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A Probabilistic Assessment of Water-Resource Sustainability: Using the Middle Rio Grande As a Test Bed

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INTRODUCTION

Water-resource sustainability is a problem of international proportion. According to a recent study sponsored by the US Agency for International Development, a quarter of the world's population is expected to face severe water scarcity in the next 25 years. Achieving sustainable water-resources management is complicated by the fact that 80% of the world's largest rivers are shared by at least two countries. Water-stressed regions will need analysis tools to improve the cooperative management of their water resources.

In this study, we have used the Middle Rio Grande as a test bed to develop our modeling techniques. The Middle Rio Grande Basin provides an excellent test bed since the basin has been the subject of extensive study. Moreover, the Rio Grande provides an example of an arid watershed that typifies many water-stressed regions. One hundred years ago, water use in the Middle Rio Grande Basin was primarily from the river or from shallow wells that were hydrologically connected to the river. Within the last 50 years, however, the population has grown more than tenfold and has spread out of the inner valley on both sides of the river. Municipal wells now tap the aquifer lying beneath the valley, and the basin's non-agricultural withdrawals come almost exclusively from groundwater. Once considered inexhaustible, this aquifer is rapidly being depleted as the population grows and requires more water.

The agricultural sector relies primarily on the diversion of surface water from the Rio Grande. Agricultural consumptive use is the largest user of water within the basin at 34%, followed by evapotranspiration within the riparian forest, the bosque, at 29%. The fastest growing use, however, is within the urban and industrial sectors, currently at 20% of the total.

The model we have built to simulate the water budget of a region is predicated on system dynamics (e.g., Ford, 1999; Sterman, 2000) which is ideally suited to tracking and managing the movement of commodities. In our case, our commodity of interest is water and the model we have built tracks its movement through a watershed. With system dynamics we are able to create a systems-level model that quantifies the feedbacks and time delays coupling system components to one another. In the Middle Rio Grande Basin, the primary feedback occurs between the surface water and groundwater systems and in the human interactions with each of these systems. In this basin, neither the surface water system nor the groundwater system is dominant and both need to be considered in holistically managing water resources.

Here are some examples of feedbacks between systems in the Middle Rio Grande:

- Groundwater extraction affects the surface water system by inducing infiltration from the river. Return flows for groundwater extracted for municipal use are returned to the river.
- A significant portion of surface water used for irrigation infiltrates beneath farm fields and replenishes the aquifer.
- As groundwater extraction has led to significant depletion from the aquifer over time, the City of Albuquerque is actively planning to reduce its groundwater use through a combination of conservation and extraction of surface water.

In groundwater systems especially, there can be significant delays between cause and effect. Water basins having a significant groundwater component can provide buffering in which shortfalls caused by drought can be supplemented by additional extraction from groundwater storage. However, the downside to such buffering is that it can also mask the long-term inadequacy of unsustainable water management strategies. Study of the whole system as a feedback system with delays is required to provide the insights needed to make long-term management decisions.

METHODS

The model considers the movement of water into and out of the Middle Rio Grande Basin beginning in 1960 and extending out to the year 2030 using an annual time step. The basin boundaries are consistent with those defined by Kernodle et al. (1995) and roughly correspond to a 110-mile stretch of the Rio Grande in Central New Mexico centered around the City of Albuquerque. Tidwell et al. (2002) provides a detailed description of the model; only a brief overview is provided here. To calculate a dynamic water budget, we account for: surface water inflows and outflows; groundwater inflows and outflows with adjacent basins; groundwater recharge along the mountain front and along mountain tributaries; stream/aquifer interactions; withdrawals for domestic, industrial, and agricultural uses (and the return flows associated with these activities); evapotranspiration from riparian and agricultural areas; and evaporation from surface water bodies. Using dynamic simulation, we can create a temporally dynamic water balance in a basin and thereby project the future consequences of current trends. Net depletion of water in storage in a basin over time suggests unsustainability that will need to be addressed through improved water management. Dynamic simulation models allow the user to readily try out various “what if” management strategies and evaluate the comparative strengths and weaknesses of each.

In our model, we account probabilistically both for parameter uncertainty and for temporal variability. Even though the Middle Rio Grande has been relatively well studied, large uncertainties remain – particularly with regard to recharge, groundwater inflows from adjacent basins, and evapotranspiration. On the demand side, significant uncertainties exist regarding population growth projections. For each uncertain parameter, we have developed a distribution representing a likelihood function that attempts to quantify our subjective uncertainty about the parameter. These distributions were developed with assistance from Barroll (2002) and are summarized in Table 1.

