# Chapter 7: Computer simulations of the aquifer system

Throughout the course of the Middle Rio Grande Basin Study, a revised ground-water-flow model of the basin has been viewed as the culmination of the study. The revised model incorporates new information gathered since 1995 into a “state-of-the-art” understanding of the hydrogeology of the basin.

The scale of a ground-water-flow model has important effects on how the aquifer system is simulated, as well as the modeling results. An example of such scale-dependent issues is the representation of faults. Though a large number of faults have been mapped in the Middle Rio Grande Basin, only those that affect the basinwide flow system are represented in the McAda and Barroll (2002) model. However, in a ground-water-flow model designed to examine the effects of a leaking underground-storage tank, smaller faults might have an important effect on local ground-water movement and, thus, need to be represented in the model.

## Ground-water-flow model of the basin

Since Reeder, Bjorklund, and Dinwiddie (1967) constructed the first ground-water model of an area in the Middle Rio Grande Basin, there have been a large number of models with different goals (see Box *L*) covering all or parts of the basin. Most of these models cover fairly small areas and have been used in conjunction with site investigations for hazardous-waste cleanup.

In 1995, Kernodle, McAda, and Thorn published the results of a ground-water-flow model covering the entire Middle Rio Grande Basin. This model used new interpretations of the hydrogeology of the basin to project future effects of ground-water withdrawals on the Santa Fe Group aquifer system, with an emphasis on the Albuquerque area. Though the results from this model greatly expanded the understanding of the hydrogeology of the Middle Rio Grande Basin, it also raised questions about certain components of the system that were poorly understood. Kernodle (1997, 1998) updated this model with revisions and corrections.

Tiedeman, Kernodle, and McAda (1998) modified the ground-water-flow model of Kernodle, McAda, and Thorn (1995) to test several hypotheses regarding the hydrogeology of the basin. Though the Tiedeman, Kernodle, and McAda (1998) model used fewer cells and layers, in many respects it was a more complex representation of the hydrogeology of the basin. This model was done with the aid of a newer version of the modeling software that used statistical methods to aid in model calibration (Hill, 1992). In 1999, the NMOSE adopted a modified version of this model to help administer ground-water resources in the basin (Barroll, 2001).

McAda and Barroll (2002) constructed a new ground-water-flow model of the Middle Rio Grande Basin to incorporate the large volume of new hydrogeologic data collected since 1995. This new model consists of nine layers that get increasingly thicker with depth (about 20 to 1,000 feet thick for the upper seven layers and variable thickness for two deeper layers) (fig. 7.1). Each layer is divided into a grid of cells containing 156 rows and 80 columns, and each cell is 3,281 feet (1 kilometer) on a side (fig 7.2). Thus, the model contains 112,320 cells, 50,449 of which are active. The model encompasses the entire thickness of the Santa Fe Group in order to reproduce probable flow paths in the lower portions of the

# L

## Ground-water-flow models and how they are used to study the basin

Thomas E. Reilly[1] and Douglas P. McAda[2]

During the past several decades, computer models for simulating ground-water and surface-water systems have played an increasing role in the evaluation of ground-water development and management alternatives. The use of these models has provided an opportunity for water managers to quantitatively understand how ground water moves and to estimate the effects of human use of the water.

In the most general terms, a model is a simplified representation of the appearance or operation of a real object or system. Ground-water-flow models attempt to reproduce, or simulate, the operation of a real ground-water system with a mathematical counterpart (a mathematical model). Mathematical models may use different methods to simulate ground-water-flow systems (Konikow and Reilly, 1999). One such method is called the finite-difference method (for example, McDonald and Harbaugh, 1988), which is the method used to simulate the ground-water system in the Middle Rio Grande Basin.

In a finite-difference model, a ground-water system, such as the example in figure *L.1*, is represented by a set of rectangular cells (fig. *L.2*). The Darcy equation is used to calculate the flow of water between cells (fig. *L.3*). The interaction of the ground-water system with streams, recharge, and other boundaries of the ground-water system are also represented by equations. The computer model is the collection of all the equations that represent ground-water flow between the cells and across the boundaries. All the equations are solved simultaneously to account for all flow of water through the entire system and for each cell. Thus, the model simply calculates the volume of water flowing both horizontally and vertically between the cells and any changes in the volume of water stored in each cell. If the cells and boundaries represent the actual ground-water system reasonably, then the model is a mathematical description of the water levels and flows in the system.

The underlying philosophy of the simulation approach is that an understanding of the basic laws of physics and an accurate description of the specific system under study will enable an accurate, quantitative understanding of the relations between ground-water flow-system stress (for example, pumpage) and response (for example, water-level decline). This understanding enables forecasts (projections) to be made for any defined set of conditions. Precise forecasts of future behavior of the ground-water system will rarely be possible because of the uncertainties in knowledge of the ground-water system associated with sparse or inaccurate data, errors in the scientists' understanding of the system, and poor definition of future

