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Research Article

System dynamics modeling for community-based water planning: Application to the Middle Rio Grande

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Abstract. The watersheds in which we live are comprised of a complex set of physical and social systems that interact over a range of spatial and temporal scales. These systems are continually evolving in response to changing climatic patterns, land use practices and the increasing intervention of humans. Management of these watersheds benefits from the development and application of models that offer a comprehensive and integrated view of these complex systems and the demands placed upon them. The utility of these models is greatly enhanced if they are developed in a participatory process that incorporates the views and knowledge of relevant stakeholders. System dynamics provides a unique mathematical framework for integrating the physical and social processes important to watershed management, and for providing an interactive interface for engaging the public. We have employed system dynamics modeling to assist in community-based water planning for a three-county region in north-central New Mexico. The planning region is centered on a ~165-km reach of the Rio Grande that includes the greater Albuquerque metropolitan area. The challenge, which is common to other arid/semi-arid environments, is to balance a highly variable water supply among the demands posed by urban development, irrigated agriculture, river/reservoir evaporation and riparian/in-stream uses. A description of the model and the planning process are given along with results and perspectives drawn from both.

Key words. Decision support modeling; stakeholder involvement; interactive modeling.

Introduction

The demand for water worldwide has more than tripled since 1950 and is projected to double again by 2035 (Postel, 1997). As many as 2.4 billion to 3.4 billion people may be living in water-scarce or water-stressed conditions by 2025 (Engelman et al., 2000), with the most susceptible populations living in arid environments. To date, the growing demand has largely been met by improving and expanding reservoir capacity, and by mining fossil groundwater resources. However, both solutions have physical limits. Bringing future demand in line with available supplies will require increasingly efficient water management practices and greater conservation of water resources. The development of well-conceived, short-term and long-term regional water management plans that include input from a broad array of stakeholders is one approach for working toward these goals.

Developing management plans that are both scientifically sound and publicly acceptable is often fraught with difficulty. In efforts to build a scientifically defensible basis for decision-making, scientists and water managers commonly build models to tease apart and quantify the dynamics of complex watershed systems. However, if such models are developed "behind closed doors", their operation, application and utility can appear obscure to the general public. Rather, an open and participatory model development process can help overcome such problems by building familiarity, confidence and acceptance in models (Louks et al., 1985), while allowing a

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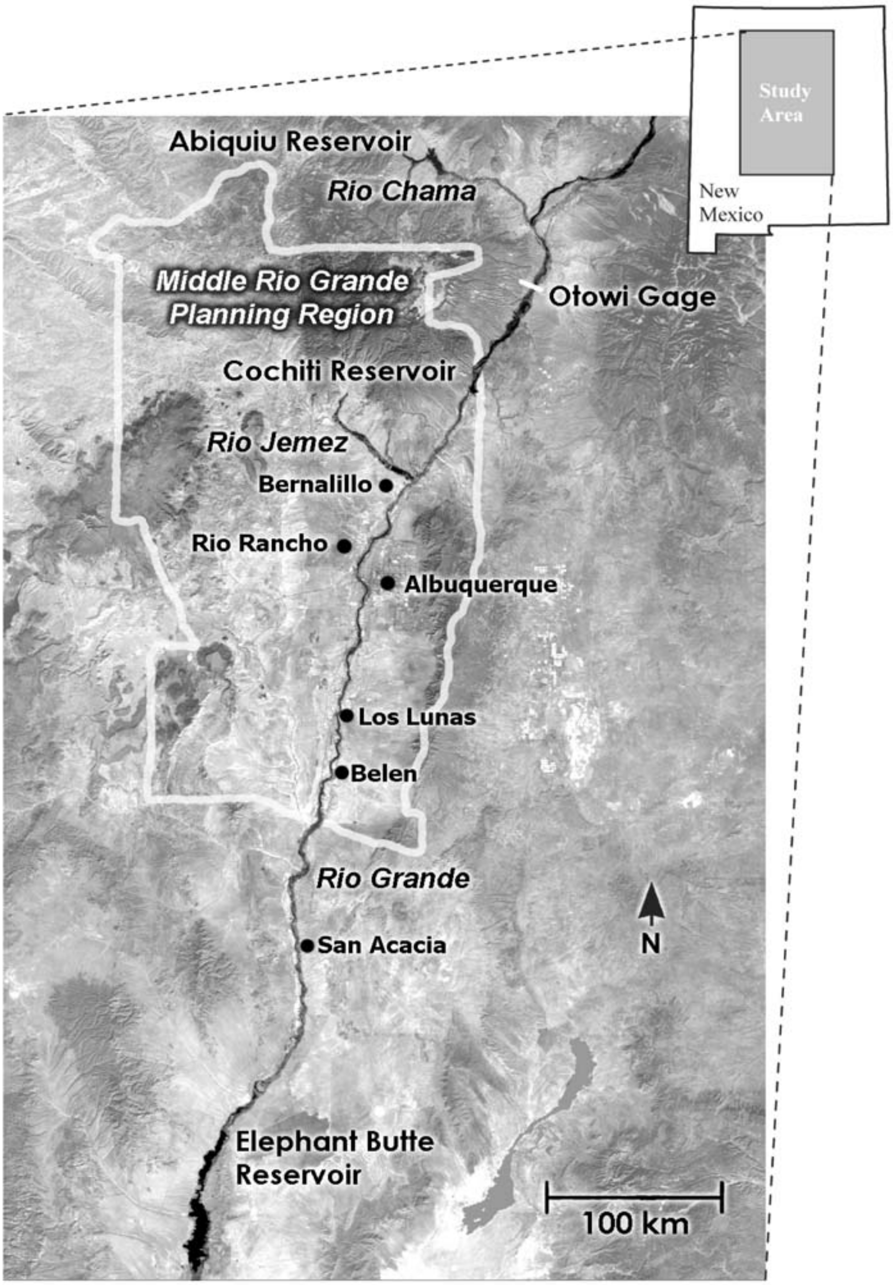

Figure 1. The Middle Rio Grande.

more diverse group of stakeholders to engage in the planning process. A few examples of models used in a regional water planning context include Wallace et al. (1988), Palmer et al. (1993), Ford (1996), Simonovic and Fahmy (1999), Stave (2003), and Cartwright and Conner (2003).

The Middle Rio Grande basin in north-central New Mexico (Fig. 1) provides an opportunity for developing a process and tool that addresses the issues named above. Growing human population coupled with a current multi-year drought in this semi-arid region have made water-resources management a critical issue reaching across social, political, economic and professional boundaries. The main regional challenge is balancing a limited supply of water, subject to wide seasonal variation, with disparate demands posed by urban development, irrigated agriculture and riparian/in-stream uses.

In this paper we describe a project aimed at creating a water resources model to assist in community-based planning for a three-county region centered on the Rio Grande. The model is developed within a system dynamics framework (Sterman, 2000; Forrester, 1990) for the purposes of 1) quantitatively exploring alternative water management strategies, 2) educating the public on the complexity of the regional water system, and 3) engaging the public in the decision process. The purpose of this paper is to convey experiences, lessons learned, and perceptions gained through the model development and community-based water planning process.

Methods

Regional water planning process

A statewide water planning process was initiated in New Mexico in the mid 1990s in response to mounting concern over water issues. The New Mexico Interstate Stream Commission (ISC) took responsibility for the process and divided the state into 16 planning regions. Each region was tasked with defining its future water supply and demand, along with preparing a 50-y water plan that balances the water budget. The planning process in each region was structured around a partnership between local governments with oversight responsibility and volunteer organizations that spearheaded the actual planning. In the Middle Rio Grande Planning Region this partnership principally existed between the Mid Region Council of Governments (MRCOG) and the Middle Rio Grande Water Assembly (MRGWA), with input from a variety of other stakeholders (Table 1).

