7. A Dynamic Water Budget for Evaluating Sustainable Water Policy Options[1]

7.1. Introduction

7.1.1 Problem Statement

Freshwater resources are finite, while demand has more than tripled since 1950 (Postel, 1997, pg. 39). Growing demand has largely been met by improving and expanding storage and distribution systems as well as through the mining of fossil groundwater resources—both of which are unsustainable in the long term. To make matters worse, the demand for water is expected to grow, potentially doubling in the next 35 years (Postel 1997, pg. 39). As a result, 2.4 billion to 3.4 billion people may be living in water-scarce or water-stressed conditions by 2025 (Engelman et al. 2000).

To bring demand in line with available supplies, that is achieving resource sustainability, two approaches are available. One involves the development of technology to create new freshwater resources (e.g., desalination) or create new access to existing resources (i.e., transfers from wet to arid climates). Alternatively, implementation of efficient water management and conservation practices can help society make better use of existing supplies. Both approaches must be called upon to mitigate this growing crisis.

Here, we consider the second of these paths, water resource management. In recent years, water management schemes have come under considerable scrutiny. This scrutiny has, in part, grown from new demands placed on water resources. Traditional demands from irrigated agriculture, power generation and navigation must now compete with growing municipalities, high-tech industries, threatened/endangered species, recreation, and cultural needs. Equitable allocation amongst these varied needs is complicated by the difficulty of assigning representative values to each demand. Additionally, political and legal constraints must be respected when formulating solutions.

As demand grows, available supplies and their temporal availability must be forecast with an increasing degree of precision. Ability to achieve such precision is challenged by the complexity and uncertainty of the natural system. Complexity in the physical system arises from a number of sources. First, water supply is governed by multiple processes such as climate, surface/groundwater hydrology, and ecology, each of which is subject to multiple subprocesses. Second, the governing processes tend to be tightly coupled yielding strong non-linear system response. Third, these coupled processes operate over a wide range of spatial and temporal scales. Finally, the processes and their related material properties are subject to spatial and temporal variability.

Management decisions are multidisciplinary and are of concern to the water professional and layperson alike. The manner with which water resources are managed impact our society, economy, and environment. These decisions have multiple spheres of

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[1] Dick Thomas, Steve Conrad, Vince Tidwell, Department 6115, Sandia National Laboratories

influences starting at the local-scale and spreading outward to the river basin, nation, and bordering nations. As such, water management decisions must be based on an integrated view of the problem. That is, a view that crosses scientific, engineering, political, legal, and societal boundaries. Unfortunately, creating cross-boundary programs is hampered by the fact that responsibility for managing water is broadly disseminated over local utilities and multiple state, federal, and international agencies.

7.1.2 Background

Water resource management defines the interface between of the social and natural sciences, spanning a broad spectrum of time and length scales. Because of the inherent complexity, viable water management solutions are rarely apparent. Rather, numerical models are needed to understand the system and make appropriate decisions. No single modeling platform is able to address the full range of water management problems, hence numerous tools are available to the decision-maker. Below we review four broad classes of models, moving from simple to complex.

Water budget modeling has enjoyed wide application for many years. Examples include traditional models like the Thornthwaite-Mather (Alley, 1985) and the Vanderwiele (1992) models as well as ad hoc applications for specific basins (Makhlouf and Michel, 1994; Najjar, 1999). Such modeling is predicated on simple mass balance where the fluxes into and out of the system are tracked along with the change in storage. This balance of fluxes is computed as a spatial aggregate over some discrete hydrographic basin. The most common application involves the calculation of a static water balance based on historic mean annual flows. In rare cases fluxes are treated in a probabilistic context rather than as a known deterministic value (Papadopulos & Associates, 2000). Water balance modeling is particularly attractive for developing a first-order understanding of the hydrologic system and in support of long-term sustainability analyses. Its advantages are its computational ease, low data requirements, and conceptual simplicity, while its disadvantages include lack of spatial/temporal discretization and general lack of physical detail.

Reservoir routing models are extensively used by state and federal agencies for managing the day-to-day operations of reservoirs and irrigation systems. Examples include RiverWare (Zagona et al., 2001), which was developed for the US Bureau of Reclamation, and the Corps of Engineers' Watershed Modeling System (USACE, 2001). In this approach the modeled surface water system is divided into distinct reaches within which flows are routed and gains and losses calculated. Physical processes are modeled by simple analytical and/or empirical relations. Time steps range from daily to monthly with total simulation times from weekly to several years. Many of the reservoir routing models also have rule-based operation capabilities and water accounting features. These models are the key tools for day-to-day operations management and annual forecasting. One drawback of this class of model is their relatively exclusive focus on the surface water system.

Graphical Information Systems (GIS) based models are having a growing impact on water resource management. Examples include the Variable Infiltration Capacity

(VIC) model (Liang, et al., 1994), and the Spatial Water Budget Model (SWBM) (Luijten, et al., 2000). The value of these models is in their access to the burgeoning spectrum of remotely sensed data. In general, the underlying framework for these models is standard commercial GIS software (e.g., ArcView). Analysis routines are added that assimilate information across multiple GIS layers to simulate key water cycle processes. For example, information is combined from radar precipitation data, vegetative cover maps, antecedent soil moisture profiles, and digital elevation maps to estimate storm runoff and infiltration across the basin. In this way the models are fully distributed in time and space. The GIS-based models find application in investigating the complex spatial aspects of water cycle processes and the effects of humans on the environment (e.g., changing land use patterns). Potential difficulties with this approach include the need for remotely sensed data, its computational intensity, and the fact that this technology is currently undergoing rapid development.

The most complex class of models is the process-level models. These models are based on the traditional balances of mass, energy, and flux, and are usually solved using some finite difference/finite element scheme. The process-level models offer the most rigorous mathematical rendering of particular physical processes and the coupling between processes. These models are fully distributed in time and space and allow treatment of complex spatial and temporal variability. Common process-level models include MODFLOW (McDonald and Harbaugh, 1988) and MIKE SHE (DHI, 2001). The main advantage to process-level modeling is that they provide the most precise rendering of the physical system. Disadvantages include their computational intensity, data intensity, and the resource demand to develop and run these models.

We note that the distinction between these four classes of models is not as sharp as might be assumed from the discussion above. In reality, water resource modeling follows more of a continuum with the four classes representing key subgroups. That is, specific problems are often tackled by coupling models from one or more of the classes above.

