B_{da} X_{dt} + \sum_{p} B_{pa} X_{pt}.$$

Both sets of parameters B_{da} and B_{pa} are identity matrices to conform like nodes in the basin.

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[4] For example, irrigation diversions on the Rio Grande downstream of Albuquerque New Mexico cannot exceed the river's flow at that node. The river's flow at that node is found by adding the river's flow at the closest upstream river gauge, the Otowi gauge, X_{vt}^{O}, surface return flows from Albuquerque, X_{rt}^{Alb}, and groundwater flows to the river from Albuquerque, X_{gt}^{Alb}.

For each agricultural node in the basin, total water applied to farmlands is expressed as:

$$(A4a) \qquad X_{at} = \sum_{c}\sum_{k} B_{akc} \sum_{u} B_{ua} \, L_{uckt} \, .$$

Total irrigation water applied from surface and groundwater sources at each *a-th* water application node in the *t-th* year, equals total water demands. These demands are summed over crops (c) and irrigation technologies (k) based on known water application amounts per acre by crop and technology, B_{akc}. The result is multiplied by an identity matrix, B_{ua}, that conforms nodes and the number of acres irrigated at the *u-th* use node by the *c-th* crop using the *k-th* irrigation technology in the *t-th* year, L_{uckt}. That solution determines the total demand for irrigation water applications by node and time period.

2.5 Water Consumed

Any water use node's consumptive use, X_{ut}, is an empirically-determined proportion of total water applied, X_{at}. For irrigation, consumptive use is the quantity of water lost through plant evapotranspiration (ET) to any future use in the system. For urban uses, consumptive use is the percentage of water piped into the urban home not returned through the sewage line, most of which is for urban landscape. That use, which cannot be negative, is measured as:

$$(A5) \quad X_{ut} = \sum_{a} B_{au} \, X_{at} \, .$$

The parameters B_{au} are a vector of elements indicating the proportion of total water applied that is used consumptively. For urban nodes, the proportion of water applied that is consumed falls as ratepayers reduces their landscape irrigation or invest in other water-conserving measures.

For agricultural nodes, water use is measured as:

$$(A5a) \qquad X_{ut} = \sum_{c}\sum_{k} B_{ukc} \sum_{u} B_{uu} \, L_{uckt} \, .$$

Irrigation ET at the *u-th* agricultural node in the *t-th* year, is derived from total acreage in production. That use is measured as the sum over crops (c) and irrigation technologies (k) of empirically estimated ET amounts per acre by node, crop and technology, B_{ukc}, times an identity matrix, B_{uu}, that conforms nodes. The result is multiplied by the acres irrigated of each type. Irrigated acreage by use, crop, technology, and time is determined by the model's optimal solution. Where there are several choices among water application technologies, e.g. on farm choices between flood and drip irrigation, there is a separate consumptive use coefficient for each technology. Drip irrigation has lower water application rates than flood irrigation, but where drip yields are higher than flood, drip has greater ET.

2.6 Gross Surface Returns to River

Surface return flow to a stream, X_{rt}, is another proportion of water applied. At each return flow node, the return flow coefficient per unit applied, B_{ar}, is the proportion of the quantity applied, X_{at}. Total return flow at a node is:

$$(A6)\ X_{rt} = \sum_{a} B_{ar}\, X_{at}\,.$$

Hydrologic balance requires that total water applied adds up to the sum of consumptive use, gross recharge to the aquifer, and surface return flow. So for any node, $B_{au} + B_{as} + B_{ar}$ sums to 1.0, although any one of those terms can be quite different for different nodes and for varying water uses. For example, nodes located at a greater hydrologic distance from a stream will see a smaller proportion of surface return flow from a given amount of water applied. Decisions by policymakers or actions by water users that alter any one of the three coefficients will affect one or both of the other two. Nodes practicing an increased proportion of drip irrigation will see reduced surface return flows to the river.

For agricultural nodes, total surface returns to the river are measured as:

$$(A6a) \qquad X_{rt} = \quad \sum_{c} \sum_{k} B_{rkc} \sum_{u} B_{ur}\, L_{uckt}\,.$$

Irrigation surface return flows at each *r-th* agricultural node in the *t-th* year, are determined by total cropped acreage. That return flow is measured as the sum over crops (c) and irrigation technologies (k) of empirically estimated return flows per acre by crop and technology, B_{ukc}, times an identity matrix, B_{ur} that conforms like nodes. The result is multiplied by the number of acres of land irrigated by type.

