Chapter 5: How water moves through the aquifer system

One of the methods scientists use to conceptualize how an aquifer functions is to follow a hypothetical particle of water as it enters, moves through, and finally leaves the aquifer. In the Santa Fe Group aquifer system, such a flow path can be complicated because water enters the aquifer in several different settings, moves through the aquifer along a variety of paths, and then leaves the aquifer in several different ways. A wide variety of methods have been used to differentiate how water recharges, moves through, and finally discharges from the aquifer. This is critical to understanding how the aquifer operates and, ultimately, how much ground-water withdrawal an aquifer can support.

Recharge and underflow—How ground water enters the aquifer system

There are many processes and settings by which water enters a basin-fill aquifer, such as that in the Middle Rio Grande Basin, and they can be classified in a number of ways. In this report, recharge is discussed by the setting in which it occurs. There are four main settings in which water enters the Santa Fe Group aquifer system: mountain fronts and tributaries to the Rio Grande, the inner valley of the Rio Grande, the Rio Grande itself, and subsurface basin margins. Water entering the aquifer in the first three settings is usually termed recharge, whereas water that enters the basin in the subsurface is usually termed underflow.

Mountain-front recharge

Some of the surface water that enters the basin originates as springs or precipitation in uplifted areas adjacent to the basin. Some of this water is recharged at the basin margin (mountain-front recharge), some is recharged to ground water through the bottoms of tributaries and arroyos (tributary recharge), some is lost to evaporation and transpiration, and some reaches the Rio Grande as surface water. Mountain-front and tributary recharge are often grouped together because determining an exact division between the two can be difficult. In addition, ground-water underflow from mountains surrounding the basin is very difficult to quantify and is usually included as a component of mountain-front recharge.

Generally speaking, *infiltration* refers to water that moves into the soil, though it may never reach the saturated zone because of evaporation or transpiration. *Recharge* refers to water that ultimately enters the saturated zone and thus contributes water to the aquifer.

The *chloride-balance method* for estimating recharge uses the concentration of chloride in ground water near the mountain front compared with the chloride concentration in rainfall. By assuming that rainfall is the only source of chloride in the ground water (among other assumptions), an estimate of recharge is calculated. Variations of this technique have been applied to arid areas throughout the world (Anderholm, 2000).

The *water-yield regression method* for estimating recharge derives an equation relating precipitation, drainage area, and measured streamflow in drainages with streamflow gages in order to characterize the volume of streamflow flowing past the mountain front in drainages without streamflow gages. It is assumed that all this water infiltrates into the aquifer and that evaporation and transpiration are small enough to be ignored (Anderholm, 2000).

Traditionally, the quantity of mountain-front recharge has been difficult to measure and has often been calculated indirectly through water-budget or modeling methods. The ground-water-flow models of Kernodle and Scott (1986), Kernodle, Miller, and Scott (1987), and Kernodle, McAda, and Thorn (1995) relied on unpublished estimates of mountain-front recharge made using a water-yield regression method. These estimates for mountain-front recharge along the east side of the Middle Rio Grande Basin were approximately 72,000 acre-feet per year. The mountain-front areas in the southwestern part of the basin (Ladron Peak, Mesa Lucero, and the Sierra Lucero) were estimated to contribute about 7,600 acre-feet per year. A ground-water-flow model by Tiedeman, Kernodle, and McAda (1998) estimated 58,000 acre-feet per year of mountain-front recharge along the east side of the basin. Sanford and others (2001) estimated 3,000 acre-feet per year of mountain-front recharge along the east side of the basin.

Prior to the model of McAda and Barroll (2002), mountain-front recharge estimates were poorly constrained in ground-water-flow models of the Middle Rio Grande Basin. Consequently, several studies have been done to improve understanding of the process. Anderholm (2000) estimated mountain-front recharge along the east side of the Middle Rio Grande Basin using the chloride-balance method and water-yield regression equations developed by other authors. (The water-yield regression method calculates only recharge from streams and not underflow from aquifers in the mountains.) Anderholm's recharge estimates ranged from about 11,000 acre-feet per year for the chloride-balance method to 38,000 acre-feet per year for the larger of the two water-yield regression estimates. The ground-water-flow model of McAda and Barroll (2002) uses the chloride-balance mountain-front-recharge values determined by Anderholm (2000). The McAda and Barroll model uses a total value of mountain-front recharge for the entire Middle Rio Grande Basin of 12,000 acre-feet per year.

Another approach to determining mountain-front recharge is to make point measurements of infiltration rates at a number of selected points along the mountain front and apply these rates to similar settings. Though the point measurements may be very precise, a limitation of the approach is that the total surface area undergoing recharge must be estimated in order to calculate recharge volumes. As part of the Middle Rio Grande Basin Study, several different methods were used to determine recharge rates at different points along the margins of the basin (see Box *G*).

Using surface- and ground-water temperature, Niswonger and Constantz (2001) examined streamflow loss in Bear Canyon at the mountain front to estimate recharge (see Box *G*). Preliminary results from their study indicate that streamflow rarely reaches a distance of 1.2 miles beyond the mountain front. When completed, results from this study could be used to estimate mountain-front recharge along the Sandia and Manzano Mountains.

Ground-water geochemistry and age dating clearly indicate the presence of water in the Santa Fe Group aquifer system that originated as mountain-front recharge (Plummer and others, 2001) (see Chapter 6). Analysis of carbon-14 data in conjunction with the ground-water-flow model by Sanford and others (2001) suggests that mountain-front recharge is substantially less than estimates from earlier models and the chloride-balance method. Final analysis of these data is ongoing; however, the results may be useful for further refinement of mountain-front-recharge values.

A common misconception in the Middle Rio Grande Basin is that concrete-lined drainage channels in urban areas prevent the recharge of stormwater to the aquifer. In fact, away from the mountain front, little or no recharge occurs beneath unlined arroyos because the depth to ground water is usually several hundred feet. In a study of an unlined part of Grant Line Arroyo (in northeast Albuquerque) between 1989 and 1992, Thomas (1995) measured soil temperature and other properties at six depths beneath the arroyo. Data from September 1989 were typical of the data collected: flow in the arroyo following a precipitation event infiltrated to a depth between 3.5 and 5 feet, but no deeper. The depth to water beneath the study site was approximately 600 feet.

Tributary recharge

Some of the perennial tributaries that flow into the Middle Rio Grande Basin infiltrate completely within a short distance of the basin boundary (except during periods of precipitation runoff), such as Tijeras and Abo Arroyos and the Santa Fe River. Other perennial streams, such as the Jemez River and Rio Puerco, flow into the Rio Grande all or most of the year. Many arroyos with headwaters in the basin are ephemeral along their entire lengths, such as Arroyo de las Calabacillas. Many of the same techniques used for the determination of recharge from mountain-front streams can be applied to tributary recharge. Streams that have been studied in detail to determine recharge rates are Tijeras Arroyo (Thomas, 1995; Constantz and Thomas, 1996), the Santa Fe River (Thomas, Stewart, and Constantz, 2000), Abo Arroyo (Nimmo, Lewis, and Winfield, 2001; Stewart and Constantz, 2001), and Bear Canyon (Niswonger and Constantz, 2001) (see Box *G*).