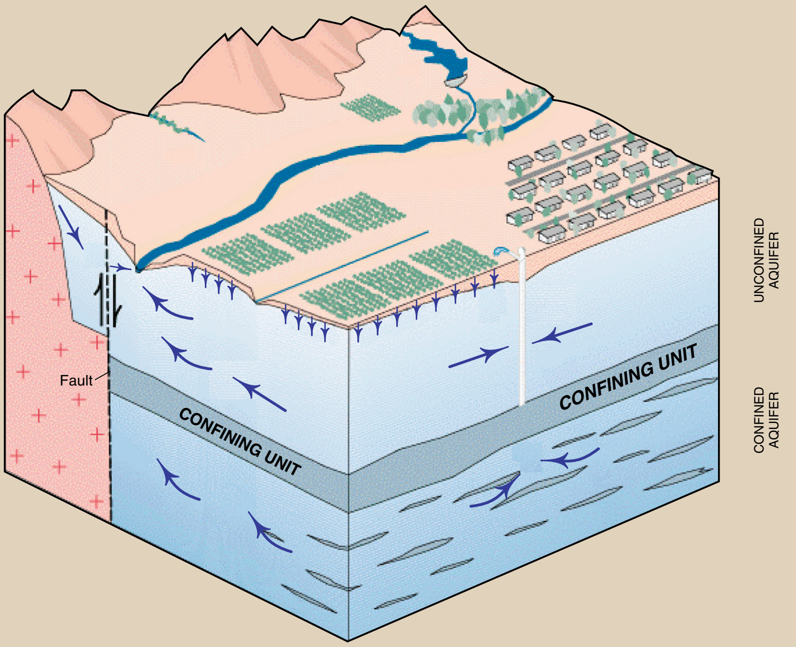

***Figure L.1.****—Block diagram of a part of a hypothetical basin-fill ground-water system. The blue arrows show the direction of ground-water flow. Among the features shown are an unconfined aquifer overlying a confining unit and confined aquifer, a gaining stream, infiltration from irrigated agriculture, and mountain-front recharge.*

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[1] U.S. Geological Survey, Reston, Virginia.

[2] U.S. Geological Survey, Albuquerque, New Mexico.

stresses. Although forecasts of future system behavior based on models are imprecise (even when developed competently and objectively), they represent the best available decision-making information at the time.

Models that accurately represent the ground-water system being evaluated are expected to produce more accurate forecasts than models that fail to represent important aspects of the system. The determination of which aspects of an actual ground-water system should be incorporated into a computer simulation depends, in part, on the objectives of the study for which the model is being developed. The objectives of a study in which a computer simulation is used as an analysis tool influence the size of the modeled area, the depth of concern, the size and shape of the model cells or elements, and the methods used to represent the boundary conditions of the system.

The model created for the ground-water system in the Middle Rio Grande Basin can be used to estimate the consequences of changes in water use on the ground-water system and the water-budget components, such as the exchange of flow between the ground-water system and the Rio Grande. In addition, the model, by virtue of its attempt to mathematically reproduce all the important aspects of the ground-water-flow system, can indicate which components of the system are best known, which are poorly known, and which components are more important than others. This information can then be used to efficiently gather the information that will most improve further understanding of the Middle Rio Grande Basin ground-water system.

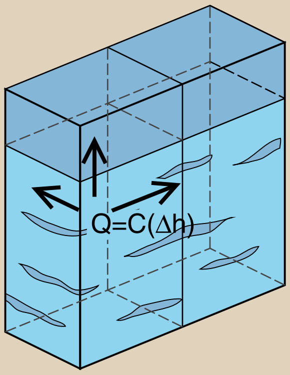


***Figure L.3.****—Subset of the model cells that represent an aquifer, indicating that flow is calculated between adjacent cells. A form of the Darcy equation, which is used to calculate flow between each cell, is shown. In the equation, Δh is the head difference between the cell and adjacent cells, Q is flow, and C is the hydraulic conductance between the centers of the cells. The hydraulic conductance (C) is a model parameter that attempts to represent the water-transmitting properties of the aquifer between cells.*