2.7 Gross Recharge to Aquifer

Gross groundwater recharge (seepage) to the aquifer at a node, X_{st}, is also a proportion of total water applied, X_{at}. Other things equal, seepage to the aquifer increases with reduced consumptive use for a given amount of water applied. Total seepage is:

$$(A7)\ X_{st} = \sum_{a} B_{as}\, X_{at}\ .$$

Seepage can be reduced by actions such as lining irrigation ditches with concrete or by substituting drip for flood irrigation. These actions, which reduce the value of $B_{a\,s}$, may reduce the quantity of water irrigators divert from the stream, but they also reduce groundwater recharge to the aquifer. Whether the overall benefits of any one of those actions exceed its costs depends on how the action influences the economic productivity of water (e.g. increased crop yield), as well as on the cost of the action, such as paying to install and maintain a drip irrigation system.

For agricultural nodes, gross aquifer recharge is measured as:

$$(A7a) \qquad X_{st} = \sum_{c}\sum_{k} B_{skc} \sum_{u} B_{us}\, L_{uckt}\, .$$

That recharge results from irrigation from either surface or groundwater sources, at *s-th* agricultural node in the *t-th* year, and is based on total irrigated land in production. That recharge equals the sum over nodes (s), crops (c), and irrigation technologies (k) of empirically observed groundwater recharge amounts per acre by crop and technology, B_{skc}, times an identity matrix, B_{us}, that conforms nodes. The result is multiplied by the number of acres of land irrigated of each type.

2.8 Net Groundwater Recharge

Net groundwater recharge, X_{nt}, is the difference between seepage to an aquifer in a given time period that is produced by seepage, X_{st}, and pumping from the aquifer, X_{pt}. Net recharge to the aquifer can be positive or negative. It is measured as:

$$(A8)\ X_{nt} = \sum_{s} B_{sn}\, X_{st} - \sum_{p} B_{pn}\, X_{pt}\, .$$

where the *Bs* are coefficients indicating presence (1) or absence (0) of seepage and pumping effects on net groundwater recharge at the *n-th* net groundwater recharge node, and X_{pt} is the amount of water pumped from the *p-th* node the aquifer in period *t.*

2.9 Groundwater Flow to River

Groundwater can flow from an aquifer to a river, making the river a gaining reach, or it can flow from the river to the aquifer, making it a losing reach. Choices made by water users or policymakers influence which of the two outcomes occurs. Other things equal, increased pumping increases groundwater flows from the river to the aquifer, while increased water applied to lands near near the river, through increased aquifer recharge, increase groundwater flows from the aquifer to the river. Cook and Balleau (1998) analyze some of the basin's groundwater relationships. Kernodle et. al (1995) analyze the connection between pumping by the city of Albuquerque and the flow of the Rio Grande.

Impact on streamflow is a simple proportion of groundwater recharge. The lag time from groundwater recharge to impact on the stream is highly variable, varying from the current year only (no lag) to twenty or more years. For simplicity and for promoting conservative water administration (Glover and Balmer, 1954),[5] we assume a zero lag for the current version of the model. Groundwater inflows to or outflows from the river at any time, *t*, X_{gt}, is:

$$(A9)\ X_{gt} = \sum_{n} B_{ng}\, X_{nt}\ .$$

where the B_{ng} term, a proportion between 0 and 1, is the impact on river flow in period t from net seepage in the same period.

2.10 Groundwater Flow to Aquifer

Groundwater recharge not affecting the flow of the river in the current period affects that period's aquifer storage. The addition to aquifer storage at the *q-th* aquifer node in the *t-th* period, X_{qt} , is measured in the model as:

$$(A10)\ X_{qt} = \sum_{n} B_{nq}\, X_{nt}\ .$$

Hydrologic balance requires that any unit of groundwater recharge is split into that part affecting the aquifer and that part affecting the river. So $B_{ng} + B_{nq}$ is constrained by conservation of mass principles to

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[5] Glover, R.E., and Balmer, C.G., 1954, River depletion resulting from pumping a well near a river: American Geophysical Union Transactions, 35, part 3, 468-470.

equal 1.0. Groundwater activity near the stream has a value of B_{ng} closer to 1 and a value of B_{nq} closer to zero.