The amount of tributary recharge has been difficult to measure in the Middle Rio Grande Basin because many of the streams are ephemeral through at least part of their reach and because there are huge uncertainties regarding the amount of evaporation and transpiration; hence, this recharge has been calculated indirectly through water-budget or modeling methods. The ground-water-flow model of Kernodle, McAda, and Thorn (1995) estimated annual recharge to be 12,000 acre-feet from the Jemez River and

Two photographs of Tijeras Arroyo at the Four Hills bridge in southeast Albuquerque. The upstream view from the bridge shows flowing water; the downstream view from the bridge taken at the same time shows a dry channel.

G

How mountain-front recharge is studied

James R. Bartolino[1] and Jim Constantz[2]

One of the most difficult components to quantify in the hydrologic budget of a basin is the amount of recharge to ground water at mountain fronts along the basin margins. In the Middle Rio Grande Basin, the first estimates made of mountain-front recharge either were derived from water budgets or ground-water-flow models or were calculated as a percentage of the ratio of precipitation to drainage area. Consequently, recharge estimates were regarded as highly uncertain. In response to this uncertainty, several projects of the Middle Rio Grande Basin Study investigated methods of directly measuring the amount of mountain-front recharge in the basin.

Research on mountain-front recharge for the Middle Rio Grande Basin Study occurred at two main sites: Bear Canyon and Abo Arroyo. Bear Canyon, east of Albuquerque on the west side of the Sandia Mountains, is typical of approximately 100 small ephemeral streams along the front of the Sandia and Manzano Mountains on the eastern margin of the basin. (Bear Canyon is also known as Bear Arroyo or Bear Canyon Arroyo in its lower reaches.) Abo Arroyo, entering the basin between the Manzano and Los Pinos Mountains, is the largest stream in the southeastern part of the basin. Multiple methods were used at these two sites to allow for comparison of the recharge estimates independently derived from the different methods.

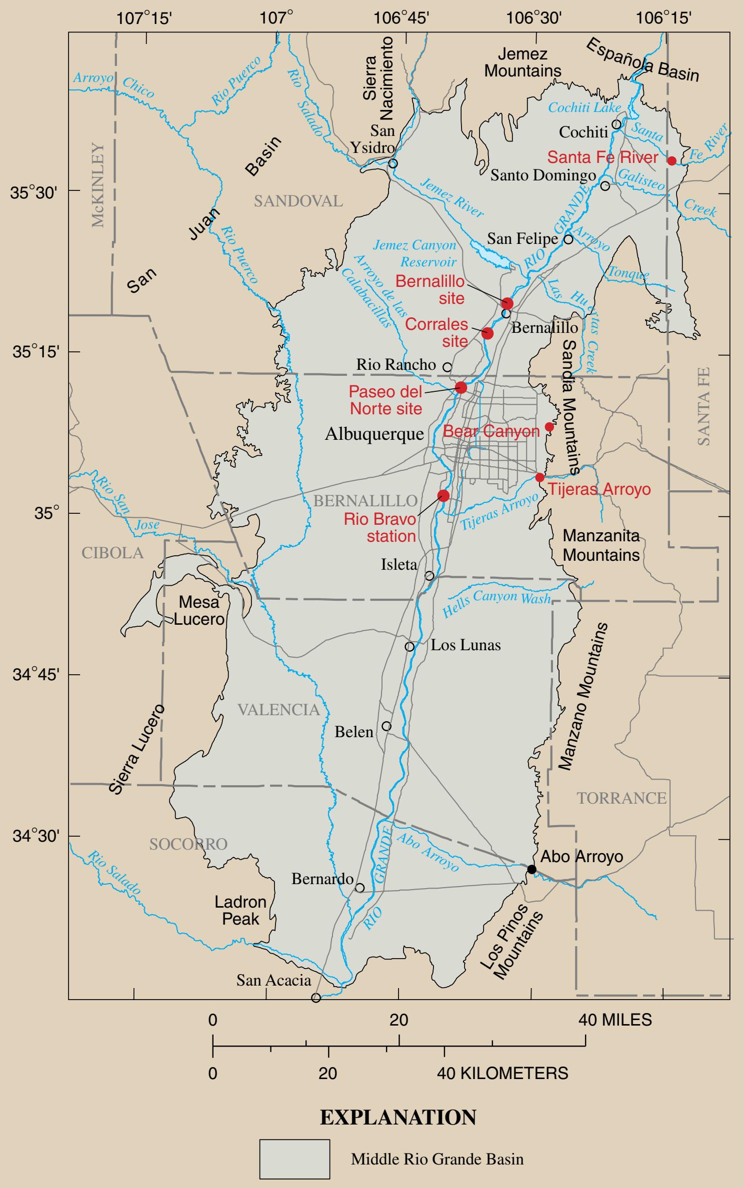


***Figure G.1.**—Locations of study sites for mountain-front recharge and water temperature in the Middle Rio Grande Basin.*

[1]U.S. Geological Survey, Albuquerque, New Mexico.
[2]U.S. Geological Survey, Menlo Park, California.

Temperature has been used to quantify the amount and direction of water moving between the surface- and ground-water regimes in the Middle Rio Grande Basin along perennial reaches of the Santa Fe River, Tijeras Arroyo, and the Rio Grande (fig. *G.1* and Box *H*). However, the use of water temperature as a tracer was expanded into the realm of ephemeral streams at Bear Canyon and Abo Arroyo. Using vertical-temperature measurements below the streambed and surface-temperature measurements of the streambed, the downward movement of water and the downstream extent of flow in the arroyos were determined (fig. *G.2*). (See Niswonger and Constantz, 2001; Stewart and Constantz, 2001.)

Another technique applied in the Middle Rio Grande Basin was the **S**teady-**S**tate **C**entrifuge (SSC) method. The method used core samples to determine recharge rates. After a core was collected, it was split into smaller samples and the water content of each was measured. These smaller samples were then placed in a large centrifuge and spun to simulate gravity drainage of water through the sample (though at a much faster rate). By applying different amounts of water to the core sample as it was spun in the centrifuge, the hydraulic conductivity was measured. The initial water content and hydraulic conductivity were then used to calculate a recharge rate. Recharge-rate estimates were made for several reaches of Abo Arroyo and the upland areas adjacent to the arroyo. (See Nimmo, 1997; Lewis and Nimmo, 1998; Lewis, Nimmo, and Stonestrom, 1999; Nimmo, Lewis, and Winfield, 2001.)

Two geochemical methods were used to estimate recharge rates from cores collected at Bear Canyon and Abo Arroyo. The first method extracted all the water from a core sample (cores from upland areas and dry streambeds may yield only miniscule amounts of moisture). Tritium-dating techniques were then applied to these water samples to determine when the water entered the ground (see Box *I*). By using the amounts and ages of water at different depths, a recharge rate was calculated. The second method calculated recharge rates using chloride and bromide concentrations extracted from core samples from different depths, in combination with the water content of the sample to calculate recharge rates. (See Stonestrom, Akstin, and Michel, 1997; Stonestrom and Akstin, 1998.)

