Dynamic Simulation Modeling of Groundwater Basins in the Upper Rio Grande Basin, Colorado-New Mexico

Jules Campbell Parrish

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Dynamic Simulation Modeling of Groundwater Basins in the Upper Rio Grande Basin, Colorado-New Mexico

by

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Abstract

The Upper Rio Grande (URG) groundwater model is a compartmental model based on linear reservoir theory and mass conservation. It was developed using Powersim Studio® 2001 and 2003 software to demonstrate dynamic simulation of subsurface flow in the basin.

The URG Basin is an area of approximately 8700 square miles. The model examines the basin from the headwaters of the Rio Grande in Colorado to the river’s point of delivery at Elephant Butte Reservoir in New Mexico. The sub-basins evaluated were the San Luis, Española, Santo Domingo, and Albuquerque-Belen Basins. Although uniformity varies within regions, individual groundwater basins were divided by unconfined and confined aquifers, and lumped parameters were calculated or averaged within these subsystems. The groundwater model evaluates flow between the unconfined and confined aquifers within individual basins as well as flow between basins.

Recharge to the system is through precipitation, agricultural return flows, and subsurface flow from one basin to another. Discharges from the system are evapotranspiration, groundwater pumping, and surface and subsurface discharge. The model was successfully calibrated to match given water budget data.

In general, unconfined or water table aquifers were more sensitive to pumping than confined aquifer reservoirs, with the exception of the Albuquerque-Belen Basin confined aquifer, which was significantly depleted by groundwater withdrawal over
the thirty-year period of the model run. In the base model, the San Luis Basin unconfined aquifer’s volume declined by over 40%, with limited decline in the confined aquifer. The Española Basin unconfined aquifer diminished by 18% over the thirty-year run, while the confined aquifer experienced little effect. The Albuquerque-Belen Basin unconfined aquifer experienced a limited effect, while the confined aquifer volume decreased by 7%.

The model also demonstrates the effects on the URG’s groundwater resources in response to dramatic changes in precipitation or severe sustained drought. Variation in average precipitation values between low and high values affected the Albuquerque-Belen Basin unconfined aquifer volume by 400,000 acre-feet over the thirty-year run period while having no effect on the confined aquifer.

The model also evaluates aquifer response to increases in pumping, specifically in the Albuquerque-Belen Basin over the next thirty years due to increases in population growth. Variation in pumping in the Albuquerque-Belen Basin affected the unconfined aquifer volume by over 2 million acre-feet (maf) over thirty years between the low and high values, and 1 to 3 maf difference in final values overall. The difference in final values for the confined aquifer reservoir volume between the 2000 and 2015 pumping levels was just over 2 maf. Overall, pumping in the confined aquifer over the thirty-year run caused a decline of 7.5 maf.
1.0 Introduction

New Mexico is a land of limited water resources. For this reason, the state must balance the water needs of its residents with the water required to meet interstate compacts and international treaties. To help meet these demands, models must be developed that combine surface water, groundwater and economic systems. The Upper Rio Grande (URG) modeling project was created to evaluate the interactions of these systems.

The groundwater model I developed began as one part of this interdisciplinary project for the URG Basin that was conducted by the departments of Economics, Geography, Earth and Planetary Sciences, and Civil Engineering, and the Water Resources Program at the University of New Mexico. The groundwater model was produced using Powersim Studio® 2001 and 2003 software to demonstrate dynamic simulation of subsurface flow in the Upper Rio Grande Basin. The groundwater sub-basins must be managed as a system, because climatic variations and usage changes within any individual sub-basin can affect the system as whole. Michael Campana, a principal investigator of the project, supervised development of the groundwater model. The groundwater model I have created is designed to be linked directly to the surface water model already in progress by another researcher.

The URG project, funded by US Environmental Protection Agency (EPA) and National Science Foundation (NSF) grants, “coupled physical, biological, and human system models…to provide a quantitative assessment of the consequences of climate change and its impacts on water availability in the Rio Grande Valley north of Elephant Butte Reservoir” (Scuderi et al., 1999).
The URG Basin, as defined in the proposal, is an area of approximately 8700 square miles (Wilkins, 1998). For the purposes of this model, the basin is defined as the area from the headwaters of the Rio Grande in Colorado to the river’s point of
delivery at Elephant Butte Reservoir in New Mexico (Fig. 1). The sub-basins
evaluated by this model include the San Luis, Española, Santo Domingo,
Albuquerque-Belen, and Socorro Basins. The Santo Domingo sub-basin has been
integrated into the Albuquerque-Belen Basin. Elephant Butte was chosen as the end
point of the model because it serves as “the control point for supplying water to
Mexico under our treaty obligations and supplying water to Texas under an interstate
compact” (Scuderi et al., 1999). The Socorro Basin was removed from the final
groundwater model because of the extremely limited hydrogeological data available
for the basin. Instead, the model concludes with groundwater subsurface discharge at
the Albuquerque-Belen Basin boundary.
2.0 Objectives

The groundwater model includes the sub-basins of the entire study area and evaluates flow between the unconfined and confined aquifers within individual basins as well as flow between basins. The model has been used to demonstrate effects on the URG’s groundwater resources in response to dramatic changes in precipitation or severe sustained drought. This paper specifically reports the long-term effects of drought on the Albuquerque-Belen Basin.

Initially, I had hoped the model could represent steady-state conditions within the URG Basin before pumping variables had been introduced into the model. However, because data available for calibration, namely regional water budgets, already included anthropogenic influences, the model could not first be calibrated to steady-state. With pumping data inserted into the model and calibrated to published water budgets by previous researchers, the model does provide a means of evaluating the longevity of the aquifer as a municipal water supply. The model evaluates aquifer response to increases in pumping, specifically in the Albuquerque-Belen Basin, over the next 30 years due to increases in population growth. Pumping conditions were based upon data I collected from government agencies and published reports.

This is a freestanding groundwater model and while the ultimate goal would be to develop the integrated model, this project does not consider the economic components. Thus, it does not evaluate water as a commodity. The model also does not consider all surface system variables. The model evaluates the basin’s future water resources based upon historic pumping data for the region and trends in population growth. The simulation provides a quantitative assessment of the
consequences of climate change and changes in groundwater withdrawal as these variables impact water availability in the Rio Grande Basin north of Elephant Butte Reservoir.
3.0 Principles

Extensive research was conducted to obtain the hydrogeological characteristics of the sub-basins and to utilize flow theories developed by previous workers. Input values for areas with limited data were interpolated from the available geologic data, hydrogeological references, and my training in the Water Resources Program. All data gathered were averaged across large volumes in the subsurface due to the fact this model is based upon a 2-layer system: the unconfined and confined aquifers. The data I collected for these layers include, for example, basin area, thickness, porosity, specific yield, specific retention, storativity, and hydraulic conductivity. The model is a compartmental model that uses linear reservoir theory and a mass balance equation to simulate groundwater flow.

In compartmental models, the groundwater system is represented as a network of interconnected compartments or cells through which water is transferred (Campana et al., 2001). Each stock or reservoir (compartment) in the Powersim® model represents a sub-basin of the hydrogeological system. These reservoirs are differentiated based upon the boundaries of a basin and distinctions between the unconfined and confined aquifers.

The compartmental linear reservoir model assumes the presence of a threshold, below which the discharge from any individual stock or reservoir will be zero. The model simulates flow by assuming that outflow from a groundwater reservoir is proportional to the storage in the reservoir. The equation,

\[ S = K' \times Q \] (1)
describes a conceptual element known as a linear reservoir, where $S =$ storage above a threshold, below which the outflow is zero [$L^3$]; $K' =$ storage delay time of the compartment [$T$]; and $Q =$ volume rate of outflow from the element [$L^3/T$] (Campana et al., 2001). $K'$ can be a function of time. The system is a linear system. A boundary discharge volume is calculated for each cell at each iteration.

Using equation (1), the discharge from a single compartment is

$$\text{VOL}(N) = K' \times \text{BDV}(N) \quad (2)$$

where BDV = Boundary Discharge Volume. Similar to $Q =$ volume rate of outflow from the element [$L^3/T$], the boundary discharge volume is also defined as a volume rate of outflow.