2.11 Reservoir Storage

Each *r-th* reservoir's water stock is tracked for the *t-th* year. That year's water stock, Z_{rt}, equals its stock in the previous year, minus the net release (outflow minus inflow) from the reservoir, X_{Lt}, which contributes to flow at the downstream node in that year. A second term subtracts the year's evaporation from its reservoir's contents. The evaporation quantity, X_{et}, accounts for the fact that a reservoir's exposed surface area depends on its contents. A (0-1) vector of coefficients. B_{Lr} keeps track of each *r-th* reservoir's location in the basin, assuring that streamflow into it adds to the reservoir's contents, while outflows from it reduce the reservoir's contents and also add to streamflow in the downstream reach. For the basin as a whole, the term B_{eL} is an identity matrix that conforms reservoir nodes with reservoir release nodes. Reservoir contents are:

$$(A11)\ \ Z_{rt} = Z_{rt-1} - \sum_{e} B_{eL} X_{et} - \sum_{L} B_{Lr} X_{Lt}$$

Contents of the *r-th* reservoir in the initial period (*0*), Z_{r0}, are defined by beginning watershed conditions, B_{ro}:

$$(A12)\ \ Z_{r0} = B_{r0}.$$

The upper bound on each reservoir's contents is defined as:

$$(A13)\ \ Z_{rt}^{max} = C_r.$$

This equation guarantees that the *r-th* reservoir's level never exceeds its capacity. Policies that would change a reservoir's capacity, such as dredging or adding to a dam's height, are simulated by altering the value of C_r. Where policymakers have an interest in considering an optimal reservoir storage capacity, different from the current capacity, the upper bound would be specified as a variable instead of a parameter. That specification could see widespread interest in basins currently lacking storage and facing the potential consequences of reduced flows brought on by climate change.

2.12 Aquifer Storage

Aquifer storage (volume) at the *f-th* aquifer node in the *t-th* period, Z_{ft} , is equal to:

$$(A14) \quad Z_{ft} = Z_{ft-1} - \sum_{a} B_{fq} \ X_{ft}$$

where X_{ft} is the flow into or out of the *f-th* aquifer node in the *t-th* period, analogous to a surface reservoir's net releases. Aquifer storage volumes are difficult to measure with reliability, because aquifer depths as well as boundaries are uncertain. However, an aquifer's depth (to pumping), is closely related to its contents. Depth is considerably more easily measured and tracked, although depth, too, typically shows considerable variation within a single aquifer node.

2.13 Reservoir Area

The *r-th* reservoir's area, which influences its evaporation losses, typically increases with increased volume. Reservoirs located in steeper-sloped areas experience smaller increases in surface area with increased volume. These relationships are widely published in the Basin, typically summarized as area-capacity tables. With typically high erosion rates in the Basin causing reservoir capacity losses, these relations are revised periodically. For purposes of this model the relation between area and volume is simplified considerably to be linear. The *r-th* reservoir's area is modeled as:

$$(A15) \quad Za_{rt} = B_{0\,ar} + B_{1\,ar} Z_{rt}$$

Since higher volume is typically required to produce a greater surface area at a given reservoir, the term B_{1ar} can usually be expected to be positive. That term is smaller for reservoirs located in steeper canyons.

2.14 Reservoir Evaporation

Reservoir evaporation is a function of temperature, wind speed, humidity, and radiation. For the basin's six mainstem reservoirs, a reservoir evaporation in time period t, X_{et} is:

$$(A16) \ X_{et} = \sum_{r} B_{re} \, Za_{rt} \ .$$

That is, any period's evaporation from a reservoir equals the number of feet lost per acre exposed for the year, B_{re}, multiplied by the average number of acres exposed at the reservoir that year, Za_{rt}. The evaporation rate increases for basin reservoirs that are located farther downstream, which are lower in elevation and higher in radiation. At any given reservoir, the term B_{re} is difficult to change significantly through human action. However, for a system of reservoir, storing more water at locations where B_{re} is lower is one measure for reducing the system's evaporation. Evaporation per exposed acre reaches a maximum of about 10 feet per acre per year at Caballo Reservoir in southern New Mexico. Because many factors cause reservoir levels to rise and fall in this basin, especially the system's operation, measuring evaporation from its large reservoirs is complex, hard to validate, and subject to widespread, longstanding and vigorous debates.