TABLE 1

ASSIGNED DISTRIBUTIONS FOR UNCERTAIN PARAMETERS

groundwater recharge (acre-feet)	groundwater inflow (acre-feet)	groundwater outflow (acre-feet)	change in open water evaporation	change in riparian transpiration	change in agricultural transpiration	annual population growth rate
triangular min = 20,000 peak = 30,000 max = 100,000	triangular min = 15,000 peak = 30,000 max = 60,000	triangular min = 0 peak = 0 max = 15,000	triangular min = -10% peak = 0% max = 10%	triangular min = -20% peak = 0% max = 20%	triangular min = -20% peak = 0% max = 20%	normal mean = 2.0% STD = 0.2%

In addition, we also handle parameters that vary markedly over time. For example, surface water inflows from the Rio Grande can vary by as much as a factor of five from one year to the next depending on the size of the previous winter's snowpack deposited in its Rocky Mountain headwaters. For the years up to and including 1990, we use historical data. After 1990, we used the available historical data to build distributions to stochastically express the temporal variability. The distributions we have developed for surface water inflows from the Rio Grande and tributaries are given in Tidwell et al. (2002) and are consistent with those developed previously by Papadopulos & Associates (2000). Likewise, evaporation and transpiration can vary appreciably from one year to the next as a function of climate. Water is lost to the atmosphere via transpiration from agricultural crops and through vegetation growing in the bosque along the Rio Grande. Evaporative losses are also calculated for Rio Grande open water and from the network of irrigation channels within the basin. Evapotranspiration is calculated as a function of both climatic conditions (e.g., temperature, wind speed, relative humidity) and vegetative type. Distributions for temporal variability in climatic parameters are provided in Tidwell et al. (2002). The parameters for change in evaporation and transpiration in Table 1 represent subjective uncertainty in the empirical model used to calculate evapotranspiration from climatic data.

RESULTS

We used Monte Carlo analysis to propagate parameter uncertainty and variability to probabilistically project the range of potential future consequences given current water management policies. We then proposed several alternatives to current practice and we used the results from the Monte Carlo analyses to compare outcomes. We considered four alternative water management policies. Each of the first three alternatives focused on a single major water use sector – urban, agricultural, and the bosque. The fourth alternative considered a combination approach that realized saving across each of the three major water use sectors. We used Latin Hypercube sampling and found that running 1000 realizations was sufficient to arrive at stable output distributions. All alternative policies were implemented gradually, beginning in 2002 and ramping up linearly to take full effect by 2010. For all of the policy options we considered, this amounts to an aggressive (and probably optimistic) schedule for implementation. For any of the policy options that conserved the consumption of surface water, we assumed that these water savings were to be used to reduce municipal groundwater depletions. This assumption is reasonable given that the City of Albuquerque is currently developing plans to begin extracting surface water to supplement its groundwater withdrawals. Although there are persuasive ecological reasons for increasing the flow of water in the river toward predevelopment levels, we have concentrated only on reducing groundwater depletions in this initial analysis.

First, we considered the effect of continuing current trends and current water management policies into the future. Base case results, given in Figure 1a, show that the quantity of groundwater in storage in the aquifer is decreasing at an increasing rate over time, fueled by growth in the population. By 2030, mean depletions have grown to about 3.2 million acre-feet. In this simulation (as with all the other simulations as well) the uncertainties compound with time. By 2030, the standard deviation of the