In equation (3), $K'$ is defined as the characteristic length divided by the hydraulic conductivity and has the unit of time. $K'$ is the storage delay time of the reservoir, compartment, or stock of the model; $K$ is the hydraulic conductivity.

$$K' = \frac{\text{Avg} \ (L+W+D) \ of \ basin \ /3} {\ [K]} \quad (3)$$

According to Campana et al. (2001), “If equation (2) is rewritten for iteration $N+1$ and substituted into equation (4), a volume conservation equation for a given compartment or cell:

$$\text{VOL}(N+1) = \text{VOL}(N) + \text{BRV}(N+1) - \text{BDV}(N+1) \quad (4)$$

the result is

$$\text{VOL}(N+1) = \text{VOL}(N) + \text{BRV}(N+1) - \left[\text{VOL}(N+1)/K'\right] \quad (5)$$

which simplifies to

$$\text{VOL}(N+1) = \left[\frac{K'}{K' + 1}\right] \left[\text{VOL}(N) + \text{BRV}(N+1)\right] \quad (6)$$
“At iteration N+1, all quantities on the right-hand side of equation (6) are known, so VOL(N+1) can be calculated. Once this has been accomplished, then BDV(N+1) can be calculated from equation (2).” In equations 4 through 6, BRV = Boundary Recharge Volume.

In lumped parameter models, groundwater systems are treated as a whole, or in this case, individual basin layers are assigned a single value for each parameter. The flow pattern is assumed to be constant. It is clear from Amin and Campana (1996) that lumped parameter modeling is not best for diverse systems. However, when, like the Middle Rio Grande (MRG) Basin, a significant portion of the system lacks detailed hydrologic data, lumped parameter models can be useful.

The subdivisions in the URG model are based upon distinct regions of the physical system, in this case, groundwater basins. Although uniformity varies within regions, individual groundwater basins were divided by unconfined and confined aquifers, and lumped parameters were calculated or averaged within these subsystems. In a discrete-state compartment (DSC) model flow “is governed by a set of recursive equations which represents the physical system as a series of discrete states. The DSC model uses the law of conservation of mass as a constraint in the derivation of the recursive equations” (Campana and Simpson, 1984). The URG model applies conservation of mass to each stock or reservoir in the system.

To the best of my knowledge, linear reservoir theory and compartmental modeling concepts have not been utilized by previous researchers in the form of a dynamic simulation model. It is my intention that the URG groundwater model provides a test case of this application to ascertain its strengths and weaknesses.
4.0 Previous Work

Earlier workers have addressed different issues regarding the basin. The work of Hawley and Haase (1992) and Thorn et al. (1993) compiled data of the hydrogeology and hydrologic conditions of the Albuquerque Basin given the information known at a given point in time. As research continued and continues throughout the basin, the framework of the basin is refined and a greater understanding of the region’s water resources is gained.

Much of the data for the Española Basin, whose primary producing aquifer is the Tesuque aquifer, was gleaned from a study by Glenn Hearne (1980), who developed a mathematical model of the aquifer system. The modeling work of previous researchers was often used as a guide to reasonable values for a variety of hydrogeological variables and reasonable outcomes in the modeling process. For example, the finite-difference model in two dimensions developed by Leonard and Watts (1988) for aquifer simulation of the San Luis Basin in Colorado was a useful source for comparing older style models with those using current codes, such as those done by HRS Consultants using MODFLOW. In 1999, the consulting firm designed a groundwater model for the San Luis Basin using this USGS 3-D finite difference code.

Dozens of reports were used to form a conceptual framework of the basin system and to determine reasonable values or figures to use in this model. Our understanding of water resources continues to be enhanced, with each new model evaluating the work of previous researchers. One of the most current models for the Albuquerque Basin is that of McAda and Barroll (2002), who designed a multi-layer
model of the Santa Fe Group aquifer system near Albuquerque using MODFLOW 2000. This study was particularly helpful in evaluating the true size of the Albuquerque-Belen Basin’s viable aquifer.
5.0 Model Algorithms

5.1 The Upper Rio Grande Model

The URG Basin groundwater model has been developed in the Powersim®
dynamic modeling environment. Water is typically modeled as flowing through one
or more cells or compartments. In this case, each groundwater basin is represented as
a stock or reservoir, with each basin connected to at least one other basin. A series of
mathematical algorithms were formulated to describe flow into and out of the basins
of the system.

Though the model is represented in two-dimensional space, it attempts to
model flow in a three-dimensional network, allowing flow of water from the surface
to the groundwater system; flow between the unconfined and confined aquifers; and
lateral movement from upstream to downstream basins.

Each stock or reservoir in the Powersim® model represents a region of the
hydrogeological system. Regions are differentiated based upon the boundaries of a
basin and distinctions between the confined and unconfined aquifers. The initial
value of the reservoir is comparable to the variable, water volume of the aquifer.

Typical mixing cell models, such as the one by Campana and Simpson (1984),
track the concentration of a tracer through the cells of the model over time using a
mass balance equation. This model does not use a tracer, though it does use a mass-
balance equation:

\[ \text{VOL}(N+1) = \text{VOL}(N) + \text{BRV}(N+1) - \text{BDV}(N+1) \]  

(4)
For each time step (one year) for the multi-basin model, BDV equation is applied to move water through the system. Specifically, the BDV for the upstream groundwater basin becomes a portion of the total inflow for the downstream groundwater basin, such that

\[ \text{BDV} = \frac{\text{Aquifer Volume}}{K'} \]  

(7)

where \( K' \) can be a function of volume or iteration number. The BDV or System Boundary Discharge Volume (SBDV) is the volume of water discharged per unit time by the aquifer given the known hydrogeologic parameters. As described in the principles section of the paper, the model simulates flow by assuming outflow from a groundwater reservoir is proportional to the storage in the reservoir. The model incorporates a minimum threshold volume for the compartment, below which the discharge from the compartment is defined as zero. A boundary discharge volume is calculated at each iteration. Unless such factors as precipitation, groundwater withdrawal, leakage or evapotranspiration are varied with the use of arrays or other media, the only unknown in the system is the BDV or SBDV.

In the groundwater portion of the model, each basin’s confined and unconfined aquifer is represented as a stock. This requires groundwater parameters to be averaged across a broad geographical area and thickness. As in Figure 2, for each groundwater basin, a single value in the model must account for multiple layers of a variety of thicknesses, sediment layers, and lithofacies. In order to develop the model, data from multiple sources were considered before a value was calculated or estimated as the single or final input for a hydrogeological parameter in the model.
For example, in Table 1, several values of unconfined aquifer thickness of the San Luis Basin found by previous researchers are listed.

<table>
<thead>
<tr>
<th>Author</th>
<th>Suggested thickness</th>
</tr>
</thead>
<tbody>
<tr>
<td>Seitz et al. (2001)</td>
<td>Thickness of 50 feet, thought possibly conservative.</td>
</tr>
<tr>
<td>Williams and Hammond (1989)</td>
<td>Thickness less than 100 feet.</td>
</tr>
<tr>
<td>Leonard and Watts (1988)</td>
<td>Thickness is 50 to 130 feet.</td>
</tr>
</tbody>
</table>

Table 1: Thickness comparison of the unconfined aquifer for the San Luis Basin.

The ultimate determination was made by evaluation of the parameters used to quantify a variable, date of the report, and agreement by other researchers.
5.2 System Boundary Discharge Volume

The model is structured such that the System Boundary Discharge Volume (SBDV) bordering the San Luis Basin provides the initial inflow into the system in Colorado. Another portion of the inflow is the System Boundary Recharge Volume (SBRV). The SBRV for the unconfined aquifer is defined as a percentage of the volume of precipitation falling over the basin area annually and has the dimensions of $L^3 T^{-1}$. The volume of the aquifer is the product of the basin area and the thickness. The water volume of the aquifer is the product of the volume of the aquifer and its effective porosity.