Other indirect methods of quantifying mountain-front recharge have been used in the Middle Rio Grande Basin Study. In addition to the ground-water-flow model described in Chapter 7, other geochemical methods have been used and are described in Boxes *I*, *K*, and *N*. The application of multiple techniques for calculating recharge in the Middle Rio Grande Basin has allowed comparison of new techniques that can be applied in other desert areas of the world.

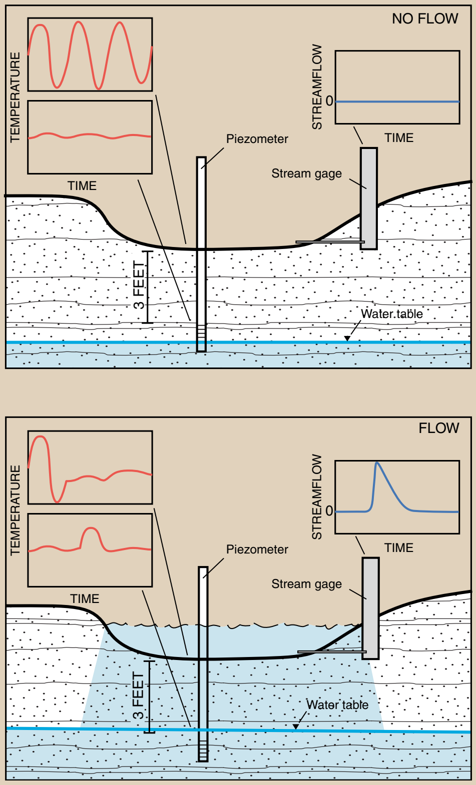
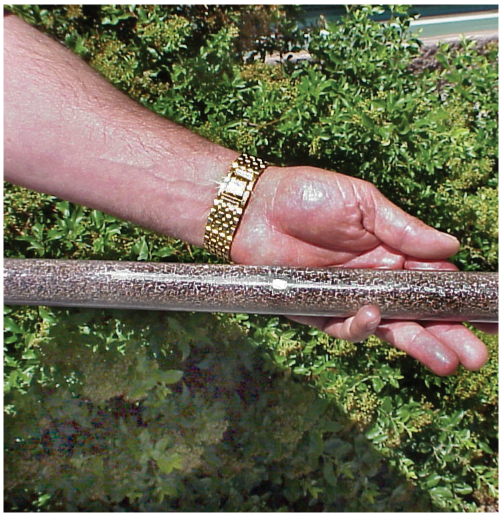


Figure G.2.*—Temperature compared to time at two depths in an ephemeral streambed during periods of no flow and flow. The top diagram shows a dry streambed with a streamflow-gaging station (right) recording no flow over approximately 3 days. On the left, the temperature over the same period of time is shown at the streambed surface (top) and at the water table (bottom). Note that the streambed-surface temperature shows the daily fluctuation in air temperature and that the water-table temperature remains relatively constant in the absence of any recharge. The bottom diagram shows the same site during flow. Note that the surface temperature starts with the same daily variation as the top diagram, but with the onset of flow (shown by the hypothetical graph of streamflow on the right), the temperature fluctuation is significantly damped. The temperature graph for the water table shows a spike in temperature after the onset of flow, indicating that water is reaching the saturated zone as recharge. Gaging stations are seldom installed on ephemeral streams because of expense, uncertainty associated with ephemeral flows, and the destructive nature of many of the flow events.*

8,000 acre-feet from the Rio Puerco. The ground-water-flow model of Tiedeman, Kernodle, and McAda (1998) estimated 11,000 and 4,000 acre-feet of recharge for the Jemez River and Rio Puerco, respectively. Sanford and others (2001) estimated 30 acre-feet per year of recharge from the Jemez River and 2,000 acre-feet from the Rio Puerco.

The ground-water-flow model of McAda and Barroll (2002) uses an estimate of 9,000 acre-feet per year of tributary recharge for 1900–99 (which includes 2,000 acre-feet per year from the Rio Puerco). For the Jemez River and Reservoir, they estimated 15,000 and 16,000 acre-feet of recharge for predevelopment and 1999 conditions, respectively. The substantial difference between the estimates of different models is largely due to different approaches to model design and calibration.



A typical core sample collected for the Middle Rio Grande Basin Study.

Analyses of sediment cores from six locations along Abo Arroyo by Nimmo, Lewis, and Winfield (2001) found that recharge varied among three reaches defined on the basis of geology. They estimated total recharge for the Abo Arroyo drainage between the mountain front of the Manzano Mountains and the Rio Grande to be approximately 1,300 acre-feet per year, a number that closely agrees with an estimate of 1,280 acre-feet by Anderholm (2000) using the chloride-balance method.

As with mountain-front recharge, the use of ground-water chemistry and age-dating data has allowed the identification of water in the Santa Fe Group aquifer system that originated as tributary recharge (Plummer and others, 2001) (see Chapter 6). Currently (2002), these data are still being analyzed; however, it is probable that the results will further refine estimates of the sources and amounts of tributary recharge.

Rio Grande and inner-valley recharge

The main sources of recharge to ground water in the inner valley of the Rio Grande are infiltration from the Rio Grande, irrigation canals, segments of interior drains that are now above the water table, and applied irrigation water. Other sources of recharge in the inner valley are infiltration of septic-tank effluent and precipitation (Kernodle, McAda, and Thorn, 1995; Anderholm, 1997).

The direction and amount of water flowing between the Rio Grande and the Santa Fe Group aquifer system is one of the most important hydrologic issues in the Middle Rio Grande Basin. Not only do the volume and direction of flow between surface and ground water affect the amount of water in the river, they affect the volume of ground water available in the aquifer. In the Albuquerque area, ground-water pumping has lowered ground-water levels so that the river loses more flow to ground water than it did during predevelopment conditions. However, in the river reaches upstream and downstream from Albuquerque, ground-water flow is to the river and, thus, the river gains flow from ground-water discharge. This latter case is discussed later on page 81. Ground-water recharge from reservoirs in the Middle Rio Grande Basin is usually included as a component of river recharge.

> The interaction between a stream and an aquifer can usually be described by whether the stream gains water from or loses water to the aquifer. A *gaining stream* receives or gains flow from ground water. A *losing stream* is one that loses or contributes flow to ground water.

During the irrigation season, irrigation water within the inner valley of the Middle Rio Grande Basin is diverted from the Rio Grande at three points: Cochiti Dam, Angostura, and Isleta (fig. 4.1). Diverted water then flows through the inner valley in a series of irrigation canals and smaller ditches for application to fields. This water recharges ground water, is lost to evaporation or evapotranspiration by plants, or is intercepted by interior drains and returned to the river. The other main component of the inner-valley surface-water network is a system of riverside drains, which are deep canals that parallel the river immediately outside the levees. The drains are designed to intercept lateral ground-water flow from the river, thus preventing waterlogged conditions in the inner valley. Within the Middle Rio Grande Basin, riverside drains and levees are present on the east bank, and typically both banks, of the river (Kernodle, McAda, and Thorn, 1995; Anderholm, 1997).