7.1.3 Approach

Although decision makers have a relatively broad range of water resource management models from which to choose, one important gap exists. Specifically, there is need for an "integrated" watershed model that couples the complex physics governing water supply with the diverse social and environmental issues promoting water demand. Decision makers need an integrated tool that helps them quantify the full consequences associated with alternative water management strategies, changing/uncertain climatic conditions, and growing resource demand. For example, a decision maker may evaluate, with the aid of a single model, the effects of drought on water supply as well as other key systems like critical habitat, agriculture, municipal water demand, energy production, land development, economic growth, and water quality.

Utilization of current modeling approaches (see above) within the context of integrated watershed modeling offers several significant obstacles. First and foremost is the tractability of the problem. Because of the shear number of processes interacting over multiple time and length scales, attempts at fully distributed modeling will quickly overwhelm the largest parallel processor and exhaust the healthiest of project budgets. Data to support detailed distributed modeling is also difficult to come by. Even in the most studied basins, large data gaps exist. Also, the complexity of the distributed models makes it difficult to simulate different test cases, which often require structural modifications to the model.

For this reason we offer an alternative approach to integrated watershed modeling based on the principles of system dynamics (e.g., Sterman, 2000). Within the framework of system dynamics integration of both the natural and social systems is accommodated, capturing the complex cause and effect relationships that characterize diverse watershed systems. Fundamentally, the simulation architecture is based on a dynamic commodity budget. That is the model tracks the disequilibria in key system metrics over time (i.e., water volume, revenue, endangered species population). To make the problem tractable, detailed representation of physical processes and their inherent spatial variability is minimized while effort is focused on capturing the overall structure of the system. Specifically, system dynamics strives to capture the feedback, coupling, and time delays between system elements that are key to the integrated behavior of any watershed. Another advantage of system dynamics is that it offers a decision framework that is conceptually, computationally, and operationally simple.

Although system dynamics cannot provide answers to every watershed management problem, there are many for which it can. For example, it can be used as a tool for resolving conflict among competing water demands; tool for screening alternative resource management strategies; scoping analyses to guide more detailed resource modeling and data collection; uncertainty/risk assessment; and gaining a holistic understanding of the watershed. The interactive nature of system dynamics modeling also makes it a powerful platform for conveying complex issues to stakeholders, educating the public, and explaining specific resource management decisions.

7.1.4 Objectives

The primary objective of this report is to introduce system dynamics as a method for integrated watershed modeling. To demonstrate this approach we have developed a system dynamics model for a stretch of the Rio Grande Basin including Albuquerque, New Mexico, henceforth referred to as the Middle Rio Grande (MRG). We begin with the basics of system dynamics and then describe the test bed used for our experiment. This is followed by a full description of the system dynamics model for the MRG and the presentation of some key results.

7.2 Methods

7.2.1 System Dynamics

System dynamics modeling is a technique for quantitatively studying and managing complex feedback systems. In the MRG model, the primary feedback occurs between the surface water and groundwater systems and in the human interactions with each of these systems. In the Middle Rio Grande watershed, 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 may affect the surface water system by inducing additional 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 of 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 of the past. Study of the whole system as a feedback system with delays is required to provide the insights needed to make long-term management decisions. And of course, achieving consensus for an appropriate course of action and implementing that decision will take a significant amount of time. It has been said, Real change takes so long that you have to start down the road of change far before there is a sense of urgency. -- Andrew Marshall.

In this system dynamics model of the middle Rio Grande, we have attempted to capture the structure of the environmental and human components of the water resources system along with their interactions and delays. It is from this structure embodied in the model that, as we run the model, we attempt to discern what system response patterns may be expected to develop over time – and the implications of those patterns. One of our goals is to be able to identify the important leverage points in the system, which may suggest a handful of potentially effective management options for further analysis. The model is well suited to rapidly comparing the outcomes – the response patterns generated – from various management options. But because many significant uncertainties remain that are not captured explicitly in the model, it is only in the most general sense that this model can be described as predictive. To the extent that we have captured the structure of the system correctly given our purpose, primarily we are engaged in using the model to generate insight about the patterns of system response that might be expected. It's tough to make predictions, especially about the future. – Yogi Berra

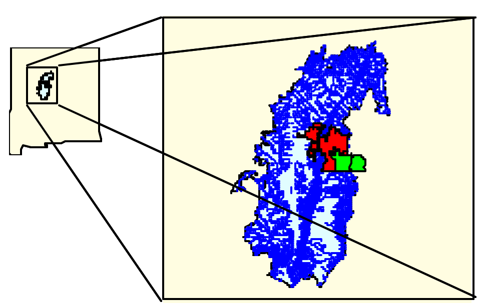

Figure 7.1. The Middle Rio Grande Basin lies in Central New Mexico.

7.2.2 Middle Rio Grande as a Test Bed

The Middle Rio Grande (MRG) basin (Figure 7.1) is similar to many water basins throughout the world in that water rights and water demands have outstripped the capacity of the natural system to meet those demands. The MRG basin is not a complete water basin in the sense of a watershed. The boundaries of the basin are co-incident with the boundaries of the MRG groundwater basin, but the watershed boundaries for this portion of the Rio Grande extend into northern New Mexico and Colorado. The City of Albuquerque is the major urban area within this basin, but it also includes the rapidly growing areas of Rio Rancho, Los Lunas, and Belen. The basin begins just below Cochiti Dam and ends near San Acacia (north of Socorro). While the dominant surface water inflow to this basin is from the Rio Grande, other inflows include Jemez River, Galisteo River, Tijeras Arroyo, Rio Salado, and Rio Puerco.

The MRG Dynamic Water Budget considers the inflow of water from the entire upper watershed, but does not specifically model the watershed parameters in the upper part of the basin. The model is primarily concerned with the supply and demand of water within this portion of the basin where the bulk of the population resides. Within the MRG basin, there are conflicting demands for water from the urban, industrial, and agricultural sectors. The pie chart in Figure 7.2 shows the distribution of current water use within the MRG basin.

The largest consumer of water within the basin is agriculture at 34%: this is closely followed at 29% by evapotranspiration within the riparian forest along the Rio Grande, also called the bosque. The fastest growing use, however, is within the urban and industrial sectors, currently at 20% of the total. High rates of population growth make residential use the fastest growing portion of the urban sector.