The MRGWA was established in 1997 by self-selected volunteers drawn from the Middle Rio Grande Planning Region (Fig. 1). The MRGWA grew to include water scientists and managers, academics, lawyers, economists, real estate developers, agriculturalists, environmentalists, business people, and others. To accommodate the broad range of views, the MRGWA organized itself around five constituency groups that focused on agriculture, environment, urban development, water management, and special technical issues.

The MRGWA began a methodical, rigorous and often contentious effort to define the terms of water supply and demand for the region, citizens' preferences for water uses, and public-supported water conservation measures. Progress was achieved through monthly meetings of the constituency groups, while quarterly meetings were held to update the public on progress and to canvas their concerns, desires and expectations concerning the water plan.

In the spring of 2003 the MRGWA began the process of balancing the water budget by drafting a series of five "scenarios", or water plans. The model described in this paper was an integral part of this scenario development process. Each scenario was developed from the point of view of the various constituency groups. These scenarios integrated various combinations of 42 water conservation alternatives identified by the public in early phases of the planning process. About half of these alternatives were quantifiable, and included such measures as low-flow appliance conversion programs, xeriscaping, elimination of exotic phreatophytes from the riparian forest (known locally by the Spanish word *bosque*, meaning "forest"), and changes to agricultural use and reservoir operations. The other half was less amenable to quantification, and included such measures as expanding public awareness campaigns, centralization of regional water management authority, coordination of regional planning, and adjudication of water rights. During the summer and fall of

Table 1. List of stakeholders and their roles.

Stakeholder	Role
Interstate Stream Commission (ISC)	Manages treaty and interstate compact deliveries of water. Oversight of the statewide water planning process.
Mid Region Council of Governments (MRCOG)	A board comprised of city and county officials. Purpose is to coordinate regional planning.
Middle Rio Grande Conservancy District (MRGCD)	Responsible for managing and delivering irrigation water to the farmers of the Middle Rio Grande region.
City Utilities and Water Cooperatives	Responsible for managing and delivering water to urban and rural water users for domestic, commercial and industrial purposes. Also responsible for capturing and treating resulting wastewater.
Federal/State Agencies	Management of waters and ecosystems of the state. Provided data, models and system understanding in the water planning process.
Middle Rio Grande Water Assembly (MRGWA)	Commissioned by the ISC with the responsibility of preparing the 50-year water plan in cooperation with the MRCOG. Membership open to the public.
Cooperative Modeling Team (CMT)	Subset of MRGWA and MRCOG participants. Purpose was to develop an interactive model to assist in the water planning process.
General Public	Participation through volunteering on the MRGWA and/or participation at quarterly public forums.

2003 the MRGWA worked closely with the MRCOG to combine the individual scenarios into a single unified water management plan that then was submitted to the ISC in the winter of 2003/2004. Each step in the water planning process was punctuated with a series of public meetings to gather feedback on draft plans.

Model development process

It became clear as the planning project grew in complexity that a model could assist in the planning process. A modeling project was initiated to:

1. provide a quantitative basis for comparing alternative water conservation strategies in terms of water savings and cost,
2. help the public understand the complexity inherent to the regional water system, and
3. engage the public in the decision process.

Construction of the model began in January 2002 and working versions of the model were released and applied to the regional planning process in spring and summer of 2003. In efforts to build acceptance and confidence in the planning model, a community-based, participatory process was adopted. Model development involved direct collaboration between Sandia National Laboratories (SNL), the MRGWA, the MRCOG, and the Utton Transboundary Resources Center of the University of New Mexico School of Law. SNL was responsible for model formulation and implementation within the system dynamics framework. The MRGWA was responsible for system conceptualization, identifying sources of subject expertise and data, model review, and most importantly, representing the views of the public and key constituency groups. The MRCOG represented the interests of the local governments that have ultimate responsibility for implementing the plan, while the Utton Center provided expertise in group facilitation.

Individuals from each institution were organized into a "Cooperative Modeling Team" (CMT) that met roughly every other week throughout 2002 and early 2003 to develop the model. Starting in spring 2003, after the bulk of the modeling work was completed, the CMT began meeting monthly to review and update the model and to monitor the use of the model in the planning process.

Model development followed a five-step process. First, the problem to be solved and the scope of analysis were defined. Second, a description of the system was developed. This step began by conceptualizing the broad structure of the system, followed by decomposing that structure into a series of manageable units defined by specific system sectors (e.g., agriculture, reservoirs). For each sector a causal loop diagram (e.g., Sterman, 2000) describing the inherent structure and feedback was developed and reviewed by the CMT. Subject experts were identified by the CMT who were then contacted for further clarification of the system and to gather necessary input data. In the third step, the causal loop diagrams were converted into a system dynamics context, and model sectors were populated with appropriate data and mathematical relations. Step four involved model review. The CMT reviewed each model sector separately, and as part of the broader model. Step five corresponded to the use of the model by the public, both for general education and for water planning.

The model development process also benefited from interactions with the community outside the CMT. Data and system understanding were gained from numerous meetings with water professionals and scientists from regional, state, and federal agencies. The model also received close scrutiny by water experts from these agencies, in many cases involving formal review. Public feedback also was gathered by way of public meetings in which draft versions of the model were previewed. Feedback also was gained through outreach activities targeting such venues as MRGWA public meetings, water forums, children's water fairs, state and county fairs, civic and professional groups, and various schools and universities.

Model architecture

Selection of the appropriate architecture for the planning model was based on two criteria. First, a model was needed that provided an "integrated" view of the watershed – one that coupled the complex physics governing water supply with the diverse social and environmental issues driving water demand. Second, a model was needed that could be taken directly to the public for involvement in the decision process and for educational outreach. For these reasons we adopted an approach based on the principles of system dynamics (Forrester, 1990; Sterman, 2000). System dynamics provides a unique framework for integrating the disparate physical and social systems important to water resource management, while providing an interactive environment for engaging the public.

System dynamics is a systems-level modeling methodology developed at the Massachusetts Institute of Technology in the 1950s as a tool for business managers to analyze complex issues involving the stocks and flows of goods and services. System dynamics is formulated on the premise that the structure of a system – the network of cause and effect relations between system elements – governs system behavior (Sterman, 2000). "The systems approach is a discipline for seeing wholes, a discipline for seeing the structures that underlie complex domains. It is a framework for seeing interrelationships rather than things, for seeing patterns of change rather than static snapshots, and for seeing processes rather than objects" (Simonovic and Fahmy, 1999).

In system dynamics a problem is often decomposed into a temporally dynamic, spatially aggregated system. The scale of the domain can range from the inner workings of a human cell to the size of global markets. Systems are modeled as a network of stocks and flows. For example, the change in volume of water stored in a reservoir is a function of the inflows less the outflows. Key to this framework is the feedback between the various stocks and flows comprising the system. In our reservoir example, feedback occurs between evaporative losses and reservoir storage through the volume/surface area relation for the reservoir. Feedback is not always realized immediately but may be delayed in time, representing another critical feature of dynamic systems.

There are a number of commercially available, object-oriented simulation tools that provide a convenient environment for constructing system dynamics models. With these tools model construction proceeds in a graphical environment, using objects as building blocks. These objects are defined with specific attributes that represent individual physical or social processes. These objects are networked together so as to mimic the general structure of the system, as portrayed in a causal loop diagram. In this way, these tools provide a structured and intuitive environment for model development.

The Middle Rio Grande planning model described in this paper was built in Studio Expert 2001 and 2003, produced by Powersim, Inc. The model operates within a PC environment and requires less than 10 s to complete a simulation. Accompanying the model is an annotated user interface for prescribing model input and viewing simulation results. Sixty-six variables can be controlled in the model interface by slider bars or switches. In this way, users can easily simulate various combinations of hydrological, economic or demographic conditions, and then run the model and view output in seconds. This interactive modeling environment allows users in private or public settings to experiment with competing management strategies and evaluate the comparative strengths and weaknesses of each.