Because the irrigation system and Rio Grande are linked through a complex series of irrigation structures, studying the processes of one component without considering the others is difficult. Thus, certain aspects of Rio Grande and inner-valley recharge often are combined for investigation. For 1994, the ground-water-flow model of Kernodle, McAda, and Thorn (1995) estimated river, canal, and reservoir leakage to ground water to be about 247,000 acre-feet; irrigation seepage to ground water to be about 28,300 acre-feet; and septic-tank effluent flow to ground water to be about 8,220 acre-feet. Similarly, the ground-water-flow model of McAda and Barroll (2002) estimated river and reservoir leakage to ground water to be 63,000 and 317,000 acre-feet per year for predevelopment and 1999 conditions, respectively. For 1999, irrigation seepage to ground water was estimated to be 35,000 acre-feet in 1999, canal seepage to be 90,000 acre-feet, and septic-tank effluent flow to ground water to be about 4,000 acre-feet. A portion of the reservoir seepage is from under Cochiti Dam (Blanchard, 1993). The Bureau of Reclamation estimated this underflow to be 35,500 acre-feet per year (Thorn, McAda, and Kernodle, 1993).

The headgate of an acequia (or ditch) near Paseo del Norte in northern Albuquerque.

Various methods have been used to study water movement in the inner valley and between the river and aquifer. These studies include direct measurement of flow (such as Bartolino and Niswonger, 1999) and indirect determinations using water-level relations, water budgets, or ground-water-flow models (such as Peter, 1987; and Kernodle, McAda, and Thorn, 1995). Some of these studies are described in Box *H*. As with mountain-front recharge, some of these studies are point measurements of water movement between the river and aquifer. Though useful for confirming recharge rates, some uncertainty can be introduced when extrapolating these rates over extended reaches of the river.

Water-chemistry studies using environmental tracers, the presence of anthropogenic chemicals, and naturally occurring constituents have expanded understanding of water movement between the river and aquifer (such as Anderholm, 1997; and Plummer and others, 2001). Water chemistry of the Santa Fe Group aquifer system is discussed in more detail in Chapter 6.

Subsurface recharge or underflow

The volume of ground water flowing into a basin from adjacent basins is very hard to determine. Often, the volume is determined indirectly from a ground-water-flow model or water budget. Underflow enters the Middle Rio Grande Basin from two adjacent basins: the San Juan Basin to the northwest and the Española Basin to the northeast

H

How ground-water/surface-water interaction of the Rio Grande has been studied

James R. Bartolino[1]

One of the most important questions being asked about the hydrology of the Middle Rio Grande Basin is how well the Rio Grande is hydrologically connected to the Santa Fe Group aquifer system. Until 1999, the New Mexico Office of the State Engineer (NMOSE) used a simplistic, theoretical formula derived by Glover and Balmer (1954) to calculate the volume of water that seeped from the Rio Grande into the aquifer in response to pumping large volumes of ground water (also known as stream or river depletion). The ground-water-flow model of the Albuquerque Basin by Kernodle, McAda, and Thorn (1995) and subsequent revisions by Kernodle (1997, 1998) showed that seepage from the Rio Grande into the aquifer in response to this pumping is much less than the Glover-Balmer equation estimates. In 1999, the NMOSE adopted a modified version of the Albuquerque Basin ground-water-flow model by Tiedeman, Kernodle, and McAda (1998) as the means by which river depletion in response to ground-water pumping would be calculated (Barroll, 2001). However, the values the ground-water-flow model provides for river depletion are derived indirectly and are estimates of the volume of streamflow lost to ground-water infiltration.

Several techniques have been used to directly measure streamflow loss from the Rio Grande. Gould (1994) installed permeameters in the active river channel. These permeameters were shallow wells completed into the top several feet of riverbed sand with a bladder of water attached to the top. By measuring how fast the water drained from the bladder

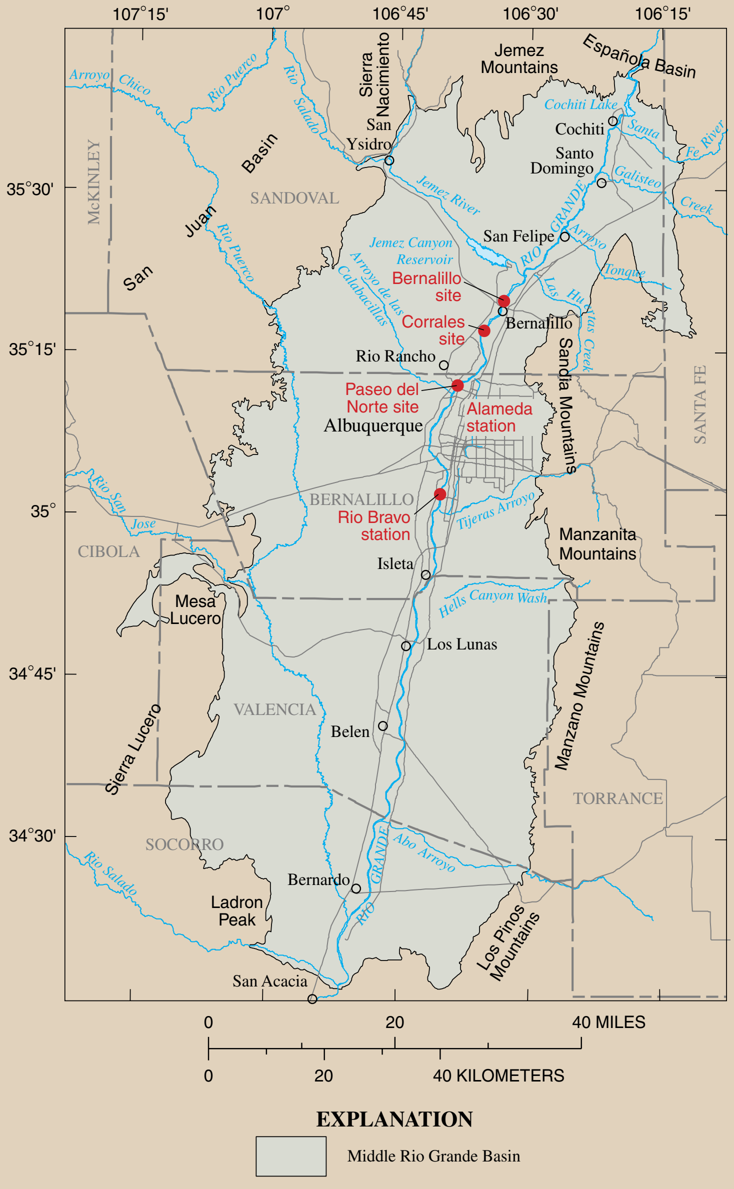


***Figure H.1.**—Locations of study sites on the Rio Grande for water temperature and flood pulses.*

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

into the riverbed, calculations were made of how fast water was seeping from the river into the aquifer.

Two studies have used “flood pulses,” in which water-level changes in the riverside drains and shallow wells close to the Rio Grande were monitored as they responded to large pulses of water released from Cochiti Lake and Jemez Canyon Reservoir (figs. *H.1* and 4.1) (Pruitt and Bowser, 1994; Roark, 1998). Water seepage from the river into the aquifer is fairly constant, and it is difficult to measure the influence of the river on the aquifer under these constant conditions. By releasing a “controlled flood” and raising the water level (or stage) in the river, a pulse of water is sent into the aquifer that can be detected in the riverside drains and wells near the river. The water-level data are then used with information on the geology of the area surrounding the river to construct simple ground-water-flow models to interpret the results.