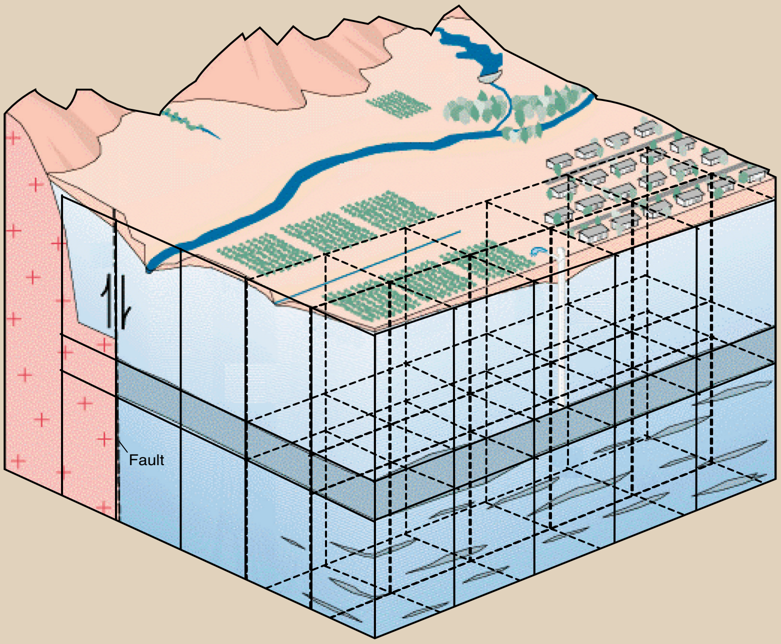
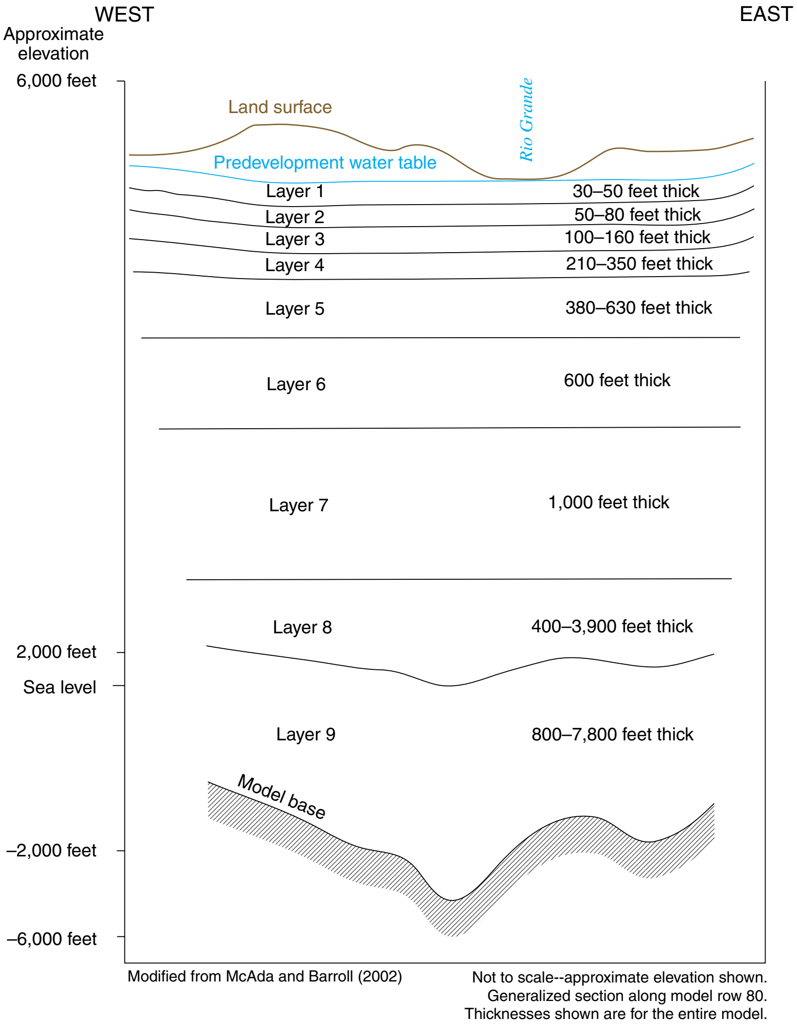


***Figure L.2.****—Block diagram of part of a hypothetical basin-fill ground-water system with some model cells shown superimposed. The model cells cover the entire ground-water system being simulated.*

The continued evolution of computers from the early days of ground-water modeling has allowed scientists and engineers to create increasingly more complex and realistic simulations of the ground-water-flow system, as well as allowed for easier calibration and improvement of methods for displaying results.

aquifer. In addition, the orientation of this model grid is north-south (parallel to the dominant trend of faults and the Rio Grande in the main part of the basin) to better align the principal directions of hydraulic conductivity in the basin. (Previous model versions aligned the model grid along the axis of the basin because of an incomplete understanding of the geologic framework; this also increased computational efficiency.)

The time simulated by a ground-water-flow model is divided into a series of stress periods. The McAda and Barroll (2002) model uses 5-year stress periods for 1900–74, 1-year stress periods for 1975–89, and irrigation/nonirrigation season stress periods for 1990–2000. Thus, the model uses a total of 52 stress periods for the entire simulation period.



Modified from McAda and Barroll (2002)

Not to scale--approximate elevation shown.
Generalized section along model row 80.
Thicknesses shown are for the entire model.

***Figure 7.1.****—Generalized configuration of ground-water-flow model layers used by McAda and Barroll (2002) along model row 80.*