The agricultural sector relies primarily on the diversion of surface water from the Rio Grande, while the urban and industrial sectors rely primarily on the use of groundwater, but this may soon change. The depletion of the MRG groundwater aquifer is a major source for concern within the basin. The rapidly dropping water table has prompted the City of Albuquerque to consider its option to use surface water from the Rio Grande. The city currently has unutilized rights to 48,200 acre-feet of the San Juan Chama water. The city plans to use their rights to this surface water to satisfy urban population growth. This

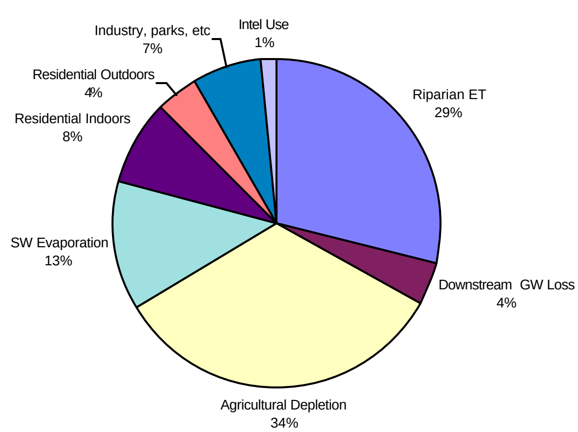

Figure 7.2. Water Use within the MRG Basin (MRG WA, 1999).

planned expansion of surface water has the potential to exacerbate the existing conflicts for water use within the basin. Additionally, the city is using its right to 22,000 acre-feet of native Rio Grande water through induced infiltration from the river caused by groundwater extraction.

The MRG Dynamic Water Budget model is a test case for the use of system dynamics as a tool for exploring (and resolving) resource allocation issues within a basin where demand exceed supplies.

7.3 Model Description

A dynamic water budget model was developed for the Middle Rio Grande Basin. The modeling framework adopted for this project was the Powersim dynamic simulation software package. An annual time step was employed in the simulation. The water budget tracks two interacting stocks, the volume of surface water stored in the basin and the stored volume of groundwater.

Below we provide a full description of the model organized according to key physical processes and water balances. We begin by documenting the modeling of two physical processes, evapotranspiration and river-aquifer interaction. This is followed by a description of the surface water and groundwater balance modules and their associated sub-models.

7.3.1 Evapotranspiration (ET)

Losses by evapotranspiration (ET) are a key component of the water balance for the MRG Basin. Specifically water is lost to the atmosphere via transpiration through the vegetation growing in the bosque along the Rio Grande River and from the agricultural crops grown in the basin. Evaporative losses are also calculated for the Rio Grande River open water, its associated saturated sandbars, and from the irrigation channel network within the basin. Note that ET is not calculated for irrigated lawns as essentially all of this water is assumed to be consumed.

The evapotranspiration rate is calculated using the Penman-Monteith (P-M) Equation (e.g., Shuttleworth, 1993). In this way calculated ET rates are a function of both climatic conditions (e.g., temperature, wind speed) and vegetative type. Specifically, the evapotranspiration rate, ET_r, is calculated using the P-M Equation for the case of a reference crop (i.e., an idealized grass crop with a height of 0.12 m)

$$ET_r = \frac{\Delta}{\Delta + g^*}(SR) + \left(\frac{g}{g^* + \Delta}\right)\frac{900 * U}{T + 275} D \qquad (7.1)$$

where U is wind speed, T is temperature, SR is net solar radiation, Δ is the vapor pressure/temperature gradient, l is the psychrometric constant, g^* is the scaled psychrometric constant, and D is the vapor pressure deficit. Additional details may be found in Shuttleworth (1993).

Using the reference evapotranspiration rate, ET_r, the potential evapotranspiration rate, $PotET_{ct}$, for a specific vegetation type is calculated. This is accomplished by multiplying the reference ET rate by the crop index specific to the crop of interest. The total evaporative loss for a particular crop is then calculated by multiplying the potential ET by the crop acreage and the average number of growing days

$$PotET_{ct} = [ET_r * K_{ct}] * A_{ct} * Gdays_{ct} \tag{7.2}$$

where K_{ct} is the crop index (dimensionless), which varies by crop (*ct*), A_{ct} is the crop area, and $Gdays_{ct}$ is the growing days per year. $PotET_{ct}$ assumes the crop is healthy and has full and continuous access to water throughout the growing season. As such, $PotET_{ct}$ represents the maximum possible value of ET. The actual ET largely depends on crop health and irrigation practices specific to the basin of interest. Based on calibration to local data, the actual ET, $AcET_{ct}$, is calculated as

$$AcET_{ct} = PotET_{ct} * 0.80 \tag{7.3}$$

The crop index, crop area, and growing day data were obtained from the U.S. Bureau of Reclamation (Brower, 2001) and are the same as used in their Upper Rio Grande Water Operations Model (URGWOM). The crop indices are yearly averages of the supplied daily values. A listing of the data is given in Table 7.1. Historic acreage values, for the period of 1960-1990, are read directly from a spreadsheet, while values after 1990 are left as user defined decision variables controlled by slider bars.

Table 7.1. Crop data used in the calculation of the MRG Basin Potential ET losses

	Crop Index	Growing Days	1999 Acreage
Alfalfa	0.95	293	23888
Corn	0.77	205	1949
Sorghum	0.65	186	556
Wheat	0.57	123	202
Oats	0.7	123	1662
Salt Cedar	0.77	231	0
Cottonwood	0.53	231	0
Riparian Wood	0.77	231	612
Riparian Shrub	0.77	231	1805
Bosque	0.77	231	21046
Fruit	0.71	365	687
Nursery	0.71	365	202
Melons	0.69	154	78
Pasture/hay	0.9	293	18453
Peppers	0.75	125	350
Misc Veg	0.75	105	756

The open water ET rate, $OWET$, for water bodies of limited area, like the Rio Grande River, is calculated using the P-M equation. In this case, the P-M equation is modified for the surface resistance of an open water body (Shuttleworth, 1993)

$$OWET = \frac{\Delta}{\Delta + g}(SR) + \left(\frac{g}{g+\Delta}\right)\frac{6.43*(1+0.536*U)}{l}D \qquad (7.4)$$

The total evaporative loss is then calculated by multiplying the ET rate by the number of days in the year and the area of water open to evaporation. Evaporation is assumed to occur both from the open water flowing in the Rio Grande River as well as from the wetted sands. A factor of 0.25 is used to correlate the evaporation of water through the sandbars, which is impeded by capillarity, to that of open water evaporation (Sorey and Matlock, 1969). Open water and wetted sand areas as a function of river discharge were adopted from the URGWOM (USACE, 2001).