Bartolino and Niswonger (1999) and Bartolino and Stewart (2001) measured the temperature of ground water in shallow wells close to the river at four sites to determine the direction and rate of flow between the river and aquifer system (fig. *H.1*). Ground water beyond the influence of surface water has a relatively constant temperature, whereas surface-water temperature fluctuates on daily and seasonal cycles. During the winter months, water in the Rio Grande tends to be colder than ground water, and in the summer months, Rio Grande water tends to be warmer than ground water (fig. *H.2*). By measuring relatively shallow ground-water temperatures at different depths next to, and distances from, the river, it is possible to use the unique temperature pattern, or “signature,” of the changing surface-water temperatures and the resulting effects on ground-water temperatures to determine the direction and rate of water flow between the river and aquifer. Results were interpreted using a heat-transport model.

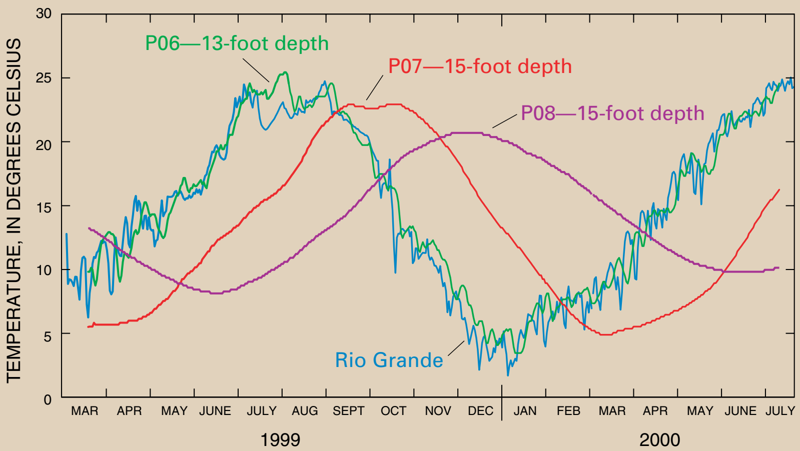


Figure H.2.*—Thermographs from Paseo del Norte section showing Rio Grande temperature and ground-water temperatures measured in wells P06, P07, and P08. P06 is on the east bank of the Rio Grande, P07 is 900 feet east, and P08 is 1,845 feet from the river and adjacent to the Albuquerque Riverside Drain. A delayed response and damping of water-temperature fluctuation can be seen with increasing distance from the river as water moves from the Rio Grande to the drain. These characteristics can be used to determine the direction and rate of water flow between the river and aquifer.*

The volume of water seeping from ground water or leaking into the aquifer along river reaches can be estimated by comparing careful measurements of Rio Grande flow and flow in riverside drains at different sites. Between December 1996 and February 1998, during the months of December, January, and February, weekly streamflow measurements were made at two sites: the Rio Grande near Alameda gaging station (08329928) and, 16 hours later, the Rio Grande at Rio Bravo Bridge gaging station (08330150). (The measurements were made 16 hours apart because that is the approximate traveltime of river water between the two stations.) At the Alameda station, there is one riverside drain on the east side of the river, whereas at the Rio Bravo Bridge station, there are drains on both sides of the river. For each measurement period, the release of water from Cochiti and Jemez Canyon Dams was held steady for 2 days prior to the first measurement and during subsequent measurements. Measurements were made in the winter months when water was not diverted into the irrigation system and flow tended to remain fairly constant. In addition, evapotranspiration is at a minimum during the winter months. Because of uncertainty associated with flow measurement in the Rio Grande, three river measurements were made and the values were averaged (J.E. Veenhuis, U.S. Geological Survey, written commun., 2002).

Bartolino and Sterling (2000) used a qualitative approach to investigating the connection between the Rio Grande and the aquifer using ground-based electromagnetic geophysical surveys along the Rio Grande. The electrical properties of the Rio Grande flood plain through the Albuquerque area were mapped during this study. With these data, reaches of the Rio Grande were delineated that were underlain by fine-grained deposits that tend to restrict water seepage between the river and aquifer. This information was then used in the construction of the revised ground-water-flow model of the Middle Rio Grande Basin (McAda and Barroll, 2002).

A *piezometer nest* consists of multiple wells screened at different depths in the aquifer at a single location. A piezometer nest may have all the wells in a single borehole or may have separate boreholes close together.

(Thorn, McAda, and Kernodle, 1993). A model of the San Juan Basin by Frenzel and Lyford (1982) estimated that approximately 1,200 acre-feet per year of ground water moved from the San Juan Basin into the Middle Rio Grande Basin as underflow. A model of the Tesuque aquifer system near Santa Fe by McAda and Wasiolek (1988) estimated that 12,600 acre-feet per year of ground water moved from the Española Basin into the Middle Rio Grande Basin. During calibration of their ground-water-flow model of the Middle Rio Grande Basin, McAda and Barroll (2002) determined underflow from adjacent basins to be 31,000 acre-feet per year, including the San Juan and Española Basins, as well as underflow from beneath the Jemez Mountains and the area around the Santa Fe River and Galisteo Creek. Geochemical methods using both standard water-chemistry and ground-water-age data also suggest the occurrence of underflow along the western and northern margins of the Middle Rio Grande Basin (Plummer and others, 2001).

Flow paths—How ground water moves through the aquifer system

Ground water travels from the area where it was recharged, through the aquifer, and to the point at which it discharges from the aquifer. The path followed by a "parcel" of water as it moves through the aquifer is known as a *flow path* or *flow line*. The discharge point can be either the natural end of the flow path, such as a spring or seep, or a well that intersects the flow path at some intermediate point. As discussed in Box *F*, water flows from areas of high hydraulic head to areas of low hydraulic head. Generally, scientists and engineers use ground-water-level maps to determine the direction of horizontal ground-water flow. By comparing water levels in piezometer nests, the direction of vertical ground-water movement can be determined. Ground-water-flow models use these head relations to determine overall directions and rates of ground-water movement.

Another method that is useful in determining ground-water movement and flow paths is ground-water age dating. By measuring the concentrations of certain substances and naturally occurring isotope ratios in ground water, calculations can be made to determine about when a parcel of water entered the aquifer. This method allows estimation of the rate at which water is moving through the aquifer. When combined with a ground-water-flow model, age-dating information can help to define the flow paths and the amount and rate of recharge.

Isotopes are different forms of the same chemical element with the same number of protons but different numbers of neutrons. The different isotopes of an element typically have slightly different chemical and physical properties that cause changes in their relative abundance as the result of different environmental processes. Isotopes can be naturally occurring, manmade, or sometimes both.

In the Middle Rio Grande Basin, interpretation of water-level data and ground-water-flow modeling led to the conclusion that prior to extensive ground-water development, ground water generally was recharged at the basin margins (or entered the basin as underflow) and moved toward the inner valley where it was discharged into surface water or evapotranspired (fig. 4.4 and Box *F*). With population growth and increased ground-water withdrawals in the Albuquerque area, City of Albuquerque production wells interrupted predevelopment flow paths. As ground-water levels declined, some flow paths reversed direction and water entered the aquifer from the river and moved toward the pumped wells. Predevelopment flow paths remain in most areas outside the population centers of the basin.