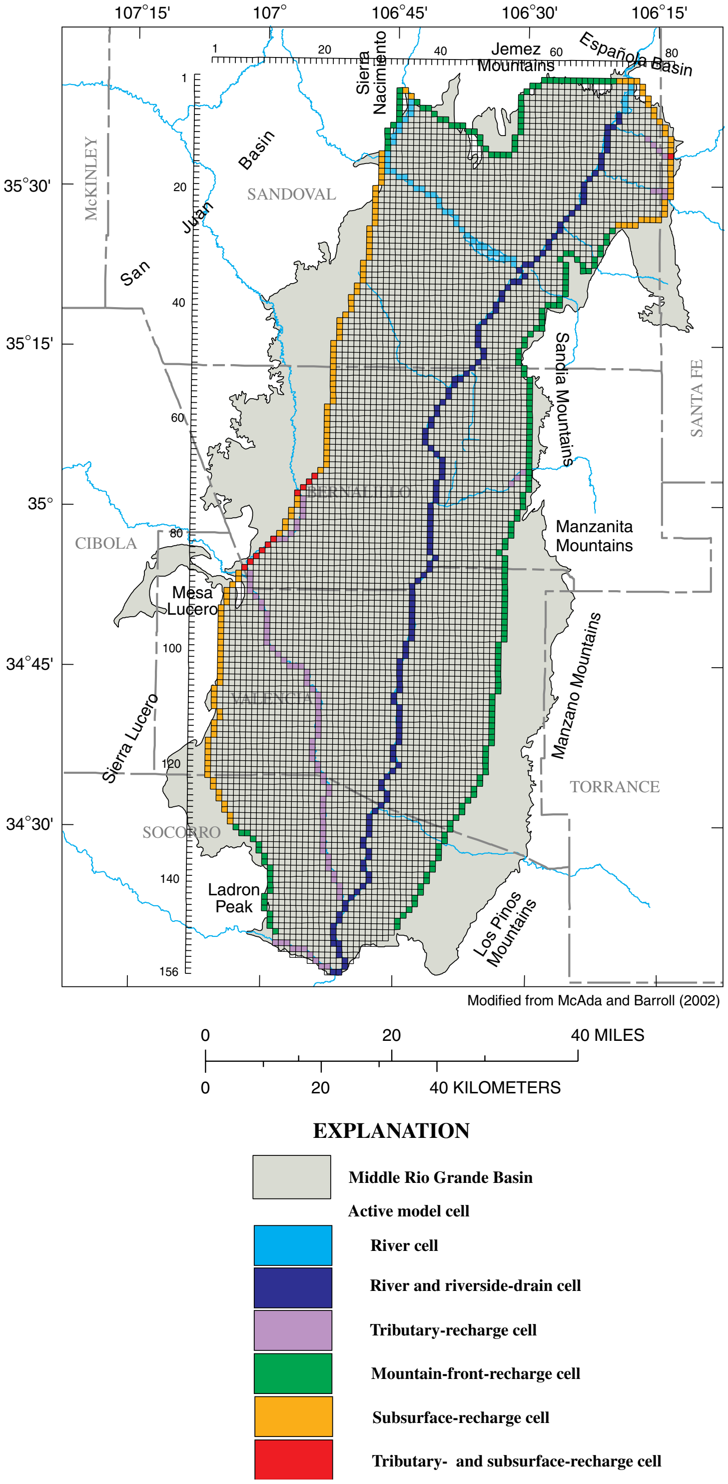


***Figure 7.2.***—*Active cells in the ground-water-flow model grid (layer 1) of McAda and Barroll (2002). Different types of recharge and drain cells are shown.*

*The Rio Salado and Ladron Peak from Interstate 25. In the ground-water-flow model of McAda and Barroll (2002) the course of the Rio Salado is simulated as tributary-recharge cells.*

# Information used in the ground-water-flow model

A vast quantity of information goes into the construction of a ground-water-flow model. First, the basic characteristics need to be established, such as the model boundaries, the orientation of model axes, the model cell size, and the number of layers. These decisions are based on the geologic framework, the amount of data available, and the ultimate purpose of the model (such as projection of water-level changes, water-rights administration, or well-field management). Next, the geologic framework needs to be translated into the ground-water-flow model by assigning hydrologic properties to the different lithologies represented by the model (see Box *M*). Finally, the characteristics of the hydrologic system need to be added by designating saturated model cells and flow rates into and out of the model.

Because it is impossible to know every piece of information needed for a ground-water-flow model, some of the values used are estimates or “educated guesses.” By using other bits of indirect information such as geophysics or water chemistry, additional information can be gained about the aquifer or flow system that can be used to refine some of the estimates used in the model (see Box *N*).

The hydrogeology in the McAda and Barroll (2002) model is primarily based on the geologic framework developed as part of the Middle Rio Grande Basin Study and described in Chapter 3. However, information on some specific areas of the basin is based on the work of others, such as that of Hawley and Haase (1992).

Because ground-water levels in wells are some of the most important data used in calibrating ground-water-flow models, the expanded ground-water-level network and new monitoring wells have contributed a large amount of new information unavailable to previous modelers. Though long-term data are lacking for these newly installed monitoring wells, they do provide information on vertical hydraulic gradients within the aquifer as well as ground-water levels in areas that previously lacked wells.

*An unlined canal near Paseo del Norte in northern Albuquerque. Such canals are now represented in the ground-water-flow model with variable leakage rates.*

The most important features or processes simulated in the McAda and Barroll (2002) model are:

- **Mountain-front recharge:** The findings of the various studies of mountain-front recharge described in this report have constrained previous estimates.
- **Tributary recharge**: Tributary recharge is simulated from streams and arroyos tributary to the Rio Grande.
- **Subsurface recharge or underflow:** Ground-water inflow from adjacent basins is simulated.
- **Pumpage:** Domestic-well pumpage is estimated on the basis of population. NMOSE-permitted wells use data through 2000 based on reported values. Actual monthly pumping figures for several water utilities and some industrial wells are used in the model; where only annual values are available, seasonal pumping volumes are estimated.