As illustrated in Figure 3, the SBDV for the unconfined aquifer (equation 8) is partially defined by the variables of hydraulic conductivity, characteristic length, and $K'$. Characteristic length is based upon the average length, width, and thickness of the aquifer section. The average length and width must be evaluated and modified so as not to be greater than the known surface area. An average of the three numbers defines the characteristic length. In equations 8 and 9, the numeral one represents the unconfined aquifer; the numeral two represents the confined aquifer.

$$\text{SBDV}_1 = \frac{\text{Unconfined Volume}}{K'} \quad (8)$$

Where evapotranspiration is relevant in the system, namely for the unconfined aquifer layers, it is incorporated in the SBDV calculation. From the unconfined aquifer SBDV, a percentage percolates to the confined aquifer. Also, the confined aquifer SBDV provides a percentage of upward flow to the unconfined aquifer, which varies based upon data from individual basin systems. Thus far, these data are subjective, in terms of low, medium, and high—ranging from 5% to 15%
in the model. The SBDV from the previous or upstream basin is combined with the SBRV and upward flow from the confined aquifer to provide the total inflow to each successive unconfined aquifer in the system.

The SBDV for the confined aquifer (equation 9) relates the three variables of hydraulic conductivity of the confining layers, characteristic length, and \( K'_2 \). The latter is the characteristic length of the confined aquifer divided by its hydraulic conductivity.

\[
SBDV_2 = \frac{\text{Confined Volume}}{K'_2} \quad (9)
\]

5.3 Unconfined Aquifer Volume Minimum

The Unconfined Aquifer Volume Minimum, or Unconfined \( V_{\min} \) shown in Figure 4, is the product of the specific retention and the water volume of the aquifer. It is defined as

\[
\text{Unconfined } V_{\min} = (\text{Specific Retention}) \times (\text{Water Volume of the Aquifer}) \quad (10)
\]

This, in effect, is the volume below which the unconfined volume cannot decline.
At any given time, the amount of water discharged from the aquifer (or cell) is less than the amount of water stored in cell. Discharge cannot be greater than Volume Minimum. At Volume Minimum, BDV(N) = 0.

Figure 4. Unconfined \( V_{\text{min}} \). This figure illustrates linkages of the related variables.

5.4 Confined Aquifer Volume Minimum

The Confined Aquifer Volume Minimum or Confined \( V_{\text{min}} \) has been defined in two ways. First, the Confined \( V_{\text{min}} \) is defined by area, thickness, porosity, and storativity of the confining layers:

\[
\text{Confined } V_{\text{min}} = (\text{Volume of the Aquifer} \times n_e) \times (1 - \text{Storativity})
\]  

(11)

Because portions of the model were shutting down a few years into the model run time with the Confined \( V_{\text{min}} \) defined in this way, a second Confined \( V_{\text{min}} \) was written into the model. This modification was required because the San Luis and Española Basins were falling below the Confined \( V_{\text{min}} \) threshold three to five years into the model runs, thus causing the model to discontinue iterative calculations. The second
Confined $V_{\text{min}}$ is defined as the product of volume and specific retention (equation 12), allowing the confined aquifer to mimic an unconfined aquifer. It is defined as

$$\text{Second Confined } V_{\text{min}} = \text{Area} \times \text{Thickness} \times \text{Specific Retention} \quad (12)$$

The equation for the second Confined $V_{\text{min}}$ (Fig. 5) does not include porosity because doing so would allow the confined aquifer volume to be diminished to unreasonably low levels. As written, the second Confined $V_{\text{min}}$ allows the confined aquifer volume to be depleted by an additional one- to two-thirds of the capacity established by the first Confined $V_{\text{min}}$.

Figure 5. Confined $V_{\text{min}}$ and second Confined $V_{\text{min}}$ connected with associated variables.
5.5 The Interrelationship of the Concepts

The illustration of the model in Figure 6 shows the relationship between the confined volume, SBDV, and outflow. In the confined aquifer, the system revolves around a confined volume reservoir. The SBDV for each basin is then redefined at the outflow of each aquifer (or reservoir in the model) to become the SBRV transmitted to the next basin. Inflow in the confined aquifer is based upon leakage from the unconfined aquifer and the subsurface SBRV from the upstream basin.

Outflow from the unconfined volume is an equation based on the unconfined $V_{\text{min}}$, the unconfined aquifer volume or stock, pumping, and the SBDV for the unconfined aquifer.

![Figure 6. Interrelationship of the concepts. Model example showing linkages of inflow, outflow, pumping, confined volume stock, and SBDV (#3 in the schematic is for this example and is not a section of the actual model).](image)

Pumping is linked to outflow and is based upon known data from the study areas or projections provided by technical reports, or a combination of the two. Pumping is based on water rights at the present time and does not allow for pumping
to increase in the base model because the Rio Grande is already over-appropriated.

Pumping was varied in sensitivity runs.
6.0 Model Development and Data Discussion

Given these variables and calculations, the model allows communication between the unconfined and confined aquifers in any individual basin; it also allows for subsurface flow from one unconfined aquifer to the next, and from one confined aquifer to the next. The model assumes that subsurface flow mimics topography, and that water flows in the subsurface from areas of higher elevation to areas of lower elevation.

Before discussing data for individual sub-basins, it is important to pause at this point and review the data used in the model and its sources. For example, sub-basin area is based on published reports, and precipitation is the average precipitation over the last 30 to 40 years. The porosity of a given aquifer, if not provided by geological reports, is estimated based on sediment and rock layer descriptions and average porosity values from hydrogeologic textbooks (e.g., Fetter, 2001; Domenico and Schwartz, 1998). Based on published reports and geologic cross-sections, the thicknesses of the confined and unconfined aquifers vary greatly across the study area; an average thickness was calculated for the lumped parameter approach.

The Powersim® model has been developed such that the model can be improved as better data become available. Climatic changes and water use changes can be reflected in the model. Improvements can be made in understanding the exchanges between the confined and unconfined aquifers, as well as basin discharges to downstream systems. Due to the extreme variation of hydrogeologic data across areas and depths of the study area, parameters and values used in the model were either established from previous studies of the area or from current data available...
from government agencies. Where necessary, data were applied or averaged over significant surface areas and depths in the subsurface.

Lower porosities assigned to the confined aquifers are consistent with data gathered in the study area and take into account that deeper sediments have been compacted by overburden pressure. Volumetric flow between reservoirs or stocks in the model is intended to mimic subsurface flow and relative life spans of the aquifers.

I have defined flow systems between the unconfined and confined aquifers and the groundwater basins. This required an initial set of specifications based on groundwater budgets for the individual basins. Especially important were the inputs for the “upstream” basin, the San Luis Basin in Colorado. This basin has been thoroughly examined by previous researchers, and the data are considered to be highly accurate. After all data were gathered for the model to the most accurate level obtainable given the constraints, the model was calibrated by adjusting hydraulic conductivity values so that the inputs and outputs of the basins closely resembled groundwater budgets determined by researchers.

Due to the complexity of sources and variables in the model, I have limited the following discussion to those requiring some explanation of their derivation. Actual values for variables, equations and definitions not discussed in the following section can be found in the appendices.
7.0 San Luis Basin

The headwaters of the Rio Grande Basin begin in the San Luis Basin, also known as the San Luis Valley (SLV) in Colorado (Fig. 7). Wilkins (1986) defined the surface area of the San Luis Basin as 3640 square miles. Schenk et al. (1999) reported basin precipitation averages of 6-10 inches per year. The model was run with an average precipitation of 0.67 ft per year based on the work of Leonard and Watts (1988).

![Figure 7. The San Luis Basin (Image source: CDWR and CWCB, 1998).](image)

7.1 San Luis Basin Unconfined Aquifer

The work of Leonard and Watts (1988) provided data for the estimate of 7% of the annual precipitation applied to the SBRV in the model. SBDV from the upstream basin aquifer includes total alluvial underflow of 10,000 acre-feet per year (AFY) as part of the estimation of groundwater inflow from the San Juan Mountains.
(Harmon, 2000a). Together, the previous basin’s SBDV and the SBRV from precipitation provide the total inflow to the SLV unconfined aquifer.