Recent water-chemistry studies by Plummer and others (2001) and Bexfield and Anderholm (2002) suggest that, except close to the basin margins, the predominant ground-water-flow direction in the basin has historically been north to south. Because water-chemistry patterns develop over long periods of time (as much as tens of thousands of years), these flow directions likely represent predevelopment conditions and not current conditions. Water chemistry of the Santa Fe Group aquifer system is discussed in more detail in the next chapter.

Discharge—How ground water leaves the aquifer system

Ground water leaves the Santa Fe Group aquifer system several ways: through pumpage from wells, seepage into the Rio Grande and riverside drains, springs, evapotranspiration, and outflow to the Socorro Basin (Kernodle, McAda, and Thorn, 1995; Anderholm, 1997).

Pumpage

As discussed on page 63, the volume and location of ground-water withdrawals from wells in the Middle Rio Grande Basin are poorly constrained estimates. Table 4.2 shows water-use estimates by county, though the data are for whole counties (not only the portion that lies in the Middle Rio Grande Basin). The area between Bernalillo and Belen is the most densely populated area of the basin; consequently, most of the ground-water pumpage occurs in this area. The ground-water-flow model of McAda and Barroll (2002) used a value of 150,000 acre-feet per year of ground-water withdrawal.

The Bernalillo Riverside Drain at Bernalillo. Such drains form part of a complex irrigation network that is intimately linked with the Rio Grande and Santa Fe Group aquifer system.

Seepage to drains and the Rio Grande and springs

Most of the seep or spring discharge from the Santa Fe Group aquifer system is into the drains of the inner valley or the Rio Grande. Because this discharge tends to be diffuse and below the water surface of the drains or river, it is difficult to measure and quantify directly. The ground-water-flow model of Kernodle, McAda, and Thorn (1995) estimated the flow volumes for 1994 to be 44,400 acre-feet of discharge into rivers, canals, and reservoirs and 219,000 acre-feet of discharge into drains. For 1999, the ground-water-flow model of McAda and Barroll (2002) estimated that 208,000 acre-feet per year of ground water discharged to riverside drains and 134,000 acre-feet per year of ground water discharged into interior drains. Box *H* describes other methods that have been used to quantify flow between the river and the aquifer.

I

Environmental tracers and how they are used to understand the aquifer

L. Niel Plummer[1]

Environmental tracers are natural and anthropogenic (manmade) chemical and isotopic substances that can be measured in ground water and used to understand hydrologic properties of aquifers (Alley, 1993; Cook and Herczeg, 1999). These substances occur in the atmosphere or soil and are incorporated into precipitation and into water that infiltrates through the soil to recharge the aquifer. Different types of environmental tracers can provide different types of information about an aquifer. For example, the concentrations of environmental tracers in ground water can be used to identify water sources, trace directions of ground-water flow, measure the time that has elapsed since recharge (ground-water age), and interpret environmental conditions that occurred during recharge. The most useful environmental tracers in hydrologic studies (fig. *I.1*) do not react chemically in the aquifer after recharge, have concentrations that vary according to source and(or) age of the water, and can be measured analytically with sufficient accuracy to allow detection in the aquifer.

Environmental tracers take several forms. Some are anthropogenic gases like chlorofluorocarbons (CFC's, Freon compounds). CFC's, first manufactured in the 1930's for use in refrigeration, air conditioners, and many other uses, were released into the atmosphere over time. Very small quantities have dissolved naturally in water and, because of extremely low analytical detection limits, are detectable in ground water recharged since the

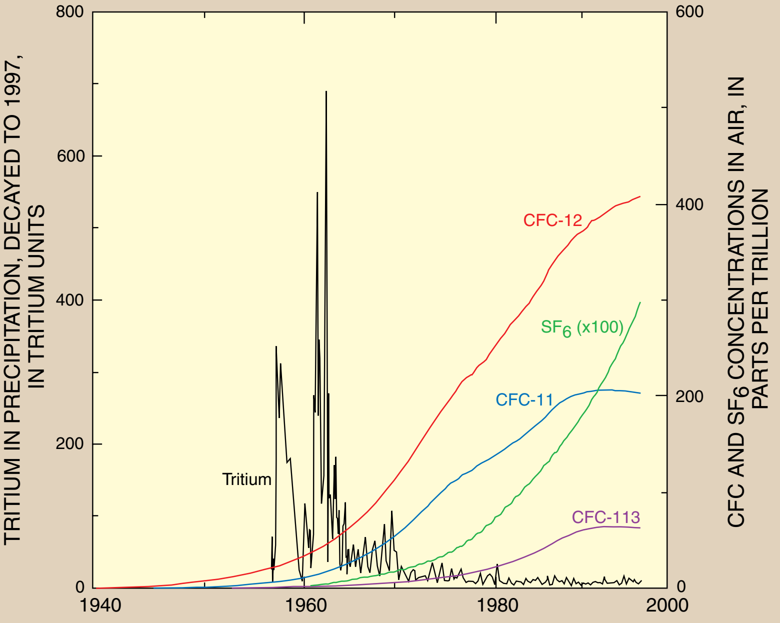


Figure I.1.—*Concentrations of tritium (^3H) in precipitation, chlorofluorocarbons (CFC-11, CFC-12, and CFC-113) in air, and sulfur hexafluoride (SF_6) in air over North America, 1940–97. The tritium concentrations in precipitation were decayed to 1997 for comparison with tritium concentrations (expressed as tritium units [TU]) measured in ground water as part of this study. A sample of water containing 1 TU has one tritium atom in 10^{18} hydrogen atoms—that is, 1:1,000,000,000,000,000,000. CFC and SF_6 concentrations in air are expressed as parts per trillion by volume (pptv). One pptv is one unit volume of the gas in 10^{12} volumes of air—that is, 1:1,000,000,000,000 by volume.*

1940's. Because CFC's allow scientists to find water that recharged recently, they improve the capability in the Middle Rio Grande Basin to trace seepage from the Rio Grande and recent recharge from arroyos and mountains and to detect leakage from landfills, industrial wastes, and septic tanks.

Some environmental tracers differ naturally in their isotopic composition, such as isotopes of hydrogen and oxygen in the water molecules themselves or isotopes of sulfur or carbon dissolved in ground water. Isotopes of a particular element have the same number of protons in the atomic nucleus but different numbers of neutrons. Thus, isotopes have the same atomic number but different atomic weights—a difference that permits precise

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analysis of their relative abundance. On Earth, most of the element hydrogen is in the form of ^{1}H (or hydrogen-1), called hydrogen; only 0.015 percent of all natural hydrogen on Earth occurs as the isotope ^{2}H, called deuterium; and less than 10^{-14} percent occurs in the form of ^{3}H, called tritium (Coplen, 1993), yet stable isotopes of hydrogen (and oxygen) are important environmental tracers in hydrology because their local abundance varies significantly with environmental factors such as temperature and altitude of precipitation, source of moisture, amount of rainfall, and extent of evaporation.