Open water ET is also used to calculate the evaporative losses from irrigation channels in the MRG Basin. Irrigation channel ET, *ICET*, is calculated by

$$ICET = OWET * A_c * \Delta t \qquad (7.5)$$

where A_c is the open water area of the channel, and Δt is the number of days water is flowing in the irrigation channel (245 days).

Meteorological data used as input to Equations 7.1 and 7.4 are taken as yearly averaged values. Historical meteorological data is read into the model from a spreadsheet at each time step. This dataset represents the historical period, 1960 to 1990. After 1990, stochastically generated values are used. The historical record from 1960 to 1990 was used to generate frequency distributions for each of the meteorological parameters. These are given in Table 7.2. The frequency distributions were chosen using the Anderson-Darling statistic, which weights the tails of the distributions more heavily as it evaluates goodness-of-fit. Strong correlations between parameters (R>0.5) were maintained. Temporal correlations were not evaluated.

7.3.2 Surface Water/Groundwater Interaction

Several components contribute to the total transfer of water from surface water to groundwater or vice-versa. These include:

- agricultural recharge,
- irrigation channel leakage,
- river leakage,
- groundwater pumping induced river leakage, and
- groundwater discharge to riverside and interior drains.

Below we document the modeling of each of these components.

Table 7.2. Stochastic distributions for simulating meteorological data after 1990.

Parameter	**Distribution Type and Parameters**	**Correlation Coefficients**
Radiant energy (MJ/m^2*d)	Extreme Value Mode = 24.7 Scale = 1.07	-0.59 with relative humidity
Maximum temperature (ºC)	Weibull Location = 20.2 Scale = 1.12 Shape = 1.57	0.90 with average temperature
Minimum temperature (ºC)	Extreme Value Mode = 5.95 Scale = 0.52	0.61 with average temperature
Average temperature (ºC)	Extreme Value Mode = 15.45 Scale = 0.50	0.90 with maximum temperature 0.61 with minimum temperature
Relative humidity (%)	Logistic Mean = 44.0 Scale = 1.55	-0.59 with radiant energy 0.62 with Rio Grande inflow
Wind speed (m/s)	Extreme Value Mode = 4.21 Scale = 0.22	

Irrigation Channel Leakage: As the irrigation channels are located near the margins of the inner MRG Basin, they generally lie well above the water table. Given their hydraulic disconnection with the groundwater aquifer, leakage rates are assumed to be essentially constant, at a value of 0.24 cfs/mile (USACE, 2001). The annual volumetric leakage is calculated by multiplying the leakage rate by the total length of channel times the number of days water is flowing in the irrigation channel system.

Recharge from Agricultural Irrigation: Recharge from irrigated agriculture, *AgRc*, is simply taken to be the difference between the total agricultural irrigation, Irr_{tot} and agricultural ET

$$AgRc = \left[Irr_{tot} - AgET \right] \tag{7.6}$$

where agricultural ET, *AgET*, is the sum of all ET losses from irrigated agriculture in the basin. Total agricultural irrigation is computed as

$$Irr_{tot} = \sum_{ct=1}^{n} Irr_{ct} * A_{ct} \tag{7.7}$$

taking Irr_{ct} to be the amount of water required by a particular crop and A_{ct} is the acreage for that crop. Irr_{ct} is assumed to equal the yearly average ET of the crop plus one acre foot/acre of water to account for over watering and annual flushing of salts from the soil.

River Leakage: Throughout the MRG basin the river and aquifer are in intimate contact with flows of water moving back and forth between the two. To prevent water logging of irrigated land along the river, drains have been installed along much of the length of the MRG. The drains are designed to capture a portion of both the river leakage and agricultural recharge and return it to the river. Our interest is in the net transfers of water from the river to the aquifer. As such, river leakage, *RivLeak*, and groundwater discharge to the drain system, $GWDis_D$, are combined and treated as a net gain or loss, $RivLeak_{tot}$

$$RivLeak_{tot} = RivLeak - GWDis_D \tag{7.8}$$

This value is not calculated directly, but through mass balance. Under ambient conditions (i.e., unaffected by pumping) the following balance of mass for the shallow aquifer must be sustained on an annual basis

$$RivLeak_{tot} = AgRc + ICLeak - BqET + MtRc \tag{7.9}$$

where *ICLeak* is the leakage from the irrigation channels, *AgRc* is agricultural recharge, *BqET*, is the total ET loss from bosque and riparian areas, and *MtRc* is mountain front and tributary recharge. Estimates for *MtRc* were derived from Kernodle et al. (1995) where the yearly average is approximately 110,000 acre-feet, which varies annually according to departures from the long-term mean annual precipitation.

Pumping Induced River Leakage: In some areas of the basin, particularly the vicinity of Albuquerque, groundwater pumping greatly disturbs the balance in Equation 7.9. That is, the aquifer experiences a net depletion. Pumping induced leakage, *PumpLeak*, is calculated using the Glover Balmer equation

$$PumpLeak = Q_w * erfc\left(\sqrt{\frac{Sd^2}{4Tt}}\right) \tag{7.10}$$

where d is the distance between the pump and river, T is aquifer transmissivity, S is the storage coefficient of the aquifer, and Q_w is the pumping rate. The storage and transmissivity values are consistent with those used in the USGS MRG groundwater model (Kernodle et al., 1995) while Q, D, and time to start of pumping were determined through calibration. Should pumping stop the leakage rate would not fall to zero; rather, it will follow the relation offered by Jenkins (1968)

$$Q_s = Q_w \left[1 - erf\left(t_a / 4t\right)^{1/2}\right] - Q_w \left\{1 - erf\left[t_a / 4\left(t - t_p\right)\right]^{1/2}\right\} \tag{7.11}$$

where t_p is the time pumping ended, t is time after pumping started, and t_a is

$$t_a = d^2 S / T$$

In the pumping impacted regions of the basin the net recharge to the aquifer, *RZRc*, is modeled as

$$RZRc = AgRc + ICLeak - BqET + MtRc + PumpLeak \qquad (7.12)$$

which we refer to as riparian zone recharge. The region impacted by Albuquerque pumping is taken to extend roughly from Corrales to Isleta. This is based on the predicted extent of the groundwater cone of depression in the year 2020 following current pumping practices (Kernodle et al., 1995). As data become available, similar calculations could be made for other cities whose pumping may affect the Rio Grande River.