Conceptual model

The MRG Planning Region includes Bernalillo, Sandoval, and Valencia Counties of north-central New Mexico (Fig. 1). The region is characterized by basin and range topography with mountains along the east, and arid valleys and mesas central and west. The principle drainage for the basin is the Rio Grande. A deep alluvial aquifer, whose boundaries roughly coincide with that of the planning region, is in direct communication with the Rio Grande. Vegetation classes found within the region range from riparian along the Rio Grande to desert grassland, pinyon-juniper woodlands and mixed coniferous forest at higher mountain elevations. The planning region includes Albuquerque, the principal urban center of New Mexico, along with several smaller communities including Rio Rancho, Belen, Los Lunas and Bernalillo. These communities are located along the Rio Grande, while sparse rural populations characterize outlying areas. From 1900 to 2000 the population of the three-county region grew from about 51,000 to about 713,000 (a 1298% increase), according to the U.S. Census Bureau. The most recent doubling of population occurred from about 1970 to 2000.

The basic structure of the planning model is that of a dynamic water budget. Specifically, each supply and demand component is treated as a spatially aggregated, temporally dynamic variable. The spatial extent of the basin is delimited according to the boundaries of Bernalillo, Sandoval and Valencia counties. Thus, the various water supply, demand and conservation terms are aggregated over the three-county region; however, in some instances features outside the planning region must be simulated to accomplish these calculations (e.g., Elephant Butte Reservoir). Temporally, the model operates on an annual time step encompassing the period 1960–2050. This period includes a 41-year calibration period (1960–2000) and the prescribed 50-year planning horizon (2001–2050). An annual time step was used because it matched the annual basis of calculation for key metrics in regional water planning (i.e., Rio Grande Compact obligations and groundwater depletions).

At the highest level, the model is organized into two separate but interacting water budgets, one for surface water and the other for groundwater. In both budgets the water stored in the basin varies annually in response to changes in the associated inflows and outflows. Figure 2 shows the causal loop diagram for this system, documenting the primary elements of the system and the paths of interaction. Below we describe the basic elements contributing to these inflows and outflows. We also describe the modeling of 24 different water conservation strategies identified by the public as being important to regional planning efforts. Additional modeling detail may be found in Passell et al. (2003).

Inflows

Surface water. Surface water inflows to the planning region include the mainstem of the Rio Grande, its associated tributaries, wastewater return flows, and San Juan-Chama (SJC) Project interbasin transfers. Rio Grande inflows are modeled at the Otowi gage located downstream of the confluence of the Rio Chama and Rio Grande (Fig. 1) and average 1190 million cubic meters (Mm^3)/y for the years 1950 to 1998. Gaged tributary flows within the planning region include the Rio Jemez, Santa Fe River, Galisteo Creek, Tijeras Arroyo, and storm water flows

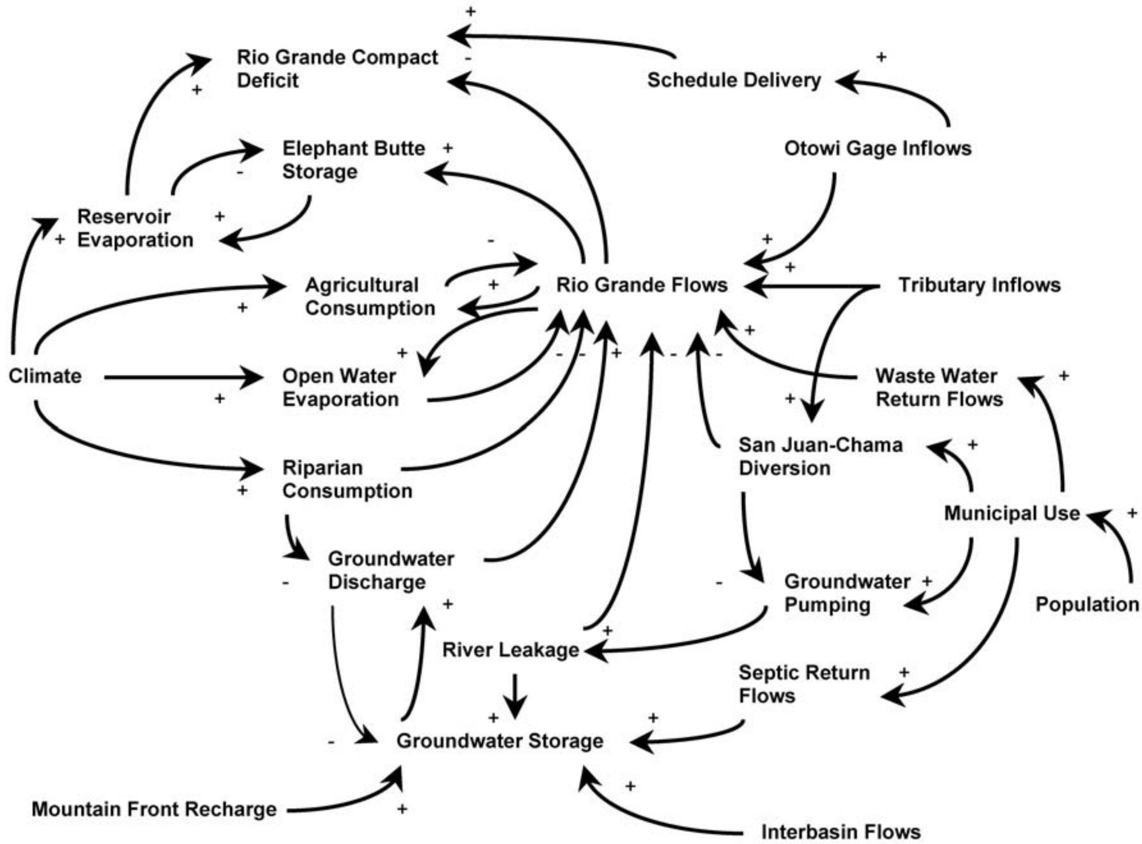

Figure 2. Causal loop diagram depicting the key elements influencing water supply and demand in the Middle Rio Grande Planning Region. The arrows denote interaction between elements and the sign designates whether the feedback is reinforcing (positive sign means as element at base of arrow increases the element at the head of the arrow increases) or balancing (negative sign meaning opposite to above). To facilitate presentation, only elements with first-order effects are presented.

from the City of Albuquerque (CoA). Combined tributary inflows to the planning region average 117.18 Mm^3/y.

The mainstem and tributary flows for the period 1960–2000 are based on historic gage data (USGS, 2002). Post-2000 mainstem/tributary flows are generated stochastically and based on 1950–1998 gage data. This period was selected because it provides both a period of significant drought (1950s and 1960s) as well as an extended wet period (1980s and 1990s). Correlation among the different tributary and mainstem flows was maintained where significant (i.e., $r^2 > 0.5$). Modifications to this record can be made in the model to simulate sustained climate change. Such changes are modeled by simply reducing basin inflows by a constant percentage. The user can control the year in which the change begins and ends, and the intensity of the change relative to historic inflows.

Wastewater returns are disaggregated into four categories, including the population on publicly supplied water in each of the three counties, and the population across all three counties on private water systems. Return flows are assumed to be equivalent to the total indoor water use for residential, commercial and industrial customers on public systems. This amount equates roughly to 50% of the total municipal use. In 1998 the total wastewater discharge was approximately 84 Mm^3.

SJC Project water has been delivered to the MRG Planning Region since 1971 through a transmountain diversion from the San Juan River (in the Colorado River basin) to the Chama River, a tributary of the Rio Grande. Contracted deliveries include 59.45 Mm^3 to the CoA, 25.78 Mm^3 to the Middle Rio Grande Conservancy District (MRGCD) and lesser amounts to several other contractors. From 1971–2000, historic data are used to model actual deliveries. The default settings in the model assume a constant delivery of 93.55 Mm^3/y based on average deliveries made over the period of 1990–1998 (SSPA, 2000). The model user has the option to reduce this delivery.