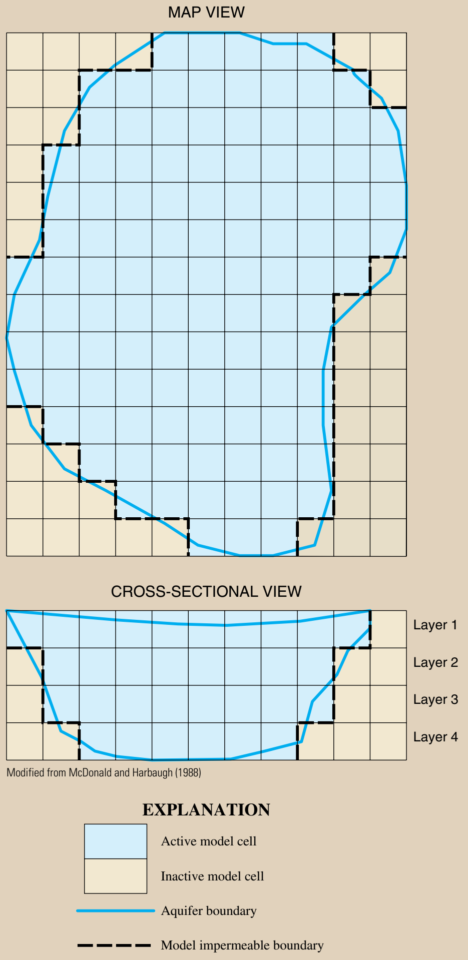
- **River leakage:** River leakage is simulated from the Rio Grande and Jemez River. Previous models simulated river leakage from only the Rio Grande.
- **Drain leakage:** Though earlier models simulated riverside and interior drains, they could only gain water. The model now allows riverside drains to gain or lose water, though interior drains can still only gain water.
- **Canal leakage:** Earlier models assumed that canals were in direct connection with the water table, and leakage varied with changes in the elevation of the water table. The canals and water table are no longer connected, and the leakage rates change over time in the model.
- **Discharge from septic fields:** Ground-water recharge from septic fields is simulated.
- **Seepage to ground water from irrigation:** Irrigation seepage is simulated in the uppermost active model layer along the Rio Grande and Jemez River. Previous models simulated irrigation seepage along only the Rio Grande.
- **Evapotranspiration:** Evapotranspiration is simulated along the Rio Grande and Jemez River. Previous models simulated evapotranspiration along only the Rio Grande.
- **Anisotropy:** Hydraulic conductivity is simulated by different values in three directions. The ratio of north-south to east-west hydraulic conductivity changes, though the ratio of east-west to vertical hydraulic conductivity is fixed at 150:1.
- **Specific storage and specific yield:** These hydraulic parameters are simulated as uniform throughout the model.
- **Reservoir leakage:** Reservoir leakage is now simulated from Cochiti Lake and Jemez Canyon Reservoirs, whereas previous models simulated leakage from only Cochiti. In addition, stage changes are now simulated in both reservoirs.

*The upstream end of Cochiti Lake. The ground-water-flow model simulates leakage from the reservoir.*

# M

## How the geologic framework is translated into a ground-water-flow model

Douglas P. McAda[1] and James C. Cole[2]



Modified from McDonald and Harbaugh (1988)

***Figure M.1.****—Schematic representation of an aquifer in a finite-difference ground-water-flow model.*

Ground-water-flow models are mathematical representations of real ground-water-flow systems, as described in Box *L*. With the finite-difference method used to model the Middle Rio Grande Basin, the system is represented by a set of rectangular cells (fig. *M.1*). Mathematical equations are used to calculate the flow of ground water between adjacent cells and between cells and the hydrologic boundaries of the system (for example, lateral boundaries of recharge and discharge, and boundaries between ground water and the surface flow of rivers and streams).

The hydraulic characteristics used in the ground-water-flow model depend on the kinds of rock present and their hydraulic properties (see the “Aquifer productivity” section on page 58). The ground-water system of the Middle Rio Grande Basin consists primarily of various sedimentary deposits that vary widely in their hydraulic properties (see Box *C*). Direct or indirect measurements of these characteristics are obtained by tests conducted in wells or outcrops, but such test data are available for only limited parts of the whole ground-water system. One of the challenges in building a credible ground-water-flow model, then, is to understand what kind of rock was tested at various locations, to relate those test data to similar rock elsewhere, and to understand the geologic framework well enough to predict what kinds of rock probably lie in areas that have no wells. This then is the purpose of a geologic model: to define the three-dimensional distribution of rock units of broadly similar hydraulic characteristics. These make up the starting values for the mathematical calculations of the ground-water-flow model.