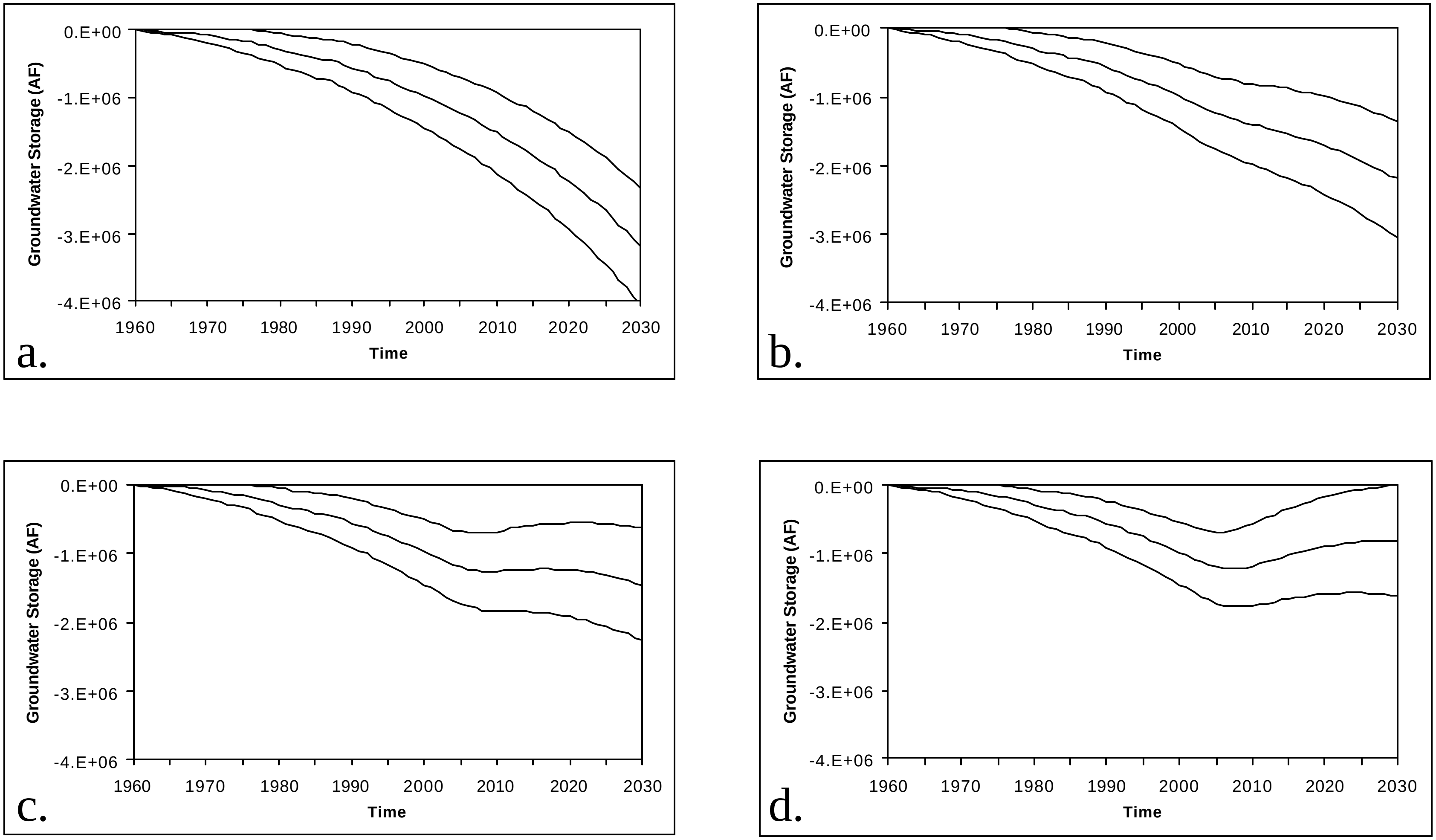

Figure 1. Changes in groundwater storage (in acre feet) relative to 1960. The heavier central line shows the mean values of the 1000 realizations; the lighter lines on either side show +/-1 standard deviation. Lines having a non-negative slope indicate sustainable conditions. The water management scenarios are: (a) base case (current trends continue); (b) cutbacks in residential consumption; (c) cutbacks in agricultural consumption; (d) a policy combining residential conservation, a shift in agriculture to crops that consume less water, and rejuvenation of the bosque.

output distribution has grown to about 860 thousand acre-feet. Although the total storage capacity of potable water in the aquifer remains highly uncertain, the consequences of non-sustainable groundwater withdrawals are already beginning to be felt, as several municipal wells have required deepening. Beyond a certain point, water in the basin becomes increasingly mineralized with depth and water quality degrades. As depletion of storage continues, additional water production wells will be required. Since the most highly productive regions have already been exploited, the new wells must be located in progressively less productive zones.

We began considering alternatives by first looking at a management policy for the urban sector focusing on reducing per capita water use. In this scenario, we reduced residential indoor use from 90 to 60 gallons per person per day, consistent with the savings that could be expected by achieving a relatively high rate of conversion to low-water-use showerheads, toilets, and washing machines. We also reduced the residential outdoor use in all municipalities to match the use of the most efficient community, Rio Rancho, at just over 20 gallons per person per day. (Per capita outdoor use in the City of Albuquerque is currently about 2.5 times Rio Rancho's per capita use.) Results given in Figure 1b show reduced depletions from the aquifer relative to the base case, with mean depletions totaling about 2.2 million acre-feet by 2030. Between the time of policy implementation and the end of the simulation, depletions become roughly linear, with savings offsetting the increased water demand of a growing population. Although sustainable conditions were not achieved, the water savings forestall depletions by about 10 years compared to the base case – equivalent depletions were seen in the base case scenario at about the year 2020.