Both Kernodle (1992) and Hearne (1986) cited a specific yield of 0.20 in their studies of the San Luis Basin. A porosity of 0.25 was used based on a sand and gravel description of the unconfined aquifer from Schenk et al. (1999). The specific retention was estimated to be 0.05, derived by subtracting the specific yield from the porosity. The water volume of the aquifer is considered to be the amount of water in the basin’s subsurface. It is defined as the product of the porosity and the volume of the aquifer.

7.1.1 Thickness of the Unconfined Aquifer

For the thickness of the San Luis Basin Unconfined Aquifer, I used an estimate of 50 feet basinwide. Other researchers reported:

<table>
<thead>
<tr>
<th>Study</th>
<th>Thickness</th>
</tr>
</thead>
<tbody>
<tr>
<td>Seitz et al. (2001)</td>
<td>Thickness of 50 feet, thought possibly conservative.</td>
</tr>
<tr>
<td>Williams and Hammond (1989)</td>
<td>Thickness less than 100 feet.</td>
</tr>
<tr>
<td>Kernodle (1992)</td>
<td>Saturated thickness of 100 feet.</td>
</tr>
</tbody>
</table>

Table 2: Estimated thicknesses of the San Luis Basin unconfined aquifer.

7.1.2 Discharge

The Closed Basin Project (CBP) is a water salvage project to pump water “that otherwise would be lost to nonbeneficial ET in high water table zones” (Harmon, 2000b, p. 14). CBP water is pumped solely from the unconfined aquifer in the amount of 40,968 AFY and then transported to the Rio Grande in order to meet
Colorado's Rio Grande Compact obligations (Harmon, 2000b). Due to the thinness of the unconfined aquifer (approximately 50 feet thick), all other pumping in the basin model has been assigned to the confined aquifer.

Leonard and Watts (1988) estimated evapotranspiration of the SLV unconfined aquifer as 124,400 AFY. Harmon (2000c) detailed how previous researchers have evaluated evapotranspiration (ET) in the San Luis Basin. This report demonstrates that ET is highly variable across the basin due to vegetative cover and elevation differences. The figure used in this model could overestimate or underestimate ET by as much as 50%, but due to the lumped parameter nature of the model and inability to break out variations in ET in the basin area, Leonard and Watts’ estimate will be considered reasonable at the present time, though it could be varied as better data become available.

7.1.3 SLV Upward Flow from the Confined Aquifer to the Unconfined Aquifer

Upward flow from the confined aquifer is equal to a percentage of the SBDV 2, which is the system boundary discharge volume of the confined aquifer. Leonard and Watts (1988) describe the San Luis Basin as a "leaky confined aquifer," depicting subsurface vertical flow to be from the confined toward the unconfined aquifer. Additional data are needed to accurately define this variable; however, in this model the confined aquifer provides significant upward flow to the unconfined aquifer—almost 5900 AFY in the base model.
7.2 SLV Confined Aquifer

A porosity of 0.15 was used in the confined aquifer based on layer descriptions by Hearne (1986). Wilkins (1998) models 3200 feet of saturated thickness, while Kernodle (1992) simulates 3200 feet of basin fill. Schenk et al. (1999) allow for approximately 3000 feet to be modeled as the average thickness of the confined aquifer. The URG Powersim® model is designed to allow for up to 150 feet of thickness to be modeled in the unconfined aquifer, leaving 3050 feet of thickness for the confined aquifer, similar to the estimates of Wilkins (1998) and Kernodle (1992).

7.2.1 Hydraulic Conductivity

In Harmon (2000a), hydraulic conductivity (K) was estimated to be 1.5 ft/day based on tests from wells in the upper 800 feet of the 4000+ feet thick Conejos Formation. Harmon believed K values could average from 0.5 to 1.0 ft/day based on the Conejos Formation’s valley inflow from the San Juan Mountains front. Using data from Schenk et al. (1999), I developed a weighted average from their multi-layer model, calculating the arithmetic average as 18.4 ft/d and geometric average as 5.0 ft/d or 1826 ft/year for hydraulic conductivity.

Other reported averages for K include:

<table>
<thead>
<tr>
<th>Source</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>Wilkins (1986)</td>
<td>first 1500 feet of 2.3 to 134 ft/d, and second 1500 feet of 26.7 ft/d.</td>
</tr>
<tr>
<td>Kernodle (1992)</td>
<td>first 1500 feet of 40 ft/day, and second 1500 feet of 30 ft/day.</td>
</tr>
<tr>
<td>Hearne (1980)</td>
<td>geometric average at 29.7 ft/d.</td>
</tr>
</tbody>
</table>

Table 3: Hydraulic conductivity values for the SLV confined aquifer.
7.2.2 System Boundary Recharge and Leakage to the Confined Aquifer

Harmon (2000a) estimated the SBRV into the SLV confined aquifer to be approximately 90,000 AFY when considering total bedrock underflow from the San Juan Mountains. Leakage from the unconfined to the confined aquifer was loosely estimated to be 5% of the SBDV of the unconfined aquifer. In the base model, this amounts to less than 8 AFY. Typically, the confined aquifer in the San Luis Basin is considered to be a leaky aquifer, with flow rising toward the surface.

7.2.3 Confined Aquifer Pumping

<table>
<thead>
<tr>
<th>Pumping Source</th>
<th>Amount (AFY)</th>
<th>Return Flow</th>
<th>Consumptive Use (AFY)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Agriculture</td>
<td>628,000</td>
<td>1 ac-ft/acre/yr</td>
<td>0</td>
</tr>
<tr>
<td>Municipalities</td>
<td>7,477</td>
<td>67%</td>
<td>2467</td>
</tr>
<tr>
<td>Industry</td>
<td>24,070</td>
<td>Not Known</td>
<td>24,070</td>
</tr>
<tr>
<td>Domestic Use</td>
<td>530</td>
<td>50%</td>
<td>265</td>
</tr>
<tr>
<td>Total from the Confined Aquifer</td>
<td>660,077</td>
<td></td>
<td>26,802</td>
</tr>
<tr>
<td>Total from the Unconfined Aquifer</td>
<td>40,968</td>
<td>None, sent downstream for New Mexico</td>
<td>40,968</td>
</tr>
</tbody>
</table>

Table 4: San Luis Basin pumping data.

Confined aquifer pumping numbers were based on data from Harmon (2000b), which were used to evaluate pumping source, amount, and potential for return flow vs. consumptive use as follows:

1) Agriculture pumps groundwater in the amount of 628,000 AFY.

The remainder of irrigation water comes from surface water diversions.

There are approximately 628,000 acres of irrigated acres in the San Luis Basin (Salazar, 2004). Using Upper Rio Grande Water Operations Model’s
(URGWOM) value of 1.0 ac-ft/acre/year of return flow to groundwater on irrigation acres, this would allow for a zero value for consumptive use (Thomas et al., 2002).

2) Municipalities pump groundwater in the amount of 7,477 AFY. Consumptive use is considered to be 33% or 2467 AFY.

3) Industry pumps groundwater in the amount of 24,070 AFY. No data were available regarding return flow or consumptive use.

4) Domestic wells account for approximately 530 AFY. Consumptive use is considered to be 50% or 265 AFY.

Summing the consumptive use of numbers 1 through 4 gives a net pumping loss of 26,802 AFY, which is drawn from the confined aquifer in the basin model. This decision was made taking into account the thickness of the confined aquifer relative to the unconfined aquifer, and stipulating that all of the Closed Basin Project water comes from the unconfined aquifer, which Colorado does to limit losses through evapotranspiration.