Groundwater. Groundwater inflows include 38.24 Mm^3/y from interbasin inflows, 45.64 Mm^3/y from mountain front recharge, and 4.93 Mm^3/y from septic returns (McAda and Barroll, 2002). All values are constant except septic returns, which vary according to the indoor use by the population on septic systems.

Another important inflow to the aquifer system is pumping induced leakage from the Rio Grande, and its accompanying drain and irrigation system. Leakage is modeled by the simple Glover-Balmer (1954) relation calibrated to more detailed groundwater modeling results (CoA, 2002). The Glover-Balmer model relates leakage to the time sequence of groundwater pumping and is delayed in time according to aquifer properties. In this way, a dynamic feedback between river leakage and groundwater pumping is established.

Outflows

Consumptive outflows are distributed into four broad classes: open-water evaporation, bosque transpiration, agricultural evapotranspiration, and municipal consumption. Consumption in the region is roughly equally divided among the four groups. Each of the three evaporative losses are credited to the surface water system while municipal consumption is taken from the groundwater system; however, the CoA has near-term plans to divert Rio Grande flows for municipal consumption.

Other outflow terms include the Rio Grande Compact that defines the outflows necessary to meet downstream delivery obligations. Another minor outflow component involves the discharge of groundwater to the Rio Grande. Below we explore each of these outflow terms individually.

Surface water. Open-water evaporation is calculated for the mainstem of the Rio Grande and each of the modeled reservoirs. Modeled reservoirs include Elephant Butte, Cochiti, and Abiquiu (Fig. 1). Open water evaporation is calculated using a modified form of the Penman-Monteith equation (Shuttleworth, 1993) that provides a feedback loop between climatic variability and evaporative losses. Reference rates are adjusted to actual evaporation rates using a regionally-defined open-water coefficient (USBR, 2002). Evaporative losses from Elephant Butte range from roughly 61.67–308.37 Mm^3/y, while Cochiti loses approximately 6 Mm^3/y and Abiquiu 6–25 Mm^3/y. Total evaporative losses within the planning region for the Rio Grande and associated saturated sand bars average 35 Mm^3/y.

For the period of 1960–2000, historic yearly averaged meteorological data are used to populate the Penman-Monteith equation. In later years the meteorological parameters are stochastically generated in a manner equivalent to that used to simulate the stream flow data. Where significant ($r^2 > 0.5$), historical correlations between the meteorological data and Rio Grande flows are preserved in the simulated time series.

There are 9266 ha designated as bosque in the planning region (USBR, 1997). The bosque is composed of a mosaic of cottonwood, willow, Russian olive, salt cedar, New Mexico privet, elm, shrubs and grasses. Losses through bosque transpiration are determined with the Penman-Monteith equation. Because of the diverse mixing of species throughout the bosque no attempt is made to calculate transpiration rates for each individual vegetation class; rather, a single rate is used. This rate corresponds to an average annual transpiration rate of 1.1 m/y (SSPA, 2003). Subsequently, these transpiration rates are adjusted annually for year-to-year variations in precipitation. Specifically, the evaporation rate is reduced by the effective precipitation assumed to equal 50% of the annual precipitation (SSPA, 2000). Average transpiration losses equal 102 Mm^3/y throughout the planning region. Losses by bosque transpiration are accounted directly against Rio Grande flows.

An average of 20,454 ha is irrigated annually in the three-county planning region (MRGCD, 2001). A diversity of crops is grown in this region; however, forage crops like alfalfa and pasture hay represent about 80% of irrigated land. The ease of growing forage corps, high demand by the strong local dairy industry, and lack of a market for most other crops are some of the reasons for the current cropping trends.

To maintain consistency, evaporative losses are calculated according to the Penman-Monteith equation. Evaporative losses specific to each crop are estimated by employing a crop coefficient, growing days, and irrigated area particular to that crop. The annual average evapotranspiration rate, aggregated over all crops, is 0.79 m/y. Accordingly, the current distribution of crops within the planning region consumes an average of 162 Mm^3/y. Yearly evaporative losses are adjusted for annual variations in rainfall (as described above). In dry years (Rio Grande flows < 680 Mm^3/y) water use by agriculture is reduced according to fallowed alfalfa (~15% of the alfalfa cropland).

Agricultural water is principally taken from the Rio Grande and administered by way of flood irrigation. A 1230-km network of canals, laterals, and ditches maintained by the MRGCD supplies the water. Additionally, the MRGCD operates a series of riverside and interior drains designed to capture tail water and drain low-lying croplands.

Besides the water directly consumed by crops, several other losses from the irrigation system occur. Roughly 0.003 Mm^3 of water is lost per irrigated hectare of land due to percolation below the root zone, which we term irrigation seepage. Also, there is a loss of approximately 112 Mm^3/y through seepage from the conveyance system (USACE, 2002). Both irrigation and conveyance seepage are captured by the shallow groundwater system and returned to the Rio Grande. Additionally, there are consumptive losses from the conveyance system. Riparian vegetation has grown up along much of the conveyance system, drawing directly from irrigation water.

These losses are evaluated in a manner consistent with that for the bosque vegetation and result in average losses of 12 Mm^3/y. Finally, there are evaporative losses directly from the conveyance system that are on the order of 4.3 Mm^3/y that are calculated similarly to other open water losses.

Colorado, New Mexico and Texas signed the Rio Grande Compact (RGC) in 1938 to apportion the waters of the Rio Grande above Fort Quitman, Texas. Additionally, the Compact apportions water among the upper, middle and lower reaches of the Rio Grande in New Mexico. The Middle Rio Grande Planning Region falls in the middle reach, extending from the Otowi gage in the north to Elephant Butte Reservoir in the south (Fig. 1). Allowed depletions over this reach are set by a Compact schedule. At low flows, New Mexico is entitled to deplete a maximum of 43% of the water passing the Otowi gage. Once annual flows at Otowi reach 1356.83 Mm^3 the marginal entitlement to deplete is zero. The maximum depletion by the middle reach is 499.56 Mm^3. The middle region may consume the entitled native Rio Grande water plus any tributary or groundwater inflow that occurs over this reach. Compact deliveries are calculated at the Elephant Butte spillway, thus evaporative losses from the lake are credited to the middle region.

The accrued deficit may not exceed 246.70 Mm^3 at any time except when the debit is caused by holdover storage in a northern reservoir. Water may be stored in northern reservoirs provided Elephant Butte Reservoir storage exceeds 493.39 Mm^3 and adequate deliveries can be made downstream. Releases from Elephant Butte are modeled consistent with historical operations (last 40 years) with an average delivery of 851 Mm^3/y. If storage exceeds reservoir capacity, a spill is allowed and the accrued Compact balance is reset to zero.

Groundwater. The 2000 census estimated the population for the three-county planning region at 712,738 people. This population is disaggregated into four groups, including those using publicly supplied water in Bernalillo, Sandoval, and Valencia counties, plus a fourth group representing those in the planning region who use self-supplied domestic wells.

Municipal water use is calculated by multiplying the population by the corresponding per capita water use. The per capita use is broken into two different categories including residential and nonresidential (390 liters per person per day [lpd] and 307 lpd, respectively, for Bernalillo County). These groups are further divided by indoor and outdoor water use (outdoor use is approximately 60% of the indoor use for residential users and about 30% for non-residential users). The indoor per capita use is assumed to be constant, unless new conservation measures are instituted (see "Conservation Alternatives," below) while outdoor per capita use is allowed to fluctuate yearly in response to changing climatic conditions. Additionally, each public water utility reports a water use category termed unaccounted for water that measures roughly 10% of the total per capita demand. This category accounts for water distribution system leaks, inaccurate metering, and other unmeasured water uses.