The first things to be established for the mathematical flow model are the size of the cells, the number of layers in the model, and the orientation of the layers of cells in relation to geologic features. Hydraulic characteristics must be uniform within each model cell, so the cells need to be small enough to represent the real-world variation in geologic materials (fig. *M.2*). However, the cells cannot be so small that the model requires too many calculations for a computer to handle efficiently. Therefore, the dimensions of individual cells generally reflect a balance between the variation in geologic materials, the objectives for which the model is to be used, and the computation time. Because the geometric dimensions of each model cell encompass large volumes of rock, the resulting model values for hydraulic characteristics are averages. Similarly, the number of vertical

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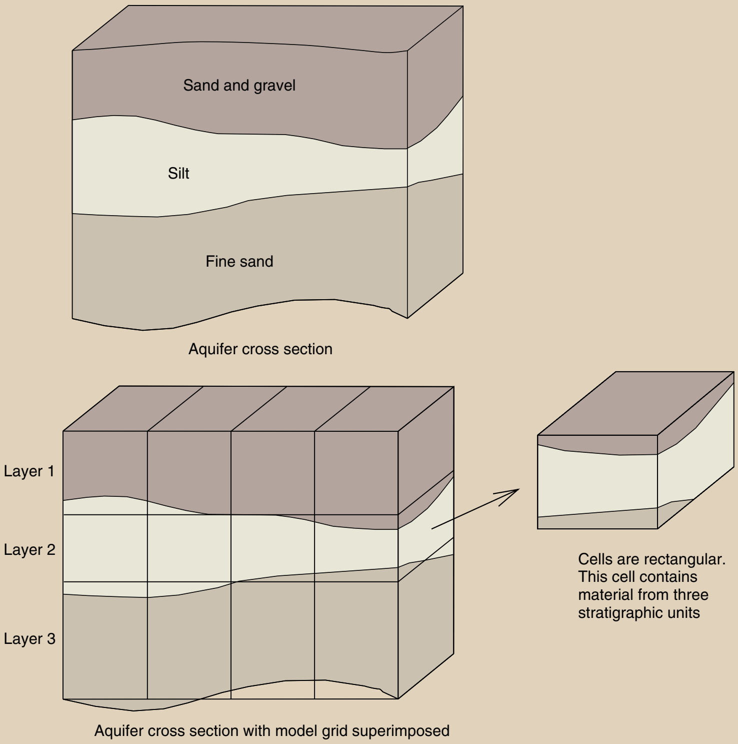
[1] U.S. Geological Survey, Albuquerque, New Mexico.
[2] U.S. Geological Survey, Denver, Colorado.

layers in the model should be enough to represent known layering in the geologic environment, but not so many that computations are unacceptably long for the intended use of the model. The orientation of the flow-model axes is generally selected so that one direction is parallel to the dominant direction of greatest hydraulic conductivity. The ground-water-flow model of the Middle Rio Grande Basin is described in Chapter 7.

The geologic environment for ground water in the Middle Rio Grande Basin can be visualized as a bathtub filled with rectangular sponges. The bottom of the bathtub is defined by rocks that are older than the Santa Fe Group (see Box *C*) and transmit much less water than the Santa Fe Group itself. In the flow model, the top of these older rocks represents the base of the model and is defined as a barrier to flow (fig. *M.1*; "inactive cells"). However, small amounts of water enter the basin through these rocks, at the sides of the bathtub, in the form of subsurface recharge or underflow (see the "Subsurface recharge or underflow" section on page 77). The hypothetical sponges, which have the dimensions of the model cells, can be thought of as representing individual volumes of Santa Fe Group deposits with differing hydraulic properties. For example, cells in the flow model that contain mostly coarse sand and gravel might correspond to a sponge with large, open pores that allow water to move freely. Model cells that contain mostly silt and clay might correspond to a sponge with small pores that restrict the flow of water.



Modified from McDonald and Harbaugh (1988)

***Figure M.2.****—Schematic representation of ground-water flow-model cells related to sedimentary deposits.*

The three-dimensional geologic framework of the Middle Rio Grande Basin is based on rock units in outcrops, wells, and extrapolations between the two. The interpretation is based on a conceptual understanding of the history of faulting and deposition in the rift basin (see Box *C*). Where the geologic framework shows that the depositional environment for the rift-fill sediments was similar over a broad area, the ground-water-flow model consists of side-by-side cells that have similar hydraulic properties. Where the geologic framework shows that the depositional environment was constant for a long period of time, the flow model consists of stacked cells that have similar hydraulic properties. Where the geologic framework shows that faulting was active during deposition of a particular kind of sediment, the flow model consists of a thicker stack of cells on the downthrown side of the fault than on the upthrown side.

During the process of model calibration, comparison of modeled results with historical data and adjustment of model-input values may continue through several cycles until the disparities are minimized. If the disparities remain large in some areas that can be resolved only by changing the kinds of geologic "sponges," then the geologic framework is reviewed and revised accordingly.

# What the ground-water-flow model tells us about the hydrologic system of the basin

*The mouth of Embudito Canyon in the Sandia Mountains. The Middle Rio Grande Basin Study has found ground-water recharge in such settings to be less than previously thought.*

A ground-water-flow model is a powerful tool for analyzing an aquifer system. Among the most important findings of McAda and Barroll (2002) are:

- Prior to installation of the riverside drains along the Rio Grande, the river was losing flow. This water probably was being evapotranspired and (or) was recharging the Santa Fe Group aquifer system. Currently (2002), the drains intercept much of this flow and divert it back into the river.
- The Rio Grande and riverside drains are so closely related, especially during the nonirrigation season, that they function as one system.
- The hydrologic connection between the Rio Grande and underlying Santa Fe Group aquifer system is variable and changes with the lithology of a particular river reach.
- In much of the Santa Fe Group aquifer system throughout the basin, water removed from storage is partially replaced during the nonirrigation season.
- Mountain-front recharge to the Santa Fe Group aquifer system is less than amounts estimated by previous models. This is partly due to the findings of the various studies of mountain-front recharge described in this report.