2.15 Aquifer Depth

The depth of the *f-th* aquifer in the *t-th* period, Zd_{ft} is modeled as a simple linear function of the aquifer's volume, Z_{ft}. That depth is:

$$(A17) \quad Zd_{ft} = B_{0_{df}} + B_{1df} \; Z_{ft}$$

where B_{0df} and B_{1df} are constants relating volume to depth for any *a-th* aquifer node. For any given aquifer, increased depth to pumping means a reduced volume, so B_{1df} is negative.

3 Land Use

Land use patterns affect the demand for water. For irrigated agriculture, total land in production is expressed as:

$$(A18) \quad \sum_{c} \sum_{k} L_{uckt} < \quad RHS_{ut} .$$

That is, irrigated land in production by node, crop, technology, and time, summed over crops and technologies cannot exceed available land (RHS_{ut}) by node and time period. In many dry rural irrigated regions of the world, like the Rio Grande, water is often more limiting than land. We we used the maximum current irrigated land capacity for each irrigation node as the upper limit on available land. However, more acreage will likely become available if greater long term water supplies can be secured and if institutions adjust to permit the extra water to be used by agriculture.

4 Institutions

4.1 International Treaty

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

$$(A19)\ X_{vt}^{M} = 60{,}000$$

where X_{vt}^{M} = annual deliveries to Mexico.

4.2 Federal Law

In 1994, the U.S. Fish and Wildlife Service listed the Rio Grande Silvery Minnow (*Hybognathus amarus*) as an Endangered Species under the US Federal Endangered Species Act.[6] A biological opinion issued by the U.S. Fish and Wildlife Service (U.S. Department of Interior, 2001) estimates that the minnow requires at least 50 cubic feet per second (cfs) of year-round streamflow in the San Acacia gauge. A regression analysis showed that total annual deficits, defined as the total additional acre-feet of water needed to overcome all shortages in streamflow below 50 cfs, takes the following form:

$$(A\ 20)\ X_{Mt} \geq \varepsilon_{0v}\ .$$

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

4.3 Interstate Compact

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

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[6] The U.S. Bureau of Reclamation maintains a web page devoted to the silvery minnow, at http://www.usbr.gov/uc/albuq/library/eis/pdfs/ba_mrg_jan_2003.pdf (accessed August 13, 2008)

of the Rio Grande (Hill, 1974). Under the Compact, each state receives more water in years with higher basin inflows. Articles III and IV of the Compact oblige Colorado to deliver water at the Colorado-New Mexico state line (See Map). These flows, $X_{vt}{}^{L}$, must be at least:

$$(A21)\quad X_{vt}{}^{L} \geq \theta_{0h} + \theta_{1h} X_{ht}{}^{c} + \theta_{2h} (X_{ht}{}^{c})^{2} .$$

This quadratic equation approximates Colorado's total delivery requirements to New Mexico defined by Compact Articles III and IV, and is based on annual source runoff measured at Colorado's relevant headwater gauges, X_{ht}^{c}. Article V of the Compact and the February 1948 resolution of the Compact oblige New Mexico to deliver water to Texas measured at the outflow of Elephant Butte Reservoir. New Mexico's delivery requirement to Texas is based on New Mexico's annual supply, defined as total flows at the Otowi stream gauge, north of Santa Fe, New Mexico. It is approximated in the model by:

$$(A\ 22)\ X_{t}{}^{E} - X_{Lt}{}^{E} \geq \delta_{0h} + \delta_{1h} X_{vt}{}^{O} + \delta_{2h} (X_{vt}{}^{O})^{2}$$

where $X_{t}{}^{E}$ is annual flow from Elephant Butte Reservoir, the location at which New Mexico delivers to Texas under the Compact, and X_{vt}^{O} indicates annual flow at the Otowi gauge. That flow at Otowi, under the Compact, is defined as New Mexico's total supply from which a proportion must be delivered to Texas. The two left-hand side terms are Elephant Butte Reservoir outflows (X_{t}^{E}) and net releases ($X_{Lt}{}^{E}$), respectively. The algebraic difference, X_{t}^{E} - X_{Lt}^{E}, when added to reservoir evaporation is equivalent to the Elephant Butte Reservoir outflow, plus net change in reservoir storage, New Mexico's annual delivery requirement to Texas.