Over the last 40 years municipal use has steadily grown, tracking the growth in population. Population growth is projected to continue throughout the basin for the next 50 years, resulting in a regional population of about 1.27 M people. These growth projections are based on the research of the University of New Mexico Bureau of Business and Economic Research (2002).

Historically, all municipal use has been met through groundwater pumping. Municipal pumping grew from 46.50 Mm^3/y in 1960 to 186.25 Mm^3/y in 1999. This increase has resulted in significant groundwater level declines and limited ground subsidence in Albuquerque. In efforts to reduce this stress on the aquifer, the CoA plans to begin using their contracted allotment of SJC water. Beginning in 2006 the city will divert 118.91 Mm^3/y from the Rio Grande as part of their drinking water project and return 59.45 Mm^3/y as wastewater, resulting in a total consumption of 59.45 Mm^3/y.

Groundwater discharge to the Rio Grande occurs intermittently along the length of the basin and intermittently in time. Such discharge is principally captured by the drain system, which then conveys the water to the river. Groundwater discharge is calculated as a balance between conveyance seepage, irrigation seepage, mountain front recharge, and bosque transpiration. Depending on the degree of bosque transpiration, groundwater discharge can be positive or negative, denoting a net gain or loss to the river. The total loss or gain to the river is the sum of groundwater discharge and the pumping induced river leakage.

Conservation alternatives

A variety of water conservation alternatives were modeled as part of the planning process. The purpose was to provide a quantitative basis for comparatively evaluating the alternatives in terms of the resulting water savings and cost to implement and maintain. A total of 24 alternatives were modeled, and are grouped according to five broad classes: residential/non-residential, bosque, agriculture, reservoirs, and desalination. A brief discussion of these alternatives is given below; greater detail, particularly in terms of costs, can be found in Passell et al. (2003).

Residential/non-residential. This group of alternatives addresses potential water savings in the municipal sector. Modeled conservation measures include low flow appliances, water re-use, xeriscaping, reduced landscaping, rooftop harvesting and price controls.

Indoor water use can be reduced by way of low flow appliances and fixtures. The user has the option of requiring all new homes (built after 2003) to be constructed with low flow appliances, including sinks, showers, toilets and washing machines. Additionally, the user can choose what percentage of existing homes will be retrofitted with low flow appliances. Reduced indoor per capita water use for the full package of appliances is roughly 165 lpd compared to 231 lpd (CoA, 2003) for conventional appliances. Here we currently assume no depreciation of water savings over time. Similar options are available for the non-residential sector including commercial, industrial, and institutional properties.

Residential homeowners have the option of on-site gray water re-use involving the capture of shower, dishwasher and washing machine discharge. Residential and non-residential customers also have the option of rooftop harvesting for offsetting use by irrigated landscaping. Volume of harvested water is simply a function of the annual rainfall, area of rooftops and a loss factor (30%).

Outdoor water use can be curtailed by way of xeriscaping. The user has the option of requiring xeriscaping around all new home construction, and the option to retrofit a user-specified percentage of existing homes. Because of the broad variation in what is termed xeriscaping, the user is allowed to define the degree of water savings to be achieved. Additionally, the user has the option of reducing irrigated landscaping in new home construction. The same options are available for non-residential outdoor use including commercial and industrial properties.

The CoA uses non-potable water to irrigate some parks and golf courses and for industrial re-use, and it plans to expand its re-use program. Non-potable water sources include raw Rio Grande water, industrial wastewater and treated wastewater. Projects total about 10.5 Mm^3/y of water per year.

Rather than establishing "command and control" policies aimed at water conservation by requiring specific low flow or conservation technologies as described above, a policy maker might also achieve water savings by increasing the price of water. Here, the change in demand for all residential/non-residential sectors resulting from a price change is assumed to be captured by the price elasticity of demand (e.g., Martin and Thomas, 1986).

Bosque restoration. Modern water management practices, flood control, and fire suppression have changed the complexion of the bosque relative to pre-settlement conditions (Crawford et al., 1996; USFWS, 2002; Passell et al., 2004). These practices have led to unusually dense stands of vegetation and a distinct shift in forest composition. In particular, non-native species including salt cedar, Russian olive, and elm are beginning to out-compete native cottonwood and willow. In this context, water conservation is achieved by thinning the vegetation and by preferentially removing vegetation with the highest water demand (i.e., non-native species).

The model allows the user to choose the bosque area to be treated in the planning region. Treatment involves the removal of all non-native vegetation leaving the mature cottonwoods and sparse understory of willows and grasses. Some level of revegetation with native grasses and shrubs also is assumed. The result of bosque restoration is to reduce transpiration by 20% annually (Stephens, 2003).

Agriculture. Several options are available to the individual farmer as well as the MRGCD to reduce diversions from the river and reduce evaporative losses. Broadly, these options include upgrades to the conveyance system, improving on-farm irrigation efficiency, changing the crop distribution, and reducing irrigated croplands.

Most of the 1230 kilometers of mains, laterals, and ditches are unlined and uncovered. Resulting losses include leakage from the canals (which is largely returned to the Rio Grande), open water evaporation, and transpiration from vegetation growing on the ditch banks. The user has the option to choose the length of canal to line or to line and cover.

Water conservation on individual farms is possible through improved irrigation practices. Primary options include laser leveling, lining of delivery ditches and gates, and drip irrigation. Users have the option of choosing the irrigated area for which each technology is implemented. Each measure will reduce the amount of water lost to irrigation seepage and, to a much lesser degree, evaporative losses.

Water use also can be reduced by eliminating some irrigated croplands or by changing the distribution of crops. A shift from alfalfa and pasture hay to lower water use crops can have a significant impact on water use. The model allows the irrigated area of each crop to be varied independently as well as the total irrigated area.

Reservoirs. Evaporative losses from Elephant Butte Reservoir average 160 Mm^3 annually and can run as high as 310 Mm^3/y when the reservoir is full. One way of reducing these losses is to transfer water out of Elephant Butte to reservoirs at higher elevations. Currently there is little available capacity for storing "additional" water in existing reservoirs at higher elevations. Of the major upstream reservoirs, Heron and El Vado remain filled to capacity when water is available, while most available storage capacity in Cochiti and Abiquiu is reserved for flood control. Other alternatives included constructing a new reservoir or storing water underground by way of artificial recharge.

The model offers four different alternatives for storing water outside of Elephant Butte Reservoir. Two options pertain to existing capacity and the other two require new construction. Of the four reservoirs north of Elephant Butte only Abiquiu, a flood and sediment control reservoir, can be configured to accept RGC water. Currently the CoA can store up to 210 Mm^3 of SJC water in Abiquiu. One option in the model involves storing native Rio Grande water in the unused portion of this pool. The other option involves the authorization of an additional 247 Mm^3 of storage in Abiquiu.

New storage options consider both a new reservoir and artificial recharge. The new reservoir is assumed to be located at Wagon Wheel Gap in Colorado with a capacity of 616 Mm^3. The artificial recharge option makes use of underground capacity created by CoA's groundwater depletions. In this option, water is taken from the Rio Grande and pumped to a 20-ha infiltration pond capable of recharging 25 Mm^3/y.

Desalination. Desalination of brackish groundwater may be one way to increase freshwater supply to the Middle Rio Grande Planning Region. Three brackish groundwater deposits in or near the MRG are considered possible sources for the desalination process. These sources include deep waters from the Albuquerque Basin, and shallower sources in Tularosa Basin and Estancia Basin. A maximum treatment capacity of 27.75 Mm^3/y is assumed.