Stable isotopes of hydrogen and oxygen are particularly useful in the Middle Rio Grande Basin because water has recharged the aquifer at different altitudes and under different climatic conditions. For example, winter precipitation has less deuterium than summer precipitation in the basin. Also, ground water originating as seepage from the Rio Grande contains water from high-altitude snowmelt in southern Colorado and northern New Mexico and has less deuterium than precipitation falling in the relatively lower Albuquerque area or even in the Sandia Mountains east of Albuquerque. In addition, precipitation that fell 20,000 years ago during the last glacial period was colder than today and had less deuterium than today's precipitation (Drever, 1988; Wright, 1989). Therefore, the isotopic composition of hydrogen (and oxygen) has large variation in ground water of the Middle Rio Grande Basin. In combination with other environmental tracers and dissolved substances in ground water, these tracers have been used successfully to recognize sources of recharge and trace flow throughout the basin (see Box *K*).

Finally, some environmental tracers are radioactive—that is, they are unstable isotopes that radioactively decay naturally into more stable isotopes. For example, tritium, the radioactive isotope of hydrogen, is part of the water molecule along with hydrogen and deuterium. Tritium, produced mostly from above-ground testing of nuclear weapons in the mid-1960's, but also occurring naturally, continues to be in rainfall but undergoes radioactive decay at a known rate (half-life). Every 12.4 years, half of the tritium in a given amount of water decays to an isotope of helium. By measuring the amounts of tritium and helium isotopes, the approximate length of time since a parcel of water fell as precipitation can be determined.

In the Middle Rio Grande Basin, CFC's and tritium and helium isotopes were used to date ground water and to locate areas where recharge has occurred within the past 50 years, such as in the inner valley of the Rio Grande and along some arroyos and mountain-front areas. The resulting ground-water ages also provide calibration data for ground-water-flow models. Other environmental tracers that have been used in the Middle Rio Grande Basin include (1) carbon-14 (^{14}C, a radioactive isotope with a half-life of 5,730 years), which has been used to date ground water recharged during the past 30,000 years (see Box *N*), (2) sulfur-34 (^{34}S, a stable isotope of sulfur), which has been used to trace water from the Rio Grande near Albuquerque, and (3) sulfur hexafluoride (SF_6, a trace atmospheric gas that also occurs naturally in granites and other rocks), which has been used to trace recharge from the Sandia Mountains.

A USGS hydrologist collecting a water sample for chlorofluorocarbon analysis. To prevent contamination of the sample, water is collected without atmospheric contact and flame sealed in a glass ampoule.

Few springs in the Middle Rio Grande Basin discharge ground water onto the land surface from the Santa Fe Group aquifer system, and all that do so have low flow rates. Most are scattered along fault scarps west of the Sandia, Manzanita, and Manzano Mountains, though at least one is on the flanks of the Jemez Mountains (White and Kues, 1992).

Water naturally flowing from the subsurface onto the land surface or into a body of water is a *spring* (Meinzer, 1923; Jackson, 1997). A *seep* is similar but typically has too little flow to be considered a spring (Jackson, 1997). The term *seepage area* is sometimes used to indicate a broader area of more diffuse discharge (Todd, 1980). All typically occur where the water table intersects the land surface or a body of water.

Evapotranspiration

The amount of ground water lost to evapotranspiration is one of the most important yet unknown quantities in studies of the Middle Rio Grande Basin. Because it is very difficult to measure evapotranspiration in a natural setting, most estimates are based on broad assumptions or are indirect values derived from water budgets or models. Most evapotranspiration in the basin occurs in the inner valley of the Rio Grande from riparian vegetation such as cottonwood, tamarisk, and Russian olive (see Chapter 2). Estimates by the Bureau of Reclamation in 1989 suggest that the transpiration rate from riparian vegetation along the river is about 3 feet per year; when multiplied by the 37,300 acres of riparian vegetation along the Jemez River and Rio Grande this yields about 112,000 acre-feet of water a year lost to transpiration in the Middle Rio Grande Basin (Thorn, McAda, and Kernodle, 1993). The ground-water-flow model of McAda and Barroll (2002) estimated that evapotranspiration was 130,000 acre-feet per year for predevelopment conditions and 84,000 acre-feet per year for 1999 for the inner Rio Grande Valley and Jemez River. The values decrease because of lowering of the water table and reduction in the area covered by riparian vegetation. The Middle Rio Grande water budget of the Action Committee of the Middle Rio Grande Water Assembly (1999) estimated that between 75,000 and 195,000 acre-feet of water is lost annually to evapotranspiration by the bosque in the river reach between Otowi (north of the basin) and San Acacia (fig. 4.11).

A new generation of tools to quantify evapotranspiration is being used in the Middle Rio Grande Basin, led by the Bureau of Reclamation. The centerpiece of these efforts is the **A**gricultural **W**ater **R**esources **D**ecision **S**upport System (AWARDS) whose purpose is "to improve the efficiency of water management and irrigation scheduling by providing guidance on when and where to deliver water, and how much to apply" (Bureau of Reclamation, 2001a). Part of the AWARDS system is the ET Toolbox, which uses a network of weather stations to "accumulate high-resolution daily rainfall and water-use estimates within specified river reaches" (Bureau of Reclamation, 2001b). These estimates are available on the Internet for agricultural and water-management uses (the reader is referred to the "References Cited" on page 122 for the Web site addresses). Work is also underway to integrate **Li**ght **D**etection **A**nd **R**anging (LiDAR) technology, radar, and other atmospheric-measurement tools with standard weather data and plant-physiology measurements of individual trees to improve evapotranspiration measurements (Bureau of Reclamation, 2001c).

Underflow

Ground-water flow out of the Middle Rio Grande Basin appears to be limited to flow from the southern basin margin into the Socorro Basin. There has been a wide range of estimates for the volume of this flow, the highest being Kernodle and Scott's (1986) estimate of 15,000 acre-feet per year. The models of Kernodle, McAda, and Thorn (1995) and McAda and Barroll (2002) did not use a separate value for underflow out of the basin because the value was very small and was indistinguishable from evapotranspiration in the southern part of the model.

Effects of ground-water withdrawals

Unlike other means of discharge from the aquifer system, pumpage is not a natural process. If water is pumped from the aquifer system faster than it can be recharged or replaced, water is removed from storage and ground-water levels decline. Because the supply of water in an aquifer is limited, such pumping rates are not sustainable and will eventually deplete the resource and cause a number of adverse effects on the long-term use of the aquifer.

Deterioration of water quality

Few analyses have been made of the water chemistry in deeper parts of the Santa Fe Group aquifer system—that is, depths below current production zones (approximately 1,500–2,000 feet below land surface). Though some of the monitoring wells described on page 54 are completed below the production zone, chemical analyses of ground water from these wells do not all indicate similar trends in water chemistry with depth or show a clear temporal trend (Bexfield and Anderholm, 2002). Undesirable chemical constituents in water tend to increase with depth or distance along a flow path in many parts of the world (Freeze and Cherry, 1979). Any such increase in undesirable constituents in deeper zones of the Santa Fe Group aquifer system may be exacerbated by the presence of evaporites in parts of the middle and lower Santa Fe Group (Hawley and Haase, 1992).