4.4 Intrastate Agreement

Based on agricultural acreage in production in New Mexico and Texas at the time of the Rio Grande Project's construction, historically, U.S. lands in New Mexico to received 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%. A considerable part of the current Texas allocation actually goes to urban users serviced by the El Paso Water Utilities. That proportion is likely to grow in future years, as agricultural uses are gradually transferred to urban uses. For this model, up to 57% of total releases at the downstream end of project storage at the Caballo gauge, X_{vt}^{CAB} minus that part delivered to Mexico under the U.S. Mexico Treaty of 1906, X_{dt}^{MX}, is available for use on New Mexico lands by irrigators in the Elephant Butte Irrigation District (EBID).

That intrastate allocation is summarized as:

$$(A\ 23)\ X_{dt}^{EBID} \leq 0.57 \left[X_{vt}^{CAB} - X_{dt}^{MX} \right].$$

The remaining 43% of project surface releases is available on Texas lands, summarized as surface use by El Paso urban users and El Paso area irrigation. That allocation is summarized as:

$$(A24)\ X_{dt}^{EPMI} + X_{dt}^{EPAG} \leq 0.43 \left[X_{vt}^{CAB} - X_{dt}^{MX} \right].$$

Quantities of water smaller than those indicated by the percentages above (57% and 43%) can be used in any given year. When that occurs, any unused part is held in project storage at either Elephant Butte or Caballo Reservoirs for future use.

5 Economics

Economic benefits are produced by water depletions at use nodes and by measured environmental conditions at reservoir nodes.

5.1 Benefits

In the Rio Grande Basin, water decisions can produce both use-related benefits and environmental benefits. Both are defined by the total willingness to pay by people who benefit from either kind of use. For agricultural uses, the willingness to pay is measured by the contribution of water to net farm income. For urban nodes, it is measured by price per unit water times the number of units sold to the customer (total water bill) plus any unpriced consumer surplus. Consumer surplus is measured as the area beneath the demand function and above actual price charged. For environmental benefits, willingness to pay is measured as the maximum price that could be charged to visitors at the Basin's water-based recreation sites. In the current implementation of the model, those sites are limited to the basin's six mainstem reservoirs. Important excluded environmental values include benefits produced by instream flows at non-reservoir nodes as well as any environmental values, such as option, existence, or bequest values influenced by variations in reservoir levels or by other water decisions.

5.1.1 Use-Related Benefits

Water uses produced by diversions in the *t-th* period and *u-th* use, XB_{ut}, create economic benefits by being applied to the following quadratic total benefits function:

$$(A\ 25)\ XBu_{ut} = B_{ou} + B_{1u}X_{ut} + B_{2u}X_{ut}^{2}$$

where B_{ou}, B_{1u} and B_{2u} are parameters for the constant, linear and quadratic terms, respectively, for the beneficial use of surface flow at each of the *u* nodes, X_{ut} . $\beta_{2u} < 0$ reflects a downward sloping demand schedule. For urban uses, a downward sloping water demand means that for any given period, greater per household use only occurs if the price per unit used falls. For agricultural uses, it means that for a given acreage, given crop prices, given irrigation technology, increases in water applied per acre produce declining increments in net farm income. More details are described on the computation of net farm income below.

Appendix Table 1 shows model parameters by sector and location for agriculture and urban uses. For agricultural nodes, incremental benefits from added water use begin small (i.e., B_{1u} is small but positive), then fall gradually with higher water use per acre as farm producers shift into water-intensive labor-saving crops, such as cattle feed (i.e., B_2 is small but negative). For urban use nodes, incremental benefits from added use begin high as basic human requirements, such as drinking and sanitation, are met (i.e., B_{1u} is large and positive). Incremental urban benefits fall rapidly as household water is applied to lower valued uses, such as outdoor landscapes, in the face of greater supplies and lower prices (B_{2u} large and negative). Similarly, displaced incremental urban benefits rise rapidly as droughts or other urban shortages become more severe and opportunities are reduced for painless conservation.

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

The equation above describes use-related benefits per household for urban uses and benefits per acre for agricultural nodes. That equation is then modified to account for future changes in population or irrigated acreage. These 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.