Next, we considered a management policy focusing on reducing agricultural water consumption. In this scenario, we reduced the area under cultivation by 25 thousand acres, cutting the current acreage by slightly more than one half. This might be considered an amplified preconception of trends that may be just beginning to take hold in the Middle Rio Grande in which farmers sell their water rights and their land in the face of urban development. Results given in Figure 1c show that as this policy takes effect, depletions slow. Groundwater depletions cease and a sustainable situation has been created by the year 2008, followed by a modest rebound until about 2016. Then slight depletions resume until end of simulation in 2030 (again fueled by continued population growth). For this management scenario, mean depletions are reduced to less than 1.5 million acre-feet by 2030, forestalling depletions by about 20 years relative to the base case.

We also considered a management policy focusing on reducing transpiration from the bosque. In the Middle Rio Grande Basin, about 20% of bosque acreage has been taken over by salt cedar, a non-native phreatophyte (Hansen and Gorbach, 1997). Thickets of salt cedar may consume as much as 50% more water than native cottonwood forest (Brower, 2001). In this scenario, we removed the salt cedar and replaced it with cottonwood. The results (not shown) yield depletion curves similar in shape to the base case, although mean depletions were reduced slightly relative to the base case to 2.9 million acre-feet by 2030. This policy may be restorative of the ecology, but did not produce great water savings. Perhaps greater water savings would have been realized had we extended the southern model boundary further south where salt cedar encroachment has been more pervasive.

Finally, we considered a management scenario in which we look for water savings in all three sectors – urban use, riparian transpiration, and agricultural consumption. In a sense, this amounts to a combination of the three previous water management scenarios described above. In this scenario, we reduced per capita use while proscribing restoration of the bosque as described in the previous management scenarios. We also attempted to realize significant savings in agricultural consumption. However, here we attempted a management scenario that differs from the one previously described. Instead of cutting acreage, we shifted crop types from high water use crops such as alfalfa and pasture hay, to crops that require less water such as fruits and vegetables. Figure 2a shows current agricultural land use by crop type; Figure 2b shows the relative water requirements for each crop. The length of the

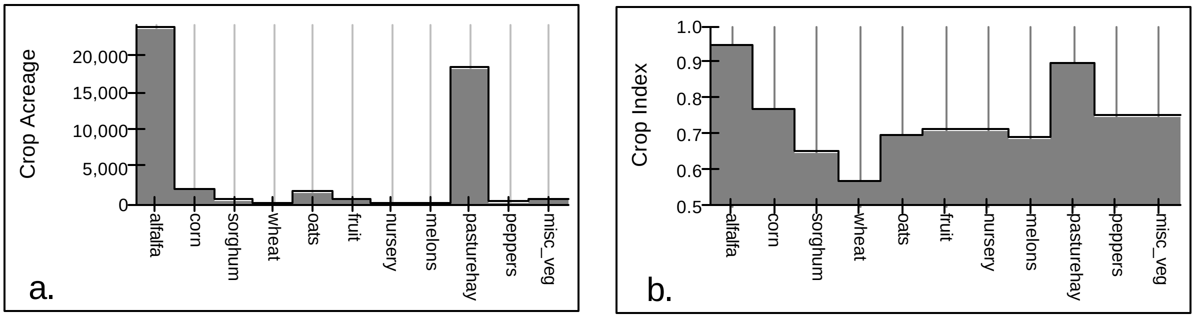

Figure 2. (a) *The crop acreage* and (b) *the crop indices* were obtained from the U.S. Bureau of Reclamation (Brower, 2001). Crop index is a measure of relative water consumption.

growing season for each crop (not shown) is also a factor in water consumption. Currently, acreage devoted to producing fruits and vegetables is less than 4000 acres. In this management scenario, we transfer about 29,000 acres from alfalfa and hay to cultivation of a variety of food crops (i.e., corn, fruit, melons, peppers, and miscellaneous vegetables). In the past, the proportion of food crops to alfalfa and hay was much higher in the Middle Rio Grande than at present. Results given in Figure 1d show that as this composite policy takes effect, depletions slow, reaching a sustainable situation at about the year 2008. Rebound begins shortly thereafter and continues until 2030, the end of the simulation period. At 2030, the mean of the aquifer depletions have been reduced to less than 820 thousand acre-feet, similar to about 1996 levels.

CONCLUSIONS

- We have developed a dynamic water balance model for the Middle Rio Grande Basin.
- We used Monte Carlo analysis to account probabilistically for parameter uncertainty and temporal variability.
- The model allows for exploration of various water management policy options.
- Our initial analysis suggests that new water conservation policies will probably need to extend across all the major use sectors to achieve sustainability.
- Even though the Monte Carlo analysis showed that uncertainties compounded dynamically over time, our results showed clear differentiation between the various policy options we investigated.

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