7.3.3 Surface Water Budget

One of the primary stocks in our model is the volume of surface water stored in the basin. This water budget is computed by tracking the incremental surface water inflows and outflows for the basin

$$SW = (dt * SWi) - (dt * SWo) \qquad (7.13)$$

where *SW* is the surface water balance(i.e., volume stored), *SWi* is the surface water inflow, *SWo* is the surface water outflow, and *dt* is the timestep. Simulations employ an annual time step. As there are no reservoirs within the modeled domain, surface inflow is assumed equal to the outflow (i.e., *SW=0*)

Surface Water Inflow: Surface water inflow is the sum of all waters that flow into the Rio Grande. These include river inflows from tributaries and urban runoff as well as return flows from the municipal sewage reclamation plants

$$SWi = RVi + SWGrtn \qquad (7.14)$$

where *RVi* is the river inflow and *SWGrtn* is the sewage return flow.

River inflows begin with the inflows for the Rio Grande River from the upper basin. Major tributary inflows occurring within the basin include the Jemez River, Galisteo River, Tijeras Arroyo, Rio Salado, and Rio Puerco. Historical river inflow is represented by measured inflows that are read into the model from a spreadsheet at each time step. This dataset represents the historical period, 1960 to 1990. After 1990, stochastically generated values are used. Historical data was used to generate frequency distributions for each of the inflows. These are given in Table 7.3. The frequency distributions were again chosen using the Anderson-Darling statistic. Some of these distributions were created from relatively short historical records. However, these particular inflows contribute negligibly to the overall surface water inflow. Also the model does not include an estimate of annual flows to the basin from un-gauged tributaries; but likewise, this value is not expected to be significant. Strong correlations between parameters (R>0.5) were maintained. Temporal correlations were not evaluated. The distributions given in Table 7.3 are generally consistent with those generated independently by Papadopulos & Associates (2000). In addition, we assume a constant inflow of San Juan-Chama diversion water of 75,844 AF/Y, again consistent with Papadopulos & Associates (2000).

The water that is returned to the river from the municipal sewage treatment plants is roughly equal to 50% of the municipal water demand (personal communication, Jean Witherspoon, 2001)

$$SWGrtn = WUswg * RTNurb \tag{7.15}$$

where *WUswg* is the water use by the population that is connected to a municipal sewer, and *RTNurb* is the return flow percentage for this population.

Surface Water Outflow: The surface water outflow is the net volume of water discharged from the basin via the surface water system. Surface water outflow is computed as the difference between the net surface water inflows and the surface water discharges occurring within the basin (i.e., assume no surface water storage within the basin)

$$SWo = SWi - SWq \tag{7.16}$$

where *SWq* is the sum of all surface water discharges within the basin, including surface water evaporation, agricultural diversions, municipal use, and river leakage

$$SWq = IrrDiv + OWET + RivLeak_{tot} + PumpLeak + URBqsw \tag{7.17}$$

where *IrrDiv* is the diversion of surface water for agricultural irrigation, *OWET* is the surface water evaporation, $RivLeak_{tot}$ is river leakage occurring under ambient conditions, *PumpLeak* is river leakage occurring in groundwater pumping impacted reaches of the river, and *URBqsw* is the diversion of surface water for municipal use. Calculation of *OWET*, $RivLeak_{tot}$, and *PumpLeak* were described in Equations 7.4, 7.9 and 7.10 respectively.

Irrigation diversions are modeled as the total irrigated volume of water, Irr_{ct} plus the water lost to irrigation channel leakage (*ICLeak*) and ET (*ICET*)

$$IrrDiv = Irr_{tot} + ICET + ICLeak \tag{7.18}$$

Here, irrigators are treated as insensitive to rainfall. In general, irrigators play it safe and use their water when it is available.

The diversion of surface water for municipal use is a possibility for the future, but it has not been done historically. The municipal use of surface water may be done in lieu of groundwater extraction. The City of Albuquerque has rights to 48,200 acre-feet of San

Table 7.3. Stochastic distributions for simulating river inflow data after 1990.

Inflow	Historical Record length	Distribution type and parameters	Correlation coefficients
Rio Grande	1940-1998	Beta Alpha = 2.72 Beta = 11.89 Scale = 5.42×10^6	0.84 with Jemez River
Jemez River	1944-1995	Beta Alpha = 1.88 Beta = 8.27 Scale = 2.48×10^5	0.84 with Rio Grande
Rio Puerco	1944-1992	Lognormal Mean = 3.17×10^4 Std. Dev = 2.54×10^4	
Rio Salado	1948-1983	Exponential 50%ile = 7.43×10^4	
Santa Fe River	1971-1992	Gamma Location = 4.54×10^4 Scale = 6.04×10^4 Shape = 0.594	
North Floodway	1968-1993	Extreme Value Mode = 4.40×10^4 Scale = 2.12×10^4	
Galesteo River	1971-1992	Weibull Location = 272 Scale = 4.66×10^4 Shape = 1.68	
South Diversion	1988-1993	Uniform Min = 164 Max = 797	
Tijeras Arroyo	1983-1993	Weibull Location = -71.2 Scale = 503 Shape = 1.83 Truncated at 0	

Juan-Chama water. Assuming that the city returns half of this water to the river, they could divert a total of 96,400 acre-feet. The model also includes the option for using retired agricultural water for municipal use.

Surface water municipal diversion is equal to the minimum of either the sewered water use (water used by people within the municipalities that are on the sewer system) or the allotted surface water use.

$$URBqsw = MIN\,(WUswg, (2 * SJCabq)) \tag{7.19}$$

where *SJCabq* is allocation of San Juan-Chama water, 48,200 acre-feet.

7.3.4 Groundwater Budget

The water budget for the groundwater system within the basin is also calculated. The groundwater budget is computed by tracking the incremental groundwater inflows and outflows for the basin

$$GW = (dt * GWi) - (dt * GWo) \tag{7.20}$$

where *GW* is the groundwater balance (i.e., volume stored), *GWi* is the groundwater inflow, *GWo* is the groundwater outflow, and *dt* is the timestep. The groundwater balance is not static, rather the aquifer is undergoing a cumulative depletion over time.