5.1.2 Environmental Benefits

For this analysis, the economic benefits of environmental quality are measured as the willingness to pay for changes in quantities of water supplied for water-based recreation at the basin's six mainstem reservoirs. More details on methods for measuring the value of water in recreation are described in Ward, Roach, and Henderson (1996) and in Ward and Beal (2000).[7] For any given reservoir node, those benefits are measured as:

$$(A\ 26)\quad XBe_{rt} = B_{oe} + B_{1e}Z_{rt} + B_{2e}Z_{rt}^{2}$$

The *B* coefficients used for this analysis are based on the published work by Ward et al (1997)[8], with updates based on more recent visitation counts at New Mexico State Parks, shown in Appendix Table 2. Generally, total gross recreation benefits at any reservoir increase up to a point where beaches and other facilities are flooded by water. The quadratic functional form was chosen to reflect the observation that further volume increases beyond that point at which the quadratic function tops out will reduce visitation and total recreation benefits.

5.2 Costs

Increased stream diversions or depletions typically require additional costs to be incurred to make suitable for human use the increased water used. For agricultural groundwater pumping nodes, the largest incremental costs are those incurred for energy and for related operation, and maintenance. For urban pumping nodes there are also considerable additional costs for purification to make the water safe and healthy for human consumption.

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[7] Ward, F.A., B.A. Roach, and J.E. Henderson. 1996. The economic value of water in recreation: Evidence from the California drought. *Water Resources Research.* 32 (4):1075-1081. Ward, F.A. and D.J. Beal, *Valuing Nature with Travel Cost Models*, Edward Elgar, Cheltenham, UK, 2000.

[8] Ward, F.A., R.A. Cole, R.A. Deitner, and K.A. Green-Hammond. 1997. Limiting environmental program contradictions: A demand systems application to fishery management. *American Journal of Agricultural Economics.* 79 (3): 803-813.

5.2.1 Use-Related Costs

Energy, operation, and maintenance cost per acre foot pumped at a pumping node is defined as δ_{peu}, while treatment costs at the same node is δ_{teu} per acre foot. Similar energy and treatment costs are defined for surface diversion nodes as δ_{deu} for energy, operations, and maintenance, while δ_{dtu} is the equivalent cost surface water treated per acre foot. For urban uses, treatment costs are considerably higher than for agriculture, but urban treatment costs are typically lower for pumped water than for diverted river water. Based on these four kinds of costs, the total cost of water delivered to any agricultural or urban node is:

$$(A27)\ XCu_{ut} = \sum_{p} \left[\delta_{peu} + \delta_{ptu}\right] X_{pt} \quad + \quad \sum_{d} \left[\delta_{deu} + \delta_{dtu}\right] X_{dt}\ .$$

where X_{pt} is the number of acre feet pumped and X_{dt} is the number of acre feet diverted in the *t-th* period. Both of these quantities are unknowns whose values are determined by the model's solution.

5.2.2 Environmental Costs

Environmental costs are everywhere becoming an increasingly important factor in determining outcomes of major water policy decisions. Two possible concepts for defining environmental costs presented themselves (1) environmental opportunity costs, equal to environmental benefits displaced by a decision, and (2) environmental operations costs, equal to the cost of additional resources required to support the protection of greater environmental benefits at a given site. Either concept for measuring environmental costs would have worked, and in principle both should produce the same optimized water policy. We chose the second alternative in order that net environmental benefits could be measured at each node. These net environmental benefits are measured as environmental benefits minus added costs needed to assure a higher quality environment. Environmental operations costs were measured as:

$$(A28)\ XCe_{rt} = \delta_{er}\, Z_{rt}$$

where δ_{er} is the added cost of managing larger volumes of water at a reservoir site, while Z_{rt} is the acre feet of reservoir volume in period *t*. For the current analysis the term δ_{er} was measured as the additional monetary budget expense required to support additional visitors attracted by larger quantities of water when those larger volumes can be stored. That same term reflects the management costs saved when smaller water volumes are stored. Measuring the added environmental cost of protecting and securing a higher quality environment in this way is a considerable simplification of the marginal cost structure of environmental improvements. More generally, that marginal cost would include any operations costs needed to preserve, protect, or improve a natural environment. Considerable research is required on this important issue.

5.3 Net Benefits

5.3.1 Use-Related Net Benefits

Use-related net benefits are the following simple algebraic subtraction of use-related costs from use-related benefits:

$$(A29)\ XNBu_{ut} = XBu_{ut} - XCu_{ut}$$

With adequate streamflows produced by sufficient snowpack, use-related net benefits will be maximized by the model at each use node as well as its sum being maximized over all use nodes.