Results

The MRG planning model was actively used by the MRGWA and the MRCOG to develop a water plan for the three-county region beginning in March 2003 and continuing into winter 2004. In this section, model results supporting the 50-y water plan are given, along with results from the community-based planning process. Results are organized according to model verification, the no action alternative, and the "preferred" 50-year water conservation plan for the region.

Model verification

The years 1960 to 2000 serve as the verification period for the MRG water-planning model. The verification process compares historical data with modeled data for four different variables (Fig. 3), including groundwater depletions, Rio Grande Compact balance, Rio Grande flows at the San Acacia gage (located just south of the planning region), and storage in Elephant Butte Reservoir. Note that historical groundwater depletions data are not based on measured values but rather on USGS MODFLOW modeling results for the basin aquifer (McAda and Barroll, 2002). These variables were selected for the verification process because they integrate information from many other model variables. Also, in the case of groundwater depletions and the Compact balance, they represent two key metrics used to evaluate alternative conservation measures.

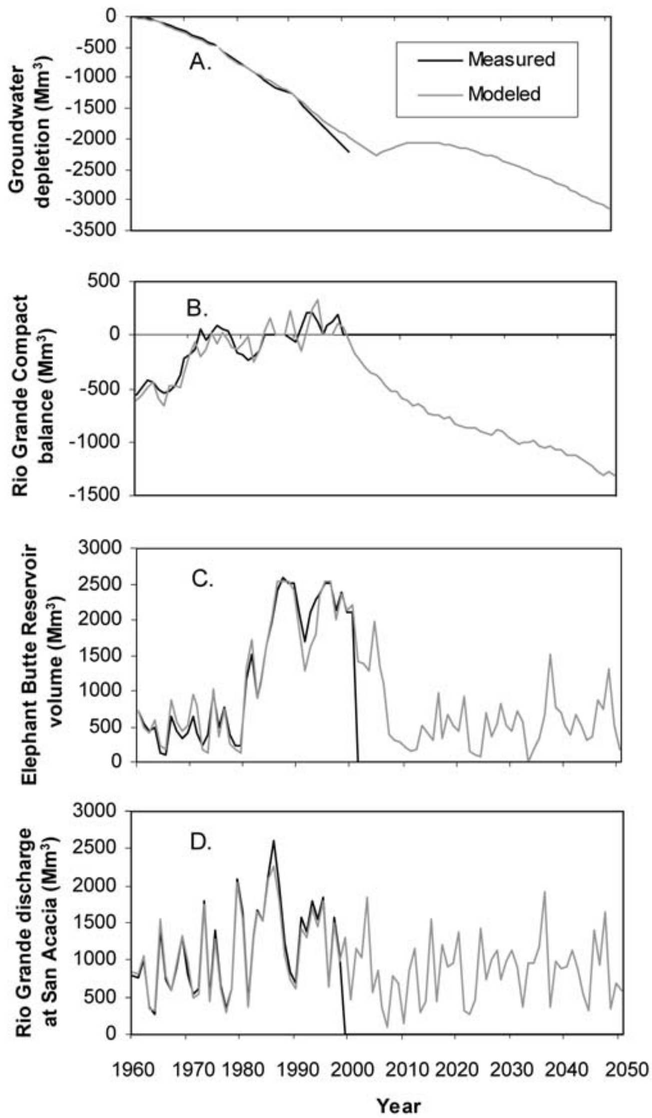

Figure 3. Each graph shows the baseline (measured data) and the "no action" model run for (A) groundwater depletions; (B) Rio Grande Compact balance; (C) Elephant Butte Reservoir storage; and (D) Rio Grande discharge. The legend is the same for all graphs.

Figure 3 shows that in all four cases the model is able to accurately reproduce the 41-y trends evident in the historical data. However, year-to-year differences are also evident between the model and data. Note that these differences are less evident in the Rio Grande gage data and in groundwater depletions because of significant temporal variability in these processes (i.e., larger vertical scale on the graphs). Nevertheless, differences between the modeled and historical data tend to be less than ±7% on average. These errors appear to be random in nature and reflect system complexity that is not fully represented in the model.

Model verification played an important role in the overall planning process. First, this effort provided a sense of credibility and confidence that the model was based on some level of reality. Second, verification of the model demonstrated that at an aggregate surface/groundwater level the modeled terms in the water budget achieve balance. Requiring the water budget to balance against historical data was important for several reasons; in particular, balancing the budget helped set reasonable bounds on parameters subject to uncertainty (e.g., mountain front recharge, agricultural consumption and bosque consumption). Historical balancing also caused careful consideration of whether data gathered from disparate sources were all measured and/or calculated in a self-consistent manner (e.g., with the same assumptions). Finally, there were critics who argued during the model development process that a term in the water budget was too high or too low. However, within the context of a historically balanced model any change made to one portion of the model required an equal and opposite change to another part of the model, and so indiscriminate changes to the model were precluded. Most importantly, the verification or balancing process made the team think more in the context of the whole system rather than the individual terms.

No action alternative

A key role of the MRG planning model was to help define and communicate water resource issues. Toward this end, the model helped quantify potential consequences resulting from a "business as usual" management strategy. Results for this "no action" alternative derive from two important assumptions. First, water use will follow the same rates and patterns through 2050 as those in effect from 1995–2000. Also, population growth will proceed through 2050 at rates consistent with those proposed in 2002 by the Bureau of Business and Economic Research at the University of New Mexico (BBER, 2002).

Figures 3A and 3B show the RGC balance and aquifer depletions for the no action alternative. It should be noted that Figures 3A and 3B show the average results for the 50 years from 2001–2050 from 100 runs of the model, with each run using a different set of 50 projected annual values for surface water inflow to the basin. Each sequence of 50 annual inflow values is generated stochastically from historical data, as described above. This approach leads to a much more robust set of results, since the chances are very small that any single set of inflow values drawn stochastically from historical data will match actual future values. Most importantly, this approach accounts for the effect of variability in year-to-year sequencing of flows as well as variations in climatic conditions (±5% change in average stream flows over the 50-year period).

Results show reason for concern relative to groundwater depletions that are projected to exceed 3700 Mm^3 by 2050. Figure 3A shows that groundwater depletions occur every year from 1960 to 2006. More importantly, the rate of the depletion increases over this period of time. This trend continues until the CoA begins using SJC water from the river for municipal supply and curtails its groundwater pumping. The reduction in groundwater pumping in 2006 allows aquifer levels to rebound briefly, but then increased demand for groundwater due to continued population growth starts driving a renewed decline.

Of equal concern is the projected RGC balance that reaches a deficit of about 1200 Mm^3 by the end of the planning horizon (Fig. 3B). Closer inspection reveals that the balance climbs out of a deficit situation in the 1960s and early 1970s, fluctuates around zero in the late 1970s through the early 2000s, and then moves increasingly into a deficit situation that reaches about 1200 Mm^3 by 2050. The deficit condition in the early 1960s is a result of the severe drought of the 1950s. The rebound was fueled by increasing precipitation coupled with low lake levels in Elephant Butte (i.e., low evaporation). Also, the 1980s and 1990s were some of the wettest years on record for the planning region. These wet years combined with several spills of Elephant Butte (which resets the RGC balance to zero) result in a Compact balance with little surplus or deficit.

The decline in the deficit after 2000 is caused by several factors. First, the climate moderates following the wet years of the 1980s and 1990s. Second, pump induced river leakage exceeds wastewater returns by 25–37 Mm^3/y until the CoA begins to curtail its pumping in 2006. Third, the CoA begins taking its full allotment of SJC water from the Rio Grande in 2006, some of which had been used in the past to assist farmers and others in times of drought. At the time of this writing, it is unclear how drought will affect future irrigation consumption when the CoA's SJC water is no longer available for supplemental use.