The pumping effect on the San Luis unconfined volume is significant (Fig. 8), diminishing the reservoir by nearly half over the thirty-year time run. At the same time, the overall drawdown of the SLV confined volume is far less significant. It would appear to be depleted by 1 million acre-feet over the thirty-year run, with substantial resources still available.
Figure 8: Effect of pumping on the unconfined and confined aquifers in the San Luis Basin.
8.0 Española Basin

Wilkins (1998) described the basin area (Fig. 9) as 1410 square miles and documented annual precipitation as 10-16 inches per year. The model uses 0.83 feet or 10 inches per year as the average precipitation. Thickness of the unconfined aquifer is modeled as 300 feet, while thickness of the confined aquifer is 3000 feet (Hearne, 1980). SBRV was set at 7% of precipitation annually falling over the study area based on data acquired for the San Luis Basin and was considered reasonable to apply to this basin. Inflow to the unconfined aquifer was calculated as roughly 17,600 AFY.

Figure 9. The Española Basin (Image source: Grauch, 2003b).
8.1 Española Basin Unconfined Aquifer

8.1.1 Porosity and Hydraulic Conductivity

A porosity of 0.20 was based on the description of subsurface layers (anisotropic, interbedded layers of poorly sorted gravel, sand, silt and clay with some intercalated volcanic ash beds) provided by Hearne (1980).

While the model uses 0.6 ft/day or 219 ft/yr for the hydraulic conductivity of the unconfined aquifer, other researchers reported:

<p>| | |</p>
<table>
<thead>
<tr>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Kernodle (1992)</td>
<td>1.0 ft/day, citing Hearne (1986) study.</td>
</tr>
<tr>
<td>Hearne (1980)</td>
<td>0.5 to 2.0 ft/day being the lower and upper limits of the plausible range of hydraulic conductivity (parallel to beds) in units of ft/day.</td>
</tr>
<tr>
<td>Wilkins (1986)</td>
<td>0.5 to 1.0 ft/day of the upper 2000 feet of the Tesuque Formation of the Santa Fe Group.</td>
</tr>
</tbody>
</table>

Table 5: Hydraulic conductivity of the Española Basin.

8.1.2 Pumping from the Unconfined Aquifer

Wilkins (1986) indicated that in 1977, 7470 AFY of groundwater was used for municipal and domestic purposes. Approximately 750 acres were irrigated using groundwater. At 3 acre-feet/acre, this totals 2250 AFY of groundwater for agriculture. Total groundwater pumping was thus 9720 AFY. In projecting groundwater pumping from the Española Basin for 2030, Kernodle (1992) considered that approximately 34.05 cfs would be withdrawn from aquifer storage. This is equivalent to 24,654 AFY.

Because these numbers span approximately 25 years before and 25 years after model development, a starting number for calibration purposes was the midpoint between the 1977 data and the 2030 projected value, or 17,187 AFY. This figure was
initially believed reasonable because the model was in development at the approximate midpoint between these two years. In Kernodle's (1992) report, 30% of the future estimated drawdown was expected from the unconfined aquifer (or 5156 AFY) and 70% from the confined aquifer. The total basin pumping was divided in this way to reflect the best data available at the time.

Additional data from Santa Fe were added to the model due to the potential for underestimating groundwater pumping from this basin. Pumping capacity of the Buckman Direct Diversion Well Field is 8730 AFY (Ransom, 2004). This amount was added to pumping from the unconfined aquifer, for a total pumping from the unconfined aquifer of 13,886 AFY.

8.1.3 Leakage from the Santa Fe River and Groundwater Discharge

Leakage from the Santa Fe River was derived using data from Wilkins (1986), who estimated leakage from the Santa Fe River to the Tesuque aquifer in the Española Basin as 24 cfs. This number is equivalent to 17,400 AFY.

Hearne (1980) described the Santa Fe River as a losing stream upstream in the basin, but a gaining stream in the downstream reaches. The report estimates the net recharge to the Tesuque aquifer, which encompasses the Española Basin, to be 2.86 cfs or 2070 AFY. He determined the net recharge to the groundwater system from the Santa Cruz River as 2.61 cfs or 1890 AFY, while the recharge to the groundwater system from the Pojoaque River and its tributaries was reported as negligible (Hearne, 1980).
Because of the extreme variation between the values in research by Wilkins (1986) and Hearne (1980), I split the difference between the two reports and used a value of approximately 10,670 AFY for recharge to the Tesuque aquifer from the rivers and tributaries of the Española Basin. Indeed, there are multiple sources of recharge to the groundwater system. However, because this model focuses on the flow within the groundwater system, these inputs are not complete and are not intended to be comprehensive.

The Tesuque aquifer discharge to the Rio Grande was approximately 22 cfs (Hearne, 1980) or 15,930 AFY. This value is used to define ‘Discharge to the Rio Grande’ from the unconfined aquifer.

8.1.4 Evapotranspiration from the Unconfined Aquifer

Although no specific data were available for evapotranspiration (ET) from the unconfined aquifer, a number was derived based on the known ET for the San Luis and Albuquerque-Belen Basin. An average volume of ET in AFY was derived per square mile of basin. This value was then applied to the area of the Española Basin, totaling 38,845 AFY.

8.2 Española Basin Confined Aquifer

8.2.1 Hydraulic Conductivity

Hydraulic conductivity began at 493 ft/yr, or 1.4 ft/day, in initial model development. This value was based on a range of 0.5 to 2.0 ft/day reported by Hearne (1980) as the lower and upper limits of the plausible range of hydraulic
conductivity (parallel to beds) in units of ft/day. These data were based primarily on the upper 2000 feet of aquifer. Hydraulic conductivity was adjusted to address issues of compaction.

8.2.2 Confined Aquifer Pumping

As previously mentioned, Kernodle's 1992 study estimated that 70% of future drawdown, or 12,031 AFY, would be from the confined aquifer. This amount was initially assigned to pumping from the confined aquifer.

As with the unconfined aquifer, additional data from the City of Santa Fe were added to the model due to the potential for underestimating groundwater pumping from the Española Basin. Total capacity of emergency drought wells in the Buckman Field is 5805 AFY (Ransom, 2004). These are deep wells, approximately 2000 feet in depth. This figure was added to the above projection for pumping from the confined aquifer for a total pumping figure of 17,836 AFY.

Because the confined aquifer reservoir was not having a demonstrable response to pumping over the 30-year model run period and knowing that emergency drought wells were required due to municipal supply shortages, I concluded this figure was still a low projection. For this reason, I increased confined aquifer pumping by an additional 70,000 AFY of confined aquifer pumping for a total of 87,836 AFY. The additional 70,000 AFY of pumping accounts for private water rights in the basin, allowing for over 20,000 domestic 72-12-1 wells (the New Mexico code for private domestic wells).
As with the San Luis Basin, Figure 10 demonstrates that pumping from the 300 feet thick Española Basin unconfined aquifer has a greater effect over the thirty-year time run of the model than pumping from the 3000 feet thick confined aquifer.
9.0 Albuquerque-Belen Aquifer

Kernodle (1992) lists specific yields ranging from 0.10 to 0.20 for this basin, with 0.15 being the average. This is consistent with Fetter's (2001) specific yield estimates for medium to fine sand. Given a porosity of 0.25, I calculated a specific retention of 0.10.

Figure 11. The Albuquerque-Belen Basin (Image source: USGS, 2001).

9.1 Basin Area

Thorn et al. (1993) described the area of the basin from Cochiti to San Acacia gauges as 3060 square miles. Wilkins (1998) defined the area of the Albuquerque-Belen and Santo Domingo Basins as 3150 square miles. McAda and Barroll (2002) demonstrated through multiple layer modeling that approximately 30% of the spatial area of the Albuquerque-Belen groundwater basin is a viable aquifer, as can be seen
by hydraulic conductivity values for several layers of their model. This report also
states that little is known about the water quality and quantity in much of the basin.
For these reasons, using 30% of the known basin area gives a more reasonable value
for aquifer volume than using the surface area of the entire basin.

9.2   Albuquerque-Belen Unconfined Aquifer

9.2.1   Hydraulic Conductivity and Thickness of the Unconfined Aquifer

For hydraulic conductivity, the model uses 182.5 ft/yr. Mathematical estimates
were made from weighted averages of thicknesses and hydraulic conductivities
based on data from Hawley and Haase (1992) and McAda and Barroll (2002).
According to McAda and Barroll (2002), estimates for hydraulic conductivity range
from 0.5 ft/day to 150 ft/day and vary greatly across the basin. Highest hydraulic
conductivity values are found in the Albuquerque area.