For irrigated agricultural nodes, net benefits are measured as net farm water-related income:

$$(A29a) \qquad Y_{uckt} = [\,P_{uc}\, Yield_{uck} - Cost_{uck}\,]\, L_{uckt}$$

That is, net farm income at the *u-th* basin node for the *c-th* crop using the *k-th* irrigation technology in the *t-th* period equals net income per acre multiplied by the number of acres. Annual net income per acre, Y_{uckt}, equals crop price, P_{uc}, times crop yield, $Yield_{uck}$, minus total production costs, $Cost_{uck}$. Generally higher yields and higher annualized costs occur as farmers shift from flood to drip irrigation. However as the public subsidy of drip irrigation's capital costs increase, the farmer's share of those costs declines. There are zero annualized capital costs for a 100 percent drip irrigation subsidy.

5.3.2 Environmental Net Benefits

Environmental net benefits are computed with a similar algebraic subtraction:

$$(A30)\ XNBe_{rt} = XBe_{rt} - XCe_{rt}$$

When there are adequate starting reservoir volumes, these environmental benefits will also be maximized by selecting reservoir volumes at which environmental benefits exceed environmental costs by the largest amount. When volumes are low and/or when streamflows are scarce each reservoir node's marginal environmental net benefits will be nonzero.

5.4 Discounted Net Present Value

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

$$(A\ 31)\ \ XNPV = \sum_u \sum_t \frac{XNBu_{ut}}{(1+r_u)^t} + \sum_u \sum_t \frac{XNBe_{ut}}{(1+r_e)^t}$$

That is, benefits from water uses and water environments are summed together.

For irrigated agriculture, discounted net present value is expressed to take account of alternative crops and alternative irrigation technologies. It is expressed as:

$$(A31a) \qquad XNPVA = \sum_u \sum_c \sum_k \sum_t \frac{Y_{uct}}{(1+r_u)^t}$$

That is, the present value of total water-based farm income for the basin sums income over nodes, crops, irrigation technology, and time periods, which discounts future incomes more heavily when there is a higher discount rate.

Water use in the upper Rio Grande Basin is heavily constrained by scarce water supplies and by existing institutions. The four existing institutions incorporated into this model are described earlier in this appendix. All four have considerable influence on the basin's allocation of water and, in the absence of active water markets promoting water trading, are rather inflexible to change in the short-run. The objective function chosen for this analysis is the maximization of discounted net present value described by the above equation. That discounted net present value included the summed stream of net use-related benefits and net environmental benefits.

6 Appendix Tables

6.1 Appendix Table 1

Appendix Table 1. Total Benefits of Consumptive use for Urban Uses of Water Per Household Per Year, Rio Grande Basin, New Mexico, Texas.*

Location	Label	State	Sector	β_{0u}	β_{1u}	β_{2u}
				($)	($/acre-foot)	($/acre-foot^2)
Albuquerque	ALB	NM	Urban	0	10843	-9627
El Paso	EP	TX	Urban	0	9507	-9392

*Functional form: Total use-related benefits = $\beta_{0u} + \beta_{1u}$ (acre-feet) + β_{2u} (acre-feet)^2. Acre-feet refers to total acre feet of consumptive use (depletions) in year *t*, $X_{ut.}$, in *(A5)*.

6.2 Appendix Table 2

Appendix Table 2. Total Gross Benefits of Outdoor Recreation at Six Mainstem Reservoirs, Upper Rio Grande Basin.

Location	Label	State	β_{0u}	β_{1u}	β_{2u}
Heron Reservoir	HE	NM	4246	7.36	-0.00209
El Vado Reservoir	EV	NM	4246	7.36	-0.00209
Abiquiu Reservoir	AB	NM	4246	7.36	-0.00209
Cochiti Reservoir	CO	NM	256	4.10	-0.00287
Elephant Butte Reservoir	EB	NM	380	2.21	-0.00503
Caballo Reservoir	CA	NM	380	2.21	-0.00503

*Functional form: Total use-related benefits = $\beta_{0e} + \beta_{1e}$ (acre-feet) + β_{2e} (acre-feet)^2. Acre-feet refers to average total acre feet of volume stored at a reservoir in year *t*, Z_{rt}, in *(A9)*.