The RGC results shown in Figure 3B played an important role in making clear for the planning community the degree of difficulty they may face in meeting future RGC obligations. Previous to the MRG model, the only existing projections for the RGC were punctual estimates for the years 2000 and 2040. SSPA (2000) found that the MRG region ran on average a 16.65-Mm^3/y credit in the year 2000 and estimated that the region will on average run a 36.76- Mm^3/y deficit by 2040. The MRG planning model yields similar annual results to that of SSPA (2000). However, when considered cumulatively, as is the case here, users can recognize that relatively small annual deficits will drive the RGC balance below the legal limit of a 246.70 Mm^3 deficit for an extended period, which would make the region legally liable for Compact non-compliance. In this case, the visual presentation of cumulative results raised awareness of the region's water issues. Public concern over the cumulative results underscores the idea that a 25-Mm^3/y deficit is not so alarming until one considers its cumulative impact over 50 years.

Preferred scenario

The main objective of the regional water planning process is to balance projected supply with demand. Operationally, the MRGWA set the objectives of ending groundwater depletion and maintaining the cumulative RGC balance so that it would not exceed a deficit of 246.70 Mm^3/y in any single year.

A "preferred scenario" of future water conservation alternatives was developed for achieving the region's objectives, and for ultimate inclusion in the state's 50-year water plan. The development of the preferred scenario followed the process described in the "Methods" section. Basic elements of the preferred scenario included municipal conservation involving the installation of low-flow appliances, xeriscaping, rooftop harvesting and reduction in landscaped areas; bosque restoration; improved irrigation efficiency through lining conveyance channels, laser leveling fields, and application of drip irrigation; transfer of limited Elephant Butte storage to Abiquiu Reservoir and to artificial recharge; expansion of the water supply through use of desalinated water; and others omitted here for the sake of brevity. Specifics for each of the preferred scenario alternatives described above are given in Table 2.

The preferred scenario results in an aquifer depletion of approximately 1200 Mm^3 by 2050 and appears to balance groundwater inflows with discharges (Fig. 4A, results here and in Fig. 4B are shown for 100 different realizations of Rio Grande/tributary inflows representing different sequencing of flows and climatic conditions). The preferred scenario also results in a mean Rio Grande Compact balance of about 950 Mm^3 in 2050, representing a surplus in favor of the planning region (Fig. 4B). However, the Compact balance runs a deficit in the early part

Table 2. Selected button and slider bar settings for the preferred scenario[1].

Category	Action	Setting
Residential	Conversion of existing homes to low flow appliances	80%
	Low flow appliances installed in all new homes	yes
	Conversion of existing homes to xeriscaping	30%
	Xeriscaping for all new homes	yes
	Reduction in size of irrigated yards in new homes	40%
	Reduction in consumption by xeriscaping	50%
	Conversion of existing homes to water harvesting	25%
	Roof top harvesting in all new homes	yes
	Conversion of existing homes to on-site gray water use	5%
	On-site gray water use for all new homes	yes
Non-Residential	Conversion of existing properties to low flow appliances	80%
	Low flow appliances in new construction	yes
	Conversion of existing properties to xeriscaping	30%
	Xeriscaping for all new construction	Yes
	Reduction in landscaping for new construction	5%
	Reduction in future per capita growth rate for parks and golf courses	80%
San Juan-Chama	Annual average delivery, from total contracted amount of 93.74 Mm^3	74 Mm^3
Bosque	Remove non-native phreatophytes from all public bosque lands	yes
Agriculture	Lined public conveyances, from a total of 1230 kilometers	1230 km
	Laser leveling of farmland, from a total of 20,235 ha	10117 ha
	Installation of drip irrigation	1011 ha
	Change crop type distribution	no
	Reduce agricultural croplands	no
Reservoirs	Increase storage capacity in Abiquiu Reservoir	yes
	Maximize upstream storage/minimize Elephant Butte Res. storage	yes
	Minimum Elephant Butte Reservoir storage volume	493 Mm^3
	Build a new northern reservoir	no
	Implement artificial recharge	yes
Desalination	Desired quantity of desalinated water	27 Mm^3
	Water source	Tularosa
	Year desalinated water becomes available	2010

[1] Table does not include all options available in the model.

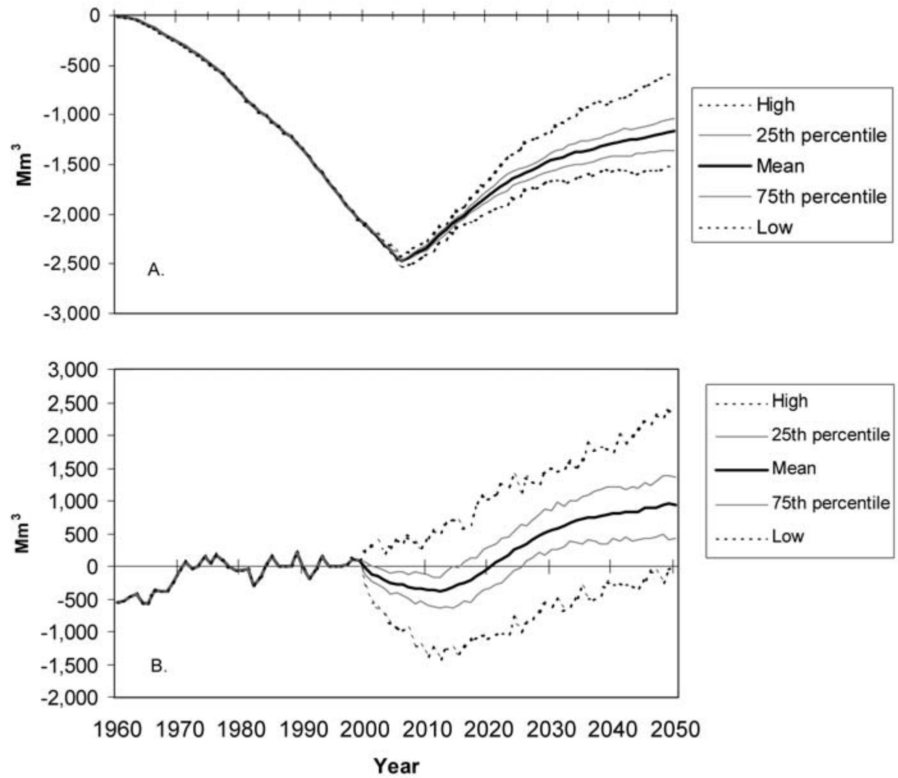

Figure 4. (A) Groundwater depletion and (B) Rio Grande Compact balance. Results from the preferred scenario for 100 model runs with a different set of surface water inflow values for the MRG region in each run. The dotted lines show the single best case and single worst case model run results: the gray lines enclose the middle 50% of the model run results; the black line represents the mean of the results from the 100 model runs.

of the century hitting its low at about 370 Mm^3 before moving to a surplus by 2030; this period of deficit represents non-compliance with the Compact. Model results not shown here place the net present value for implementing all the management strategies at about 2.3 billion US$, and the cost per Mm^3 of water saved as about 965,000 US$. A number of other graphical and tabular model results for the preferred scenario can be found in Passell et al. (2003)

In the course of developing the preferred scenario, the planning model helped express three important lessons about the regional water system and the efficient management of that system. The first lesson was that no single conservation measure can solve the region's water budget deficit. Even with extreme measures no single sector (i.e., municipal, agricultural, or environmental) can solve the regional deficit on its own. Rather, multiple conservation measures spread across different water use sectors are required. For example, groundwater depletions are due solely to municipal pumping. Thus, municipal conservation programs are the only measures available to reduce groundwater depletions; however, such actions provide little improvement to the RGC deficit. Alternatively, bosque restoration efforts directly improve the RGC deficit, yet treatment of all planning region area is insufficient to fully erase the deficit. Combining bosque treatment and improved irrigation efficiencies can mitigate the RGC deficit but have no appreciable effect on the groundwater depletions.