Thickness of the unconfined aquifer is described by Bartolino and Cole (2002,
p.47) as about 2000 feet, stating that "...only about the upper 2,000 feet of the aquifer
is used for groundwater withdrawal...Though the aquifer is under confined conditions
locally, it is considered to be an unconfined aquifer as a whole." For the purposes of
this model, the upper part of the aquifer system is treated as unconfined and the lower
part as confined. The 2000 feet of thickness is split evenly between the unconfined
and confined aquifers due to issues of compaction at depth and heterogeneity of the
aquifer due to faulting.
Initially, the Albuquerque-Belen aquifer was represented strictly according to the volume of the Santa Fe Group, the primary aquifer of the basin, with an average thickness of 2000 feet for the unconfined aquifer and 2900 feet for the confined aquifer. At this stage of the model, the charts for the unconfined and confined aquifers appeared similar to the final charts with the revised thicknesses, with the majority of reduction in aquifer volume being from the confined aquifer. Reducing the water volume of the entire aquifer by only using the viable thickness reported by Bartolino and Cole (2002) and ascertaining the feasible supply area from the work of McAda and Barroll (2002) give a more reasonable evaluation of the aquifer system.

9.2.2 Unconfined Aquifer Pumping

The Water Administration Technical Engineering Resource System (W.A.T.E.R.S.) Project is being constructed to store abstracts and preserve images of all water rights files in the custody of the State Engineer of New Mexico (DeSimone, 2002). In order to estimate unconfined aquifer pumping for the Albuquerque-Belen Basin, GIS data were obtained from the OSE-W.A.T.E.R.S. database. Reaches of the Middle Rio Grande Basin corresponding to Ann Demint's surface water model were overlain with the state's permitted well database. Well data were then extracted. Due to error and duplication within the state's database, spreadsheets were reviewed by Jess Ward (Ward, 2004) of the OSE. The pumping numbers for the Albuquerque-Belen Basin were the final summation based on Mr. Ward's corrections to the data files. Basin pumping totaled 445,318 AFY, 50% (222,659 AFY) of which was assigned to the unconfined aquifer.
9.2.3 Leakage from the Unconfined Aquifer and Evapotranspiration

Leakage from the unconfined to the confined aquifer was set at 15% of the Albuquerque-Belen SBDV for the unconfined aquifer. This translated to 11,940 AFY and is considerate of the fact that the Rio Grande is a losing stream through much of its reach in the Albuquerque Basin. Riparian evapotranspiration from the unconfined aquifer was input as 84,000 AFY according to a recent study by McAda and Barroll (2002).

9.2.4 SBRV for the Unconfined Aquifer

SBRV for the unconfined aquifer (precipitation over the basin area) was defined using the value of 7% of annual precipitation to percolate to the unconfined reservoir, based on the previously mentioned study in San Luis Basin. The actual figure likely varies between 5 and 10% when evaluating mountain-front recharge and tributary recharge separately as well as together. The weighted mean annual precipitation is 9.4 inches (Thorn et al., 1993).

9.2.5 Leakage from the Rio Grande

URGWOM data demonstrate average daily leakage from the Rio Grande to be 13.2 cfs for the Cochiti to San Felipe reach (based on gauges), 408.75 cfs from San Felipe to Albuquerque gauge at Central Bridge, and 324.50 cfs from the Albuquerque gauge to the Rio Grande Floodway gauge near Bernardo. Riparian leakage calculates to 9560 AFY, 295,960 AFY, and 234,960 AFY for these reaches, respectively, totaling 540,480 AFY for the Albuquerque-Belen groundwater basin. Of this total,
54% returns to the river through drains, and 46%, or 248,620 AFY, is lost to the groundwater system (Thomas et al., 2002).

9.2.6 Canal Seepage Loss to the Water Table Aquifer

Canal seepage loss to water table aquifer values are also from URGWOM’s model. The value for seepage loss comes from a rate of 192 cfs for “daily seepage loss to water table aquifer” for the Cochiti to San Acacia Reach of the Rio Grande for 8 months out of the year, from March 1 to October 31 (Thomas et al., 2002). The value used in the groundwater model was 92,680 AFY.

9.3 Albuquerque-Belen Confined Aquifer

9.3.1 Hydraulic Conductivity

Hydraulic conductivity for the confined aquifer was set at 90 ft/yr. In order to calculate hydraulic conductivity, weighted averages were used given data from McAda and Barroll (2002), Bartolino and Cole (2002), and Hawley and Haase (1992). For the confined aquifer, weighted averages were based on the relative thicknesses of the Upper, Middle and Lower Santa Fe Formations across the region, and known estimates of their respective hydraulic conductivities.
9.3.2 Confined Aquifer Pumping

Confined aquifer thickness was set at 1000 feet, splitting the total thickness of the viable aquifer between the confined and unconfined layers. Bartolino and Cole (2002) state the aquifer is considered unconfined as a whole, though it does act as a confined aquifer locally and only about the upper 2000 feet of aquifer is used for groundwater withdrawal. Confined aquifer pumping is 222,659 AFY, the same as the unconfined aquifer.

Though the unconfined and confined aquifers have equal thicknesses and pumping levels, the model demonstrates in Figure 12 a dramatic effect on the confined aquifer volume, declining by nearly six million acre-feet. Surprisingly, the unconfined aquifer volume experiences little change.

![Figure 12. Effects of pumping on unconfined and confined aquifers of the Albuquerque-Belen Basin in the base model.](image)
9.3.3 Canal Seepage

The model’s confined aquifer seepage value comes from URGWOM’s rate of 48 cfs for “daily seepage loss to deep aquifer” for the Cochiti to San Acacia Reach of the Rio Grande for 8 months of the year, or March 1 to October 31 (Thomas et al., 2002). URGWOM’s seepage rate relied upon an earlier study by the Bureau of Reclamation (1997). Though in reality this recharge would pass through the unconfined to the confined aquifer, I have modeled it as direct recharge to the confined aquifer based on the USBR study. Canal seepage loss to the deep aquifer was input as 23,170 AFY in the URG model.
10.0 Calibration

10.1 San Luis Basin

The Unconfined Aquifer SBDV was calibrated to match the Rio Grande Decision Support System (RGDSS) groundwater outflow data by Harmon (2000a), which provided estimates of approximately 151 AFY of outflow through the unconfined aquifer and 113,707 AFY of outflow through the confined aquifer. Calibration was achieved by adjusting the value of hydraulic conductivity. The hydraulic conductivity value used to calibrate the model was 45.7 ft/day or 16,700 ft/yr, which is well within the estimated values proposed by other researchers. Other reports offer K values (see Table 6).

<table>
<thead>
<tr>
<th>Author</th>
<th>Hydraulic Conductivity in ft/day</th>
</tr>
</thead>
<tbody>
<tr>
<td>Schenk et al. (1999)</td>
<td>19.3-71.0</td>
</tr>
<tr>
<td>Kernodle (1992)</td>
<td>22-56</td>
</tr>
<tr>
<td>Wilkins (1986)</td>
<td>10-206</td>
</tr>
</tbody>
</table>

Table 6: Hydraulic conductivity values for the San Luis Basin unconfined aquifer.

A hydraulic conductivity value of 0.84 ft/day or 305 ft/yr was applied to the confined aquifer and is also within the estimated values provided by other researchers. The hydraulic conductivity values for the confined aquifer ranged from a low of 0.5 ft/day by Schenk et al. (1999) to a high 30 ft/day from Kernodle (1992).

The data used for calibration provided by Harmon’s study (2000a) are shown in Table 7. The unconfined aquifer outflow of 151 AFY was matched exactly, while the 113,707 AFY outflow from the confined aquifer was closely matched at 117,796 AFY.