Groundwater Inflows: Inflows to the groundwater system include riparian zone recharge, RZR_c described in Equation 7.12, inflows from adjacent basins, GW_{adj}, urban recharge, URB_{rch}, and septic tank return flow, $SPTC_{rtn}$.

$$GW_{in} = GWRc + GWadj_{in} + URB_{rch} + SPTC_{rtn} \tag{7.21}$$

Groundwater inflow from adjacent basins is treated as a constant and represents the amount of groundwater that is thought to be moving from adjacent groundwater basins into the Middle Rio Grande Basin. A default value of 28,400 acre-feet per year (Kernodle et al., 1995), is used but can be adjusted by the user through the use of a slider bar.

Urban recharge, is water returning to the groundwater from parks and golf courses and from other urban irrigation. The values used are constants based on estimates for 1994: recharge from parks and golf courses is 6673 acre-feet per year; recharge from urban irrigation is 1808 acre-feet per year [Hansen & Gorbach, 1997]. Currently, we assume no recharge from irrigation of residential lawns.

The return flow from individual septic systems, is assumed to go to the groundwater. This value is computed as a proportion of the water demand. This proportion defaults to 75%, but can be adjusted using a slider bar.

$$SPTC_{rtn} = WUspt * RTNspt \tag{7.22}$$

where *WUspt* is the water use by the population that use individual septic tanks, and *RTNspt* is the return flow percentage for this population.

Groundwater Outflow: Groundwater Outflow, GW_{out}, is the sum of the groundwater moving out of the MRG basin and into adjacent groundwater basins, $GWadj_{out}$, groundwater diverted by Intel Corporation, GW_{Intel}, groundwater pumped by Kirtland Air Force Base (including use by Sandia National Laboratories), GW_{KAFB}, plus municipal groundwater withdrawals, *URBqgw*.

$$GWout = GWadj_{out} + GW_{Intel} + GW_{KAFB} + URBqgw \tag{7.23}$$

Groundwater outflow to adjacent basins is the amount of groundwater that flows out of the Middle Rio Grande Basin into the Socorro Basin. This value is estimated at 15,000 acre-feet per year.

The groundwater used at the Intel Plant in Rio Rancho is the sum of the groundwater drawn from Intel's own well and water bought from the Rio Rancho water system. Intel pumps about 3 million gallons per day (3362 acre-feet per year) from their own well and buys about 1313 acre-feet per year (based on 1999 records) from Rio Rancho water system (personal communication, Colleen Logan, 2001). Intel's total annual use is about 4675 acre-feet per year. Return flow from Intel is discharged into the Rio Rancho sewer system.

The groundwater pumped by wells on Kirtland Air Force Base (KAFB) is used by both KAFB and Sandia National Laboratories. KAFB pumps about 90% of the water used on base. During the period from 1989 to 1990, the average annual total groundwater used on the base was 4671 acre-feet (Personal communication, Mark Dalzell, 2001). The total water use was the sum of the average annual water pumped from KAFB wells (4182 acre-feet) and the average annual water purchased from the City of Albuquerque (489 acre-feet). The return flow from the base is discharged into the Albuquerque sewer system. Return flow is assumed to be the same as municipal return flow, 50% of the total water demand.

The withdrawal of water for domestic and municipal use, *URBqgw*, includes water used by the municipalities of Albuquerque and Rio Rancho, WU_{Alb} and WU_{RR}, other metropolitan areas, WU_{other}, and the water used for rural domestic use, WU_{Rural}. The water that municipalities divert from surface water sources, *URBqsw*, is subtracted from this total.

$$URBqgw = WU_{Alb} + WU_{RR} + WU_{other} + WU_{Rural} - URBqsw \tag{7.24}$$

Water use (*WU*) for each municipality and for rural use is based on population (*POP*) multiplied by per capita water use (*GPCD*) for each community. The largest percentage of water use is by the population that is connected to a municipal sewage system. The proportion of the population that is on sewers is considered separately from the proportion using septic tanks because the return flow from each of these groups is handled differently. Return flow from the sewered population goes to the Rio Grande. Return flow from the septic tank population goes back to the groundwater. The proportions of the population in Albuquerque and Rio Rancho that are served by a municipal sewage system are, respectively, 95% and 99% (personal communication, Jean Witherspoon and Colleen Logan, 2001)

The losses of water through leaks in the distribution system (before the water reaches the customer), *Loss*, are included in the computation of the total water pumped, *TWP*. These losses are estimated for Albuquerque, Rio Rancho, other metropolitan areas and rural use respectively, at 12%, 11%, 12%, and 1%, of the total water pumped (personal communication, Jean Witherspoon and Colleen Logan, 2001)

$$TWP = URBqgw / (1 - Loss) \tag{7.25}$$

Municipal water use is computed in terms of per capita use, the number of gallons per person per day. Per capita use is the sum of residential per capita use and non-residential per capita use. Non-residential per capita water use for each community is estimated as 70, 48, 50, and 0 gpcd, respectively for Albuquerque, Rio Rancho, other metropolitan areas, and rural areas (personal communication, Jean Witherspoon and Colleen Logan, 2001). Residential per capita use is the sum of indoor per capita water use and outdoor per capita use. Indoor use is further disaggregated into consumption by toilets, sinks, showers, bathtubs, dishwashers and washing machines. Graphical interfaces (Figure 7.3) allow the user to adjust indoor and outdoor water use practices by moving a slider bar. Initially, water use values are set at average measured use values.

Water use for the metropolitan areas is based on population. The model uses growth rates that match historical 10-year census numbers compounded on an annual basis. Growth rates have been computed for the periods, 1960-1970, 1970-1980, 1980-1990, and 1990-2000. Population growth for periods beyond 2000 is based on the 1990-2000 growth rate. Growth rates are based on the formula for computing compounded interest.

$$Total = \Pr incipal * (1 + Rate)^{years} \tag{7.26}$$

The growth rates used in this model are shown in Table 7.4. In the absence of data the growth rates for rural areas are shown as zero.

Table 7.4. Growth rates used for major population areas.