The second lesson was that balancing the budget will require strong conservation measures and considerable cooperation across water use sectors. Over time these conservation measures will change the way the regional community looks and does business. The cities will take on more of a desert complexion as commercial and residential landscaping moves to xeric vegetation. The bosque will be thinned considerably and the vegetation composition altered. Low flow appliances and efficient irrigation practices will impact the construction and farming industries alike. Perhaps most disruptive will be the price tag for these measures, as seen in increased water bills, taxes, and costs to do business.

The third lesson involved timing of the water conservation programs. Note that in the preferred scenario the RGC deficit drops below 246.70 Mm^3 very early in the planning horizon before beginning a recovery again in 2020 or 2030. This trend occurs because of the time delay between when a conservation program is initiated and when water savings from it are fully realized. In this scenario it is assumed that 15 years are required to achieve full compliance with any conservation policy. For this reason, policies with a shorter-term focus will need to be considered to offset the projected near-term deficit.

Discussion

System dynamics modeling provides a powerful platform for cooperative, community-based resource planning. These capabilities were demonstrated within the context of regional water planning for a three-county region in north-central New Mexico. A system dynamics model was developed to assist in preparing a 50-year water plan that balances available supply with growing demand. Key to this effort was an open and participatory process in which the public was directly involved in model development and regional water planning. Both advantages and pitfalls were encountered in creating a model for use by people with both technical and non-technical backgrounds, and in a setting where data and modeling objectives were points of contention among differing interest groups. Here we share some perspectives on the community-based model development and planning process in the context of our three modeling objectives.

Providing a quantitative framework

Our first modeling objective was to build a quantitative platform for exploring alternative water management strategies in terms of costs and water savings. A system dynamics model was created that incorporates 24 conservation alternatives and a "no action" alternative. The model allows the user to select different alternatives and prescribe the degree of the implementation by moving slider bars and mouse clicking on buttons from within a user-friendly, graphical interface. Results in terms of the RGC balance, groundwater depletions, amount of water saved, costs, and other variables are returned in graphical format in a matter of seconds.

This interactive modeling environment proved valuable to the planning process, but a few reservations were registered by various reviewers. First, users have the power to make decisions in the model that could be considered unrealistic, or that require greater interpretation than can be provided on the pages of the model. For example, users can simulate the impact of a 100 percent conversion of existing homes to low flow appliances. Some analysts would contend that achieving that rate of conversion is unrealistic; and unrealistic or not, it would require fiscal and/or legislative incentives not included in the model. Users can simulate the effect on evaporation by covering all 1230 kilometers of agricultural conveyance channels in the planning region; however, covering these canals would cause significant maintenance issues. Users can also simulate the siting of a new dam and reservoir in southern Colorado at the headwaters of the Rio Grande, regardless of the political difficulties that will accompany construction. This list underscores the idea that operation of the model must be accompanied by detailed instruction on the pages of the model, or expert facilitation, or both.

Another difficulty involved the disparity in understanding between modelers and the public on what a model is, and what a model should do. Early concerns about the modeling effort were over the idea that the model would make decisions for the public, that model results would drive the planning process. This concern was eventually allayed through the cooperative, transparent nature of the modeling process and by many presentations of interim versions of the model, along with descriptions of the process, to many different groups. This concern was also allayed by making the distinction between the model as a predictive tool and the model as an instructive tool. Treating the model as a predictive tool created anxiety over its role in the planning process, while treating it as an instructive tool did not. Ultimately, the message that most helped the model find a secure place in the planning process was that the model, along with other kinds of information, allows planners to visualize both the problem and potential solutions to that problem, and to become better predictors themselves.

Given limitations in time, resources and data, some important metrics were not simulated by the model. For example, how might specific pricing or conservation programs effect economic growth, how will changes in Rio Grande flows influence endangered species (e.g., Rio Grande silvery minnow) habitat, and how do traditional and cultural values influence farming practices in this region? Certainly these are important considerations that in many circumstances were recognized and of concern to the public. Although such issues were not formally included in the model, they were factored into the planning process, albeit in a qualitative context. This result underscores the need of the planning process to function beyond the bounds of the model.

Education and outreach

Another reason for developing the model was to educate the public about the complexity of the regional water system. At the highest level, the model effectively conveyed the basic elements of the water budget. The public was generally surprised to learn that municipal consumption rivaled agricultural consumption in the basin. Also, few recognized how sizeable an element the bosque represented in the water budget.

Beyond the high level features of the water budget, the model helped convey the complexity of the regional water system. In particular, it helped demonstrate the impacts of time delays and feedback that are particularly difficult concepts to convey. The effects of time delays are visually evident in the graph of the RGC balance. Difficulties in improving the RGC deficit in the early 2000s results from the time lag between program implementation and the time water savings are realized. Time delays are also integral to the cause and effect relation between groundwater pumping and river leakage.

Probably the most interesting model results involve the feedback between system elements. While people are good at observing the local structure of a system, they are not good at predicting how complex, interdependent systems will behave (Forrester, 1987). Along these lines, the model played an important role in helping the public distinguish between consumed water and water transfers. For example, indoor municipal demand is met by groundwater pumping; however, indoor water is not consumed but transferred from groundwater to the Rio Grande through wastewater return flows. This is important when indoor water conservation measures are adopted that result in reduced groundwater pumping (and thus depletions) and reduced wastewater return flows (and a reduced RGC balance). It is also interesting to note that a time delayed feedback helps offset the lost wastewater returns in the form of reduced pumping-induced river leakage.

Feedback also plays an important role in evaluating the transfer of stored water from Elephant Butte Reservoir to northern reservoirs where evaporative losses are reduced. Such transfers depend on available northern storage, the timing of RGC surpluses, and the storage at Elephant Butte. Although this alternative looks good on paper it is difficult to find the water to transfer except in wet years, and in these wet years the limited storage capacity of the northern reservoirs is often quickly overwhelmed.

Public engagement

The third objective of the model was to engage the public in the water planning process. Over the course of the planning process a number of different "publics" interacted with the model (Table 1). There was the MRGWA, comprised of volunteers from the general public, most of whom had a particular vested interest in water (i.e., urban developers, irrigators, environmentalists). In addition, there was the general public who had enough interest in water to participate in public meetings. Local governments represented by MRCOG also engaged in the planning process along with various local, state, and federal water agencies. Interaction by these different groups with the model varied from simple one-time viewing, supplying data and system understanding, model development, model review, and model utilization in the planning process.

Probably the most important role of the model in the planning process was in promoting and initiating dialogue. In many cases the dialogue arose simply from the process of exploring alternative water conservation measures. Participants were naturally drawn to offer their "what if" scenarios for testing. This process naturally led to questions and discussions of the pros and cons of the different alternatives. In many cases, the questions led to discussions lasting weeks to months, and which often led to greater understanding and clarity. These discussions often helped participants consider the broader, system-wide implications of proposed actions.

Dialogue also was generated when unexpected results appeared. In many cases, the unexpected results served as an experience of discovery; that is, the model helped users see something that had not been considered before. In other cases the result was counter to the preconceived mental model of the user. One example of this action occurred with irrigators who knew that they apply less water to laser leveled fields. But, counter to their expectation, laser leveling showed relatively little water savings. Leveling largely reduces water lost to irrigation seepage that is not consumed but returned to the river via the shallow ground water system.

To maintain model credibility, it was very important to carefully explain such "unexpected" results. For this reason, supplementary information was provided within the modeling environment to help explain the difference between model results and users' preconceived mental models. First, multiple intermediate results were graphed for each of the individual water balance terms. For the agricultural sector such variables as irrigation seepage, river diversions, crop evapotranspiration, and others were graphed to visually convey the reason for the result. Accompanying explanatory text was also provided with the graphs. Second, efforts were made to reference the data and physical relations used in the model with institutions and individuals that are likely to be trusted by the model user.

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