Table 7.1 shows the annual water budgets simulated by the ground-water-flow model of McAda and Barroll (2002) for predevelopment steady-state conditions and for 1999 (the two seasonal stress periods ending in March 1999 and October 1999).

Table 7.1.—Simulated annual water budget for the ground-water-flow model of McAda and Barroll (2002). All values are in acre-feet per year

[--, 0 or not applicable]

| Mechanism | Steady-state conditions | | 1999 conditions | |
|---|---|---|---|---|
| | Inflow (to aquifer) | Outflow (from aquifer) | Inflow (to aquifer) | Outflow (from aquifer) |
| Mountain-front recharge | 12,000 | -- | 12,000 | -- |
| Recharge from intermittent tributaries | 9,000 | -- | 9,000 | -- |
| Underflow from adjacent basins | 31,000 | -- | 31,000 | -- |
| Canal seepage | -- | -- | 90,000 | -- |
| On-farm irrigation seepage | -- | -- | 35,000 | -- |
| Rio Grande main stem and Cochiti Lake | 63,000 | -- | 317,000 | -- |
| Rio Grande riverside drains | -- | -- | -- | –208,000 |
| Rio Grande interior drains | -- | -- | -- | –134,000 |
| Jemez River and Reservoir | -- | -- | 16,000 | -- |
| Ground-water withdrawals | 15,000 | -- | -- | –150,000 |
| Septic-field return flow | -- | -- | 4,000 | -- |
| Riparian and wetland evapotranspiration | -- | –130,000 | -- | –84,000 |
| Aquifer storage | -- | -- | 110,000 | –49,000 |
| Totals: | 130,000 | –130,000 | 624,000 | –625,000 |

N

# How carbon-14 data were used to improve the ground-water-flow model

Ward E. Sanford[1]

Carbon-14 ($^{14}C$) is a natural, radioactive isotope of carbon that can be used to estimate the length of time that a sample of water collected from a well has been in the ground-water system (Kalin, 1999). Carbon-14 is continuously being created in the atmosphere as nitrogen is bombarded by cosmic rays from outer space. Over time, the carbon-14 ($^{14}C$) radioactively decays to carbon-12 ($^{12}C$) at a known rate. An approximate balance is reached between the production and decay of carbon-14, resulting in a relatively stable concentration in the atmosphere. Carbon-12 and carbon-14 are both equally incorporated into carbon dioxide gas in the atmosphere and in bicarbonate ($HCO_3$) ions dissolved in rainwater. The constant concentration of carbon-14 in the atmosphere leads to an equilibrium concentration of bicarbonate dissolved in precipitation that recharges ground water. Once underground and sheltered from cosmic rays, no more carbon-14 is formed and the existing carbon-14 decays at a known, constant rate. Thus, the ratio of carbon-14 to carbon-12 in a ground-water sample from a well or spring reflects how long the water has been in the aquifer system. The length of time calculated from this ratio is referred to as the carbon-14 age, and the carbon-14 technique is used for dating water that has been in the ground-water system between about 1,000 and 50,000 years.

The ground-water-flow model of the Middle Rio Grande Basin is described in Chapter 7 and Boxes *L* and *M*. Typically, water levels measured in a number of wells at different locations and times and the rates of ground-water discharges measured along streams are used to calibrate (check and adjust) ground-water models. These observations are crucial but are limited in calibrating large, complex ground-water-flow models with a large number of parameters. Models that rely predominantly on water levels as observations usually have a high degree of uncertainty associated with their predictions. Previous models constructed of the Middle Rio Grande Basin (Kernodle, McAda, and Thorn, 1995; Tiedeman, Kernodle, and McAda, 1998) have relied predominantly on water levels for their calibration because ground-water movement between the Rio Grande and aquifer has been difficult to measure accurately.

Ground-water models can be used to simulate not only water levels but also the rate of speed at which water is moving through the ground at any particular location. This type of information is very useful in the estimation of the movement of a contaminant or any other dissolved substance. Computer codes have been developed, such as Pollock (1994), that work with ground-water-flow models to estimate flow paths followed by parcels of ground water and their associated traveltimes. This type of simulation is being used in the Middle Rio Grande Basin to estimate the time of travel of water from recharge areas to wells where samples have been collected and analyzed for carbon-14 (fig. *N.1*). If the model is a good representation of the system, the carbon-14 ages should agree closely with the traveltimes estimated by the model. If the values do not agree, the model can be further calibrated until a best fit can be made with all the observations. Computer codes that can make optimum fits between observations and model parameters, such as Poeter and Hill (1998), can be used in this situation. Because carbon-14 ages provide information directly related to the flux of ground water through the basin, they make inherently better observations than water levels for estimating the long-term (greater than 1,000 years) rates of natural recharge to the basin. Both long-term and current rates of recharge are important for water-resources planning because they contribute to an understanding of the potential long-term ground-water yield of the basin.

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[1] U.S. Geological Survey, Reston, Virginia.