<table>
<thead>
<tr>
<th>Data Provided (AFY)</th>
<th>Hydraulic Conductivity Value Required (ft/day)</th>
<th>Model Flow (AFY) Match was</th>
</tr>
</thead>
<tbody>
<tr>
<td>151 AFY for Unconfined Aquifer</td>
<td>45.7</td>
<td>151</td>
</tr>
<tr>
<td>113,707 AFY for Confined Aquifer</td>
<td>0.8</td>
<td>117,796</td>
</tr>
</tbody>
</table>

Table 7: San Luis Basin calibration (Data source was Harmon, 2000a).

10.2 Española Basin

Next, the model was calibrated to meet estimates of SBDV hypothesized by McAda and Barroll (2002) and Thorn et al. (1993) for the Española Basin. These estimates for subsurface basin flow to the Albuquerque-Belen Basin confined aquifer, otherwise thought of as the SBDV from the Española Basin, ranged from 12,600 AFY to 19,600 AFY for the confined aquifer (McAda and Barroll, 2002) to 49,400 AFY for the entire aquifer (Thorn et al., 1993).

A hydraulic conductivity value of 0.6 ft/day, or 219 ft/yr, was used for the unconfined aquifer. For the confined aquifer a value of 0.35 ft/day, or 128 ft/year, was the final value used in the model after calibration. Previous researchers reported hydraulic conductivity averages of 0.5 to 2.0 ft/day (Hearne, 1980). Hearne’s study (1980) reported his own findings as well as the work of previous researchers, such as Cushman (1965) and Koopman (1975), to support this range of values.

The data provided for model calibration do not give exact figures for subsurface discharge from the Española Basin to the Albuquerque-Belen Basin, as these are often estimates based on groundwater budgets. However, given the data provided in Table 8, the model was calibrated to a reasonable match.
Data Provided (AFY) | Hydraulic Conductivity Value Required (ft/day) | Model Flow (AFY) Match was
---|---|---
Unconfined Aquifer (data was non-specific) | 0.6 | 7477
12,600 to 19,600 for the Confined Aquifer or 49,400 for both aquifers | 0.35 | 31,239

Table 8: Española Basin calibration (Data source was McAda and Barroll, 2002 and Thorn et al., 1993).

10.3 Albuquerque-Belen Basin

A study by Thorn et al. (1993) estimated subsurface discharge from the Albuquerque Basin to the Socorro Basin to be approximately 15,000 AFY, while a study by McAda and Barroll (2002) shows the reversal of subsurface flow gradients such that the discharge to the Socorro Basin is zero. The model could not approach this value without setting the hydraulic conductivity value to zero. However, Anderholm (1987) suggested the Socorro Basin received approximately 100,000 AFY of subsurface inflow, which was a reasonable figure for the model to mimic.

Given the accommodations already made to the viable size of the Albuquerque-Belen aquifer used in the reservoir or stock calculations in the model, I chose to approach Anderholm’s (1987) estimates of subsurface discharge given average hydraulic conductivity values reported across the basin. The final hydraulic conductivity value for the unconfined aquifer was 182.5 ft/yr or 0.5 ft/day. The final hydraulic conductivity value for the confined aquifer was 90 ft/year or 0.25 ft/day. As can be seen in Table 9 below, the model was able to provide a reasonable match to Anderholm’s estimated figure for subsurface discharge to the Socorro Basin.
<table>
<thead>
<tr>
<th>Data Provided (AFY)</th>
<th>Hydraulic Conductivity Value Required (ft/day)</th>
<th>Model Flow (AFY) Match was</th>
</tr>
</thead>
<tbody>
<tr>
<td>Unconfined Aquifer  (Both aquifers, collectively total 100,000 AFY)</td>
<td>0.5</td>
<td>79,749</td>
</tr>
<tr>
<td>Confined Aquifer</td>
<td>0.25</td>
<td>25,475</td>
</tr>
</tbody>
</table>

Table 9: Albuquerque-Belen Basin calibration (Anderholm, 1987).
11.0 URG Model Sensitivity Run Analysis

11.1 Precipitation

Sensitivity runs were performed for the model evaluating two input variables: precipitation and pumping. Precipitation was varied across the entire study region to account for climate variation. Within each basin, precipitation was adjusted to be 50% above or 50% below the averages for the last 30 – 40 years. Table 10 below shows values of low, average, and high precipitation values. Low and high are the values for 50% below and 50% above the average, respectively.

<table>
<thead>
<tr>
<th>Precipitation (feet per year)</th>
<th>San Luis Basin</th>
<th>Española Basin</th>
<th>Albuquerque-Belen Basin</th>
</tr>
</thead>
<tbody>
<tr>
<td>Low</td>
<td>0.34</td>
<td>0.42</td>
<td>0.39</td>
</tr>
<tr>
<td>Average</td>
<td>0.67</td>
<td>1.08</td>
<td>0.78</td>
</tr>
<tr>
<td>High</td>
<td>1.01</td>
<td>1.25</td>
<td>1.17</td>
</tr>
</tbody>
</table>

Table 10: Average precipitation in feet per year for each sub-basin. (See Appendices for sources of individual basin data.)

The model demonstrated that variations in precipitation had a greater effect on the unconfined aquifer volume of the Albuquerque-Belen Basin (Fig. 13) than on the confined aquifer volume of the basin (Fig. 14), which was to be expected. The volumes of the aquifers displayed in the model are not considered to be truly representative of the amount of water available across the region and are likely overestimates. However, it is key to look at the representative differences. Variation in precipitation comprises less than 400,000 acre-feet of difference in the unconfined aquifer volume between the low and high values over the thirty-year run period of the model and no noticeable effect on the confined aquifer. The outcomes of low and
average precipitation were coincident with the high precipitation results. The unconfined aquifer volume of the Albuquerque-Belen Basin is the first 1000 feet of the subsurface. The confined aquifer volume of this basin is from a depth of 1000 to 2000 feet in the subsurface. It is reasonable and expected that variations in precipitation would not have a significant effect on the volume of the confined aquifer over this short period of time.

![Figure 13. Precipitation effects on unconfined aquifer volume of the Albuquerque-Belen Basin reflecting low, average and high values from Table 10, pumping remaining constant.](image)
11.2 Pumping

Now, I will turn to the sensitivity analysis of pumping variations within the model and how these figures were derived. Pumping was adjusted only within the Albuquerque-Belen Basin, because it is the most populated basin within the study region. For this analysis, pumping figures were derived from population projections by the Bureau of Business and Economic Research (BBER, 2004) and data from the City of Albuquerque for per capita water use and residential water use.

Data from the Albuquerque Progress Report (APR, 2004) reported that per capita water use was 193 gallons per day (gpd) in 2003, while residential per capita water use was 135 gpd. The use of either of these figures with the population numbers for 2000 listed in Table 15 underestimated current groundwater withdrawal for the entire Albuquerque-Belen Basin by a factor of 3 to 4 times.
Current groundwater withdrawal for the region, based upon the data provided by Jess Ward of the OSE, already exceeded the product of population for the entire basin and per capita municipal water use reported by the APR (2004). For this reason, adjustments in projections were made from the current known groundwater withdrawal and a future estimate of need, based strictly on population increases projected over the next 30 years. These projections can be seen in Table 11 below.

<table>
<thead>
<tr>
<th>County</th>
<th>2000</th>
<th>2015</th>
<th>2030</th>
</tr>
</thead>
<tbody>
<tr>
<td>Bernalillo</td>
<td>558,437</td>
<td>666,114</td>
<td>759,000</td>
</tr>
<tr>
<td>Sandoval</td>
<td>90,775</td>
<td>144,377</td>
<td>197,182</td>
</tr>
<tr>
<td>Valencia</td>
<td>66,699</td>
<td>97,330</td>
<td>128,922</td>
</tr>
<tr>
<td><strong>Total Persons:</strong></td>
<td>715,911</td>
<td>907,821</td>
<td>1,085,104</td>
</tr>
</tbody>
</table>

Table 11: Population projections for the Albuquerque Basin (BBER).

Using 193 gallons per day per capita water use, I evaluated the difference in projected populations between 2000 and 2030 (Table 11) to estimate the increase in water need per 15-year increment. From this estimate, I projected an increase in water usage of 41,000 AFY between 2000 and 2015 and an increase of 79,000 AFY after 2030 as seen in Table 12. These values were added to the current groundwater withdrawal from the unconfined and confined aquifers of 222,659 AFY each. This led to low, average, and high groundwater withdrawals of 222,659 AFY, 264,000 AFY, and 302,000 AFY respectively.