	Albuquerque	**Rio Rancho**	**Other Meto Areas**	**Rural**
1960-1970:	1.97%	69.86%	3.67%	0.00%
1970-1980:	3.13%	17.46%	5.26%	0.00%
1980-1990:	1.46%	12.51%	5.71%	0.00%
1990-2000:	1.55%	4.76%	1.76%	1.50%

7.4. Results

7.4.1. Model Calibration

The model was calibrated for the period, 1960 to1990, by comparing model output to two external factors, 1) the annual groundwater depletion that were estimated by the USGS and 2) the annual measured surface water outflow from the basin. Kernodle et al. (1995) estimated the annual depletion on the basis of data provided by the City of Albuquerque. The cumulative annual depletion as estimated by the USGS was compared

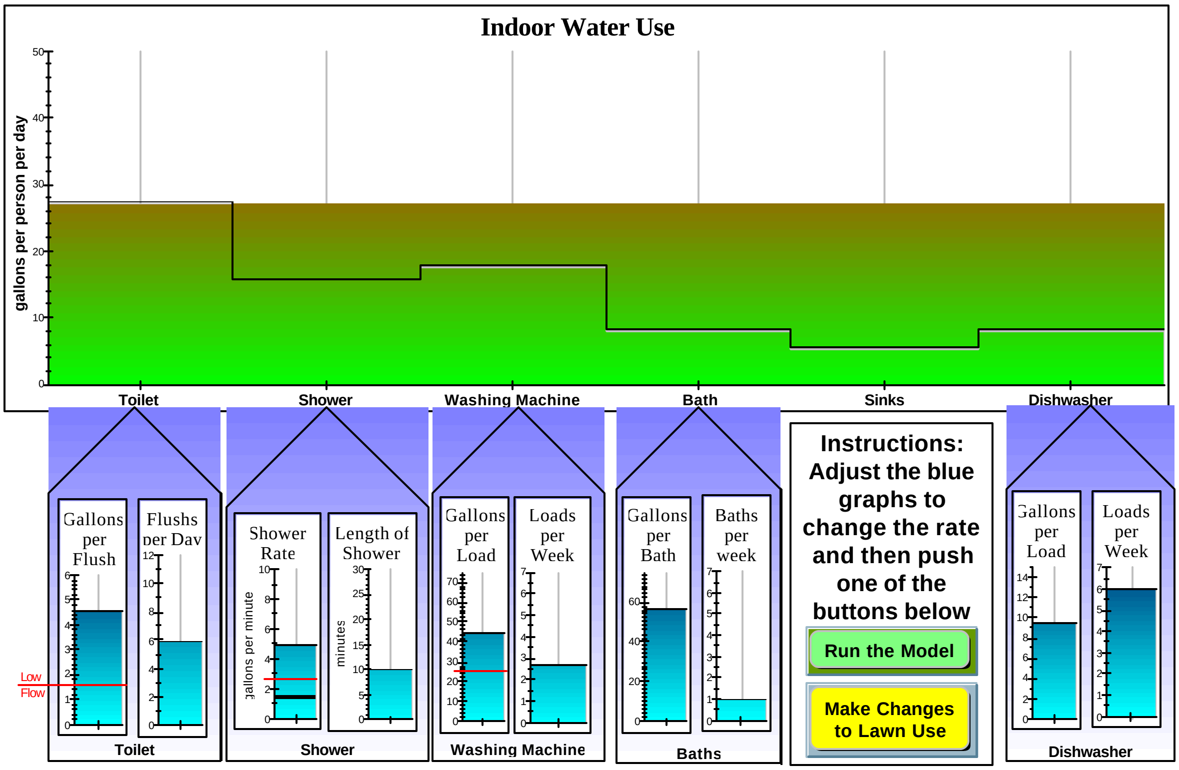

Figure 7.3. Indoor per capita use is defined in terms of a number of specific uses. Each of these uses can be adjusted by adjusting the parameters associated with that use.

with the cumulative annual depletion computed with our model (Figure 7.4). The percent difference at the end of the 30-year period was 7.4%.

The outflow from the basin is the sum of the measured flow at three Rio Grande stations: Rio Grande Floodway at San Acacia, Socorro Main Diversion Channel at San Acacia, and Rio Grande Conveyance Channel at San Acacia. The model simulates the total basin outflow, which is compared with the sum of the measured outflow (Figure 7.5). During the 30-year simulation period, the average difference between the simulated and measured outflows is 7.6%; the maximum difference is 29%.

7.4.2. Scenario Evaluation

One of the strengths of dynamic simulation modeling is in the ability to quantitatively evaluate the consequences of alternative water management strategies. Here we perform a limited analysis to demonstrate the functionality of the model and to provide an example of how dynamic simulation modeling can be employed in such a capacity. Of course, such analysis is best conducted interactively with the model. In efforts to accommodate access to the model, a web-based version of the model is being developed.

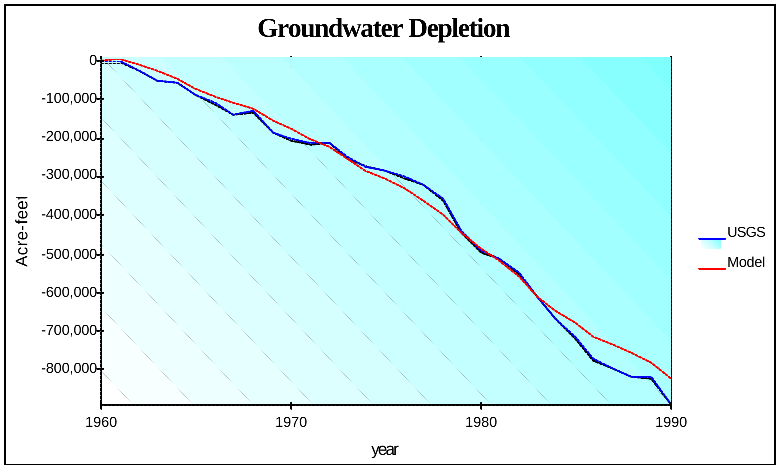

Figure 7.4. Groundwater depletion as computed by the model is compared to the depletion estimated by the USGS for the period 1960-1990.

Four broad conservation measures and their potential impact on future water supply are evaluated. These conservation measures concern population growth, agriculture, municipal water use, and the riparian corridor (i.e., bosque). The period of analysis is a 50-year window from 1990 to 2040. The analysis considers two metrics, 1) cumulative groundwater depletion for the period 1960-2040, and 2) mean annual surface water discharge from the basin, 1990-2040.

These metrics were selected because of their related environmental and societal consequences. Continued groundwater depletions could have several negative impacts on the basin. Increased depletions could lead to ground subsidence, increased depth to groundwater and hence increased pumping costs, degraded water quality by saline waters, enhanced Rio Grande River leakage, and eventually "practical" exhaustion of this resource. Likewise decreases in river flows will adversely affect the basin. Specifically impacted will be the riparian habitat and endangered species that make the Rio Grande their home. Economic impacts could be felt in terms of reduce agricultural productivity, and or by legal actions precipitated by failure to meet Rio Grande Compact delivers to downstream users.