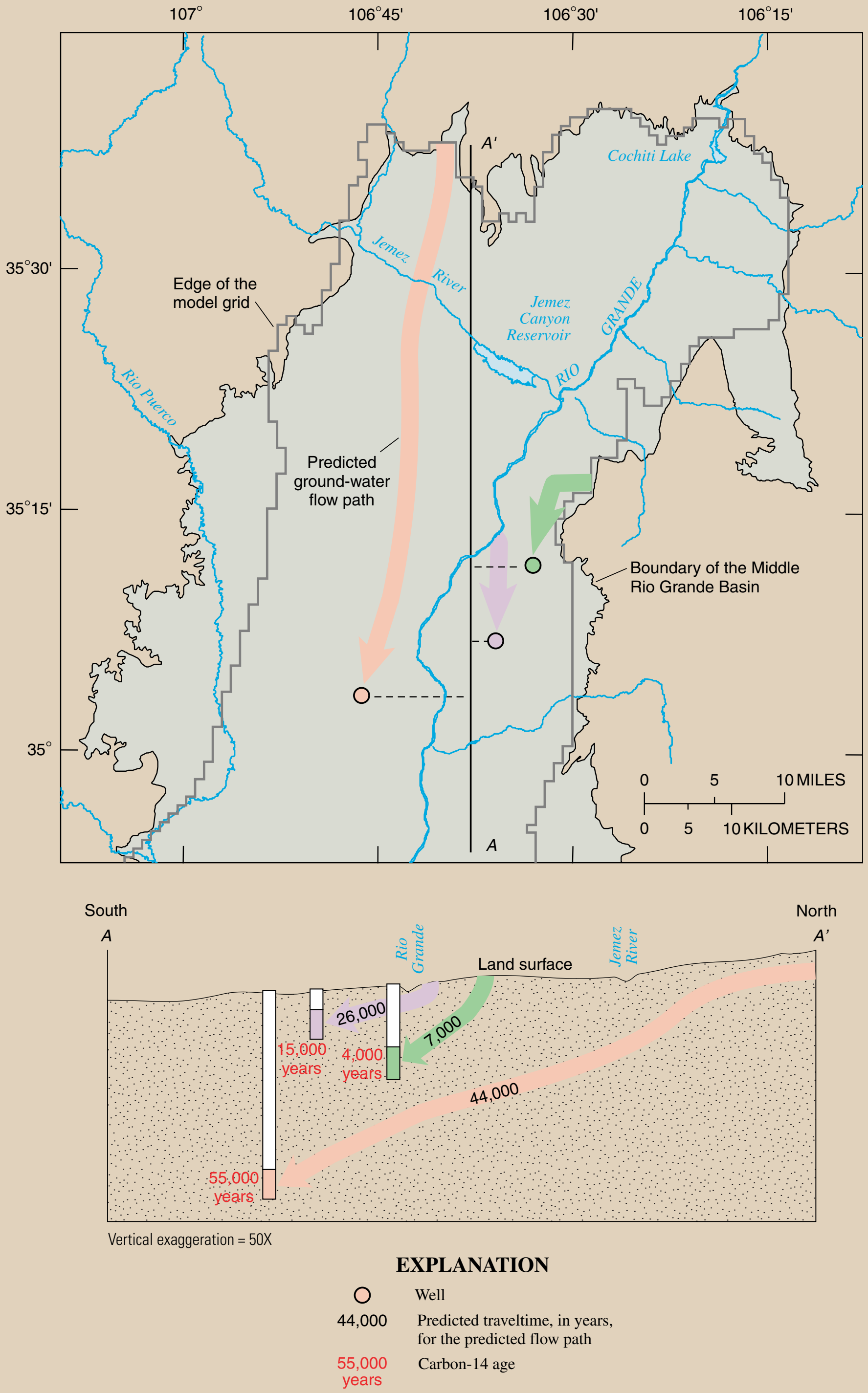

***Figure N.1.**—Traveltimes and ground-water flow paths predicted by a preliminary version of the current revision of the ground-water-flow model of the Middle Rio Grande Basin (Sanford, 1999). Three flow paths are shown that extend from recharge areas to observation wells from which samples were analyzed for carbon-14. The illustration is simplified in that no vertical mixing is shown.*

# What the ground-water-flow model tells us about future conditions

Steady-state conditions in a ground-water-flow model refer to flow conditions that do not change over time. The natural hydrologic conditions prior to ground-water development and large-scale alteration of the surface-water system are usually assumed to be steady state (Spitz and Moreno, 1996).

Ground-water-flow models are commonly constructed to make projections of future conditions based on varying management scenarios. Though these model projections are based on incomplete data and estimates of future conditions, they are often the best tool available for management decisions (Alley, Reilly, and Franke, 1999). The model of Kernodle, McAda, and Thorn (1995) included projections for conditions up to 2020, but this model was modified by CH2M Hill to make projections up to 2060 (City of Albuquerque Public Works Department, 1995). As mentioned in Chapter 2, these forecasts were instrumental in the City of Albuquerque revising its water-use strategy.

The McAda and Barroll (2002) ground-water-flow model of the Middle Rio Grande Basin does not make any projections of future conditions, though it could be modified to do so. It does provide water-resource managers a more accurate and powerful tool to evaluate the potential effects of management decisions.