<table>
<thead>
<tr>
<th>Year</th>
<th>2000</th>
<th>2015</th>
<th>2030</th>
</tr>
</thead>
<tbody>
<tr>
<td>Unconfined Aquifer(AFY)</td>
<td>222,659</td>
<td>243,159</td>
<td>262,159</td>
</tr>
<tr>
<td>Confined Aquifer(AFY)</td>
<td>222,659</td>
<td>243,159</td>
<td>262,159</td>
</tr>
<tr>
<td>Increasing Need (AFY) per Year</td>
<td><strong>41,000</strong></td>
<td><strong>79,000</strong></td>
<td></td>
</tr>
</tbody>
</table>

Table 12: Pumping projections for the Albuquerque-Belen Basin.
From these numbers, sensitivity runs were performed on the Albuquerque-Belen Basin unconfined and confined aquifers. Results of these runs are shown in Figures 15 and 16. The increase in pumping affects the unconfined aquifer volume by a difference of over 2 million acre-feet over thirty years, and similarly affects the confined aquifer volume with a difference between low and high values of just over 2 million acre-feet. It is also apparent from Figure 16 that continued pumping from the confined aquifer at present levels will have a dramatic effect on storage. Again, the actual volume shown on the y-axis cannot be considered to be the actual volume available in storage. It is the change in volume which must be recognized as being significant.

![Figure 15. Pumping effects on the unconfined aquifer volume of the Albuquerque-Belen Basin. Pumping at a constant level based on the needs of the run years.](image-url)
Figure 16. Pumping effects on the confined aquifer volume of the Albuquerque-Belen Basin. Pumping at a constant level based on the needs of the run years.
12.0 Summary and Suggestions for Future Work

The completion of the Upper Rio Grande groundwater model is the first step in a multi-disciplinary evaluation of water resources in the URG Basin. The model is a compartmental model using a mass balance equation and linear reservoir theory. The URG model was a test case for application of the compartmental model concept in a dynamic simulation multi-basin model. The outcomes of this model show the opportunity for further development of this application.

The model was successfully calibrated to water budget data provided by other researchers. Shallow unconfined aquifers responded with dramatic drops in reservoir volumes, while deep confined aquifers had more limited reactions over the thirty-year run period. Of great interest was the reverse of this reaction in the Albuquerque-Belen Basin in which the unconfined and confined aquifers were set to equal thickness. Here, the unconfined aquifer had a limited response to the model run, whereas the confined aquifer saw a severe drop in reservoir volume. I am uncertain whether this is due to the low hydraulic conductivity used for the unconfined aquifer after final calibration or if other factors may come into play.

The model demonstrated the basins as an interactive system during the calibration process, where subtle variations in the hydraulic conductivity of one basin significantly affected the amount of discharge to downstream basins. However, calibrating the model to match estimated groundwater budgets for the individual sub-basins does not mean these basins have been modeled accurately. Groundwater basin inflows and outflows are often the final value used to balance a basin’s groundwater
budget. For this reason, the use of these data for calibration can be a weakness for the model, as each of the basin’s budgets outlined by previous researchers was developed individually and did not look at the system as a whole.

The strength of this model in application of the aforementioned theories is that it provides linkages between basins and between disciplines that are not seen in other water models. Because this type of model has not been used before in a dynamic simulation, it is difficult to make comparisons between the results of this model and those of other regional models which relied on other forms of modeling, whether mathematical or spatial, or used other types of software or code for their development. It is difficult to measure whether the model’s evaluative procedures give clear results.

The simulation provides a quantitative assessment of the consequences of climate change and changes in groundwater withdrawal as these variables impact water availability in the Rio Grande Basin north of Elephant Butte Reservoir. The model has been used to demonstrate effects on the URG’s groundwater resources in response to dramatic changes in precipitation or severe sustained drought. Changes in precipitation had a greater effect on the unconfined than confined aquifers. The model also evaluates aquifer response to increases in pumping, specifically in the Albuquerque-Belen Basin, over the next 30 years due to increases in population growth. Increases in pumping in the Albuquerque-Belen Basin further depleted basin reservoirs.

Though there were many successes in the model, there is always room for improvement. For example, one limitation of a lumped parameter model is that of
spatial resolution. This type of model has difficulty accounting for localized heterogeneity. Specifically, a disparity exists between water available at municipal pumping fields in the Española Basin and the URG model results. Given that the unconfined aquifer is modeled as 300 feet thick and the confined aquifer is 3000 feet thick, the dramatic drop in the unconfined versus the confined aquifer volume is not surprising. However, current difficulties in accessing water at deeper levels are not addressed by the model.

Given these issues, a concern lies in how this model or other dynamic simulation models can account for these differences. One possible solution is to further subdivide the basins by subregions, increasing the level of detail in the model. It may also be useful to create greater subdivisions within model layers to account for variations in the subsurface beyond the broad distinction of unconfined and confined layers, of which there are often many in any individual basin. In general, regardless of the number of stocks added by further subdividing regions and model layers, lumped parameter models would have difficulty demonstrating the level of spatial resolution indicative of other groundwater models.

Within a given basin, the URG model is a lumped parameter model. There is a different delay time between the unconfined and confined layers, but no variation within layers. Integration with GIS would circumvent the “lumped parameter” approach allowing for multiple subdivision between model layers and surface regions permitting extremely detailed spatial and volumetric resolution that cannot be paralleled in a lumped parameter model in general, or in Powersim® specifically.
Another area for improvement is that of the surface water-groundwater interchange. The groundwater model simply allows for a percentage of precipitation and fixed inputs from previous researchers to infiltrate the groundwater system. The system model would improve in accuracy if linked to a detailed surface water system such as the one in progress for the Middle Rio Grande Basin or a detailed interface for the basin as a whole, thus allowing for a more realistic surface water-groundwater interchange.

Rather than apply an annual rate of evapotranspiration given water budgets and data of other researchers, the use of an algorithm taking into consideration the surface area, depth to water table and precipitation within a basin, would improve the accuracy of the model. Calculation of evapotranspiration by the use of algorithms for given climate scenarios would be more realistic than the current fixed rate. The algorithm could use either real-time data or an array of actual conditions experienced over a considerable period of record.

To improve upon the accuracy of this model, a more detailed characterization of the Española and Albuquerque-Belen Basins is also needed. Researchers must determine exactly how much water is available. At present, the USGS finds that value difficult to determine for the Albuquerque-Belen Basin (Bartolino and Cole, 2002). Without such data, it is challenging to establish initial water volumes for the stocks of the model with better accuracy. Similarly, better data are needed to estimate flows between the confined and unconfined aquifers within any individual sub-basin.

It is noteworthy that the model is most successful in mimicking current data in the San Luis Basin, which has been researched in the greatest detail of all of the sub-
basins. This result suggests that this type of model could be a useful tool for resource management assuming that available data are accurate and comprehensive.
Bibliography


List of Abbreviations

AFY—acre-feet per year
APR—Albuquerque Progress Report
BDV—Boundary Discharge Volume
BRV—Boundary Recharge Volume
CBP—Closed Basin Project
CDWR—Colorado Division of Water Resources
cfs—cubic feet per second
CWCB—the Colorado Water Conservation Board
DSC—Discrete-state compartment
EPA—U.S. Environmental Protection Agency
ET—evapotranspiration
GIS—Geographic Information System
maf—million acre-feet
MRG—Middle Rio Grande
NSF—National Science Foundation
OSE—New Mexico Office of the State Engineer
RGDSS—Rio Grande Decision Support System
SBDV—System Boundary Discharge Volume
SBRV—System Boundary Recharge Volume
SLV—San Luis Valley
URG—Upper Rio Grande
URGWOM—Upper Rio Grande Water Operations Model
USGS—U.S. Geological Survey
$V_{\text{min}}$—Volume Minimum