As a baseline, we consider the case of no change in water consumption practices. In this scenario, population growth rates are assumed to follow those experienced in the 1990-2000 time period. It comes as no surprise that this test case leads to an unsustainable water use pattern, that is, a net depletion of groundwater. Over this period of time a cumulative groundwater depletion of 5.11M acre-feet of water is projected (Table 7.5). The average surface water discharge of 0.844M acre-feet is likewise noted to be down from the 1960-1990 average of 0.878M acre-feet. The reduced surface water flow reflects increased leakage from the Rio Grande in response in increased municipal pumping.

Various policies could be adopted that might either increase or decrease the net population growth rate of the MRG basin. The effects of a higher and lower growth rate, than that experienced from 1990-2000, was assessed and the results are given in Table 7.5. Only a sight change in surface water discharge is experienced, while groundwater depletion changes by 12-25% for a 25% change in growth rate. Note that a 25% decrease in the growth rate has a larger effect on groundwater depletions than a 25% growth rate increase because of the non-linear character of the growth function. The noted changes in groundwater depletion results from increasing/decreasing pumping rates while changes in surface flows reflect changes in sewer return flows and/or the difference in pumping induced leakage.

Agricultural demand is likely to change in the next 40 years. Some farmers may choose to sell their land to make way for development or policies could be put in place to encourage growth of low water demand crops. Currently, alfalfa and hay account for roughly 85% of the irrigation in the MRG basin. Results for scenarios involving reduced

Table 7.5. Scenario analysis results for the MRG dynamic simulation model.

Test Case	Mean Surface Water Discharge (million acre-feet)	Total Cumulative Groundwater Depletion (million acre-feet)
No Change	0.844	5.11
25% increase in population growth rate	0.849	5.70
25% decrease in population growth rate	0.838	4.48
10% decrease in population growth rate	0.84	4.82
50% decrease in irrigated acreage	0.943	5.65
25% decrease in irrigated acreage	0.894	5.38
10% decrease in irrigated acreage	0.860	5.21
100% irrigated acreage with low demand crops	0.93	5.30
Low flow appliances	0.836	4.10
50% reduction in lawns	0.838	4.44
50% decrease in bosque acreage	0.91	4.38
10% decrease in bosque acreage	0.857	4.97
100% acreage with 50% Cottonwood	0.86	4.89

irrigated acreage and a shift toward low water use crops are given in Table 7.5. As irrigation water is diverted directly from the Rio Grande, distinct increases in surface water flows are noted with decreased agricultural acreage. Conversely, an increase in groundwater depletion is also experienced due to decreased recharge from farmland irrigation. However, increases in groundwater depletions could be mitigated by diverting the surface water savings to municipal uses. It is also interesting to note that a 50% decrease in irrigated acreage and 100% irrigated acreage with low demand crops yield nearly the same mean surface water discharge. A move toward low water demand crops also has relatively little effect on groundwater depletion.

As population grows, municipal demand for water increases. Policies could be established that mandate use of low flow appliances or reduction of lawns. Effects of these policy options were investigated and results are given in Table 7.5. These steps, individually, registered the greatest positive influence on cumulative groundwater depletions.

The bosque along the Rio Grande River accounts for 29% of the water consumption in the basin. Scenarios were investigated that would reduce the acreage of bosque and/or remove high-demand, non-native species (e.g., Salt Cedar). Results for various combinations are given in Table 7.5. Such actions are seen to both increase surface water flows and decrease groundwater depletions.

None of these single items has achieved sustainable use. However, there are any number of combinations that could. We envision that this model could be used as an analysis tool to explore those possibilities. We also envision that the model could provide an aid to negotiation as various stakeholder groups attempt to work out a plan, amenable to all, toward achieving sustainable use of our share water resources.

7.4.3. Future Plans

The presented model represents the foundation of a water policy analysis tool for the MRG basin. The next steps will involve expanding the model across other water related sectors, thus providing a more inclusive view of the consequences of alternative water management strategies. In particular we will consider how the availability of water impacts economic growth and how the cost of water affects the revenues within the commercial, industrial, service, and agricultural sectors. Water quality and its relation to agriculture, riparian health, water supply, and water demand is also of interest. Closely related is the environmental health of the riparian corridor and the species that make their home in this area. The model may also prove useful to factor in the role of droughts. Finally, efforts will be made to

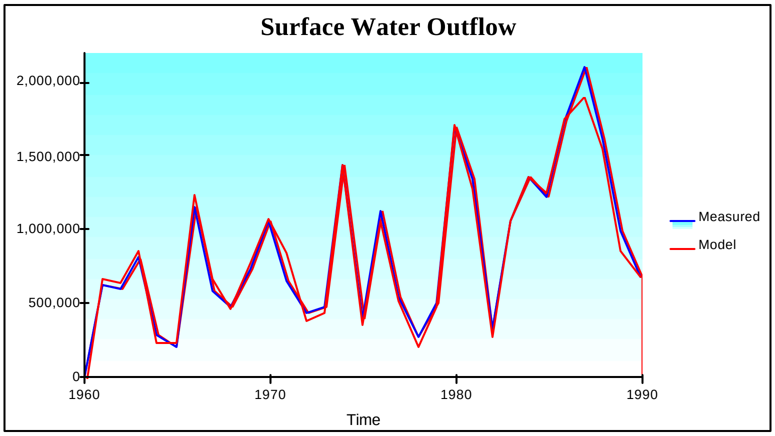

Figure 7.5. The computed surface water outflow from the basin is compared to the measured outflow for the period 1960-1990.

incorporate the recreational, aesthetic, and social/cultural value of MRG Basin resources into the model.

Although the presented simulations have been conducted in a deterministic mode, the modeling framework has been developed to allow stochastic analysis. Specifically, Monte Carlo analysis can be used to assess outcomes for ranges of uncertain input parameters or decision variables. In this way, results will be reported in terms of a distribution of potential cumulative groundwater depletions and surface water discharge.

Finally, we are keenly interested in applying the MRG model within the context of a stakeholder driven water-planning process. Such an opportunity has recently been realized with the MRG Water Assembly, a citizen group established by the New Mexico Interstate Stream Commission to develop a 50-year water sustainability plan for the basin. The Water Assembly has the dubious task of balancing the views and values of irrigators, urban developers and the environmentalists. Agreements have been made to use the MRG model to quantitatively test alternative water conservation strategies and use the model as a vehicle for communicating technical information to the public.

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