Bexfield and Anderholm (2002) conducted the only systematic analysis of long-term trends in ground-water chemistry in the Middle Rio Grande Basin. Using data for City of Albuquerque production wells collected over a 10-year period, they determined that water quality appears to be degrading over time in some locations but not in others. Moreover, different water-chemistry constituents showed different trends. Bexfield and Anderholm also determined that correlations between water chemistry and monthly pumpage volume were common but not consistent between different wells. They concluded that water in and near the production zone typically became poorer in quality with depth, although shallow water that has been affected by evapotranspiration or contamination can be of poorer quality than water at greater depths.

Aquifer *storage* refers to the ground water held in an aquifer, much as surface water is held in a reservoir. However, not all the water in storage in an aquifer is available for withdrawal. After water drains from an (unconfined) aquifer by the force of gravity, a thin film of water will remain on the rock openings in the aquifer due to capillary forces. Generally, the larger the openings in the rock, the less the volume of water retained. Fine-grained aquifer materials such as clay tend to retain a much higher percentage of water after the unconfined aquifer is drained by the force of gravity (Heath, 1983).

In some areas of the United States, withdrawal of good-quality water from the upper parts of an aquifer has allowed underlying saline water to move upward and degrade water chemistry (Alley, Reilly, and Franke, 1999). Because so little is known about water chemistry in the lower parts of the aquifer, the potential for a similar occurrence in the Middle Rio Grande Basin cannot be evaluated.

Localized subsidence has been noted in the Albuquerque area.

Water-well problems

Declining ground-water levels have two main effects on water wells. First, as the depth to water increases, the water must be lifted higher to reach the land surface. As the lift distance increases, so does the energy required to drive the pump. Thus, power costs increase as ground-water levels decline. Depending on the use of the water and energy costs, it may no longer be economically feasible to use water for a given purpose. Second, ground-water levels may decline below the bottom of existing wells, necessitating the expense of deepening the well or drilling a deeper replacement well.

Another effect related to ground-water production was described by Haneberg and others (1998) from physical measurements made on core samples from the 98th Street well. The measurements show that greater decline of water levels in the aquifer may reduce the hydraulic conductivity of the aquifer, resulting in larger water-level drawdowns and increased pumping costs.

Subsidence

Nearly every State in the Southwest has areas with land subsidence related to the withdrawal of ground water. For example, in the Mimbres Basin near Deming, New Mexico, widespread land subsidence has occurred with water-level declines of 115 feet and less (Contaldo and Mueller, 1991; Haneberg and Friesen, 1995). Though several different processes can be responsible for such land subsidence, compaction of aquifer materials is of most concern in the Middle Rio Grande Basin. Currently (2002), maximum water-level declines in the Middle Rio Grande Basin are more than 160 feet in some locations (figs. 4.4–4.6).

In the Middle Rio Grande Basin, as much as 330 feet of sediment has been eroded from the center of the basin. The additional weight created by the 330 feet of sediments originally in place compacted the aquifer sediments beyond levels expected from the current thickness of the deposit. This overconsolidation in the past allows a greater water-level decline to occur today before the onset of aquifer compaction and land subsidence. Using information from five wells in the Albuquerque area, Haneberg (1995) calculated that “there is a considerable potential for widespread land subsidence if drawdown approaches the 260- to 390-foot range.” However, these calculations involved the estimation of several parameters, and Haneberg (1995) noted that they were “imprecise and highly speculative.”

Three methods are currently being used to monitor for the onset of land subsidence in the Middle Rio Grande Basin: repeated surveys of elevation for a network of benchmarks, an extensometer, and **In**terferometric **S**ynthetic **A**perture **R**adar (InSAR) analysis (see Box *J*). Currently (2002), the surveys of the benchmark network and the extensometer have not detected land subsidence greater than 0.5 inch, though both methods monitor limited areas of the basin. However, an InSAR analysis of part of the Middle Rio Grande Basin for five periods between July 1993 and September 1999 detected land subsidence and recovery in several areas in Albuquerque and Rio Rancho (fig. *J.2*). Maximum subsidence was 2 inches and maximum uplift was 0.5 inch caused by both elastic and inelastic deformation (C.E. Heywood, U.S. Geological Survey, written commun., 2002).

A second type of land subsidence from ground-water withdrawals, the dewatering of organic soils, is occurring in the Middle Rio Grande Basin. Kernodle, McAda, and Thorn (1995) described land subsidence of as much as 2 feet in the center of broad depressions in the Rio Grande inner valley in the Albuquerque area. These areas of subsidence were correlated with “swampy or transitional wetlands mapped from 1935 aerial photography” and were attributed to the “lowering of the water table and dehydration of shallow beds of clay- and organic-rich material.” This land subsidence is permanent and irreversible; however, only limited areas of the basin in the inner valley are susceptible to this type of compaction. In addition, some areas of the basin contain hydrocompactive or collapsible soils (Connell, Love, and Harrison, 2001). Though not related to ground-water withdrawals, the collapse of these soils has caused damage to roads, utilities, and buildings in the basin and throughout the State and may be mistaken for subsidence.

Hydrocompactive or *collapsible soils* are loose, dry, low-density deposits with high porosity. When wetted, such as by irrigation, they disaggregate and compact, with the individual grains collapsing to a more compact arrangement much in the same way that a house of cards collapses. In the Middle Rio Grande Basin, typical geologic settings for these deposits are young, alluvial-fan, alluvial-slope, or valley-fill environments that have not been saturated since deposition (Dennen and Moore, 1986; Connell, Love, and Harrison, 2001).

J

Land subsidence and how it is being studied in the basin

Charles E. Heywood,[1] James R. Bartolino,[1] and Devin L. Galloway[2]

Galloway, Jones, and Ingebritsen (1999) defined land subsidence as “a gradual settling or sudden sinking of the Earth’s surface owing to subsurface movement of earth materials.” Though they noted that several different Earth processes can cause subsidence, more than 80 percent of the subsidence in the United States is related to the withdrawal of ground water. They also defined three main mechanisms by which ground-water withdrawals cause land subsidence: compaction of aquifer systems, dewatering of organic soils, and collapse of subsurface cavities. Of these three mechanisms, only the first two are of potential concern in the Middle Rio Grande Basin.

Because water supplies in the Southwest are primarily from ground water, most Southwestern States have areas that have experienced or are experiencing subsidence caused by ground-water withdrawal. When ground water is pumped, the removal of water reduces the pore-fluid pressure, which in turn transfers more stress to the rock matrix of the aquifer system (intergranular or effective stress). As long as ground-water levels remain above a certain elevation (which depends on the geologic and water-level history of the aquifer system), pore-fluid pressure is maintained and the effective stress remains above a critical level. Water-level fluctuations above this critical stress threshold cause elastic, or reversible, deformation of the aquifer system. If ground-water levels fall below this elevation, however, the aquifer-system matrix may compact to a more stable arrangement, resulting in a more substantial volumetric reduction that is inelastic, or irreversible. Subsidence is the surficial manifestation of this inelastic compaction and is especially prevalent over aquifer systems containing large deposits of fine-grained sediment and significant long-term water-level declines. Excessive pumping of ground water in the Santa Clara Valley of California, for example, caused more than 14 feet of land subsidence in downtown San Jose. Despite a reduction of pumping and subsequent rebound in ground-water levels, this subsidence was permanent. Land subsidence from ground-water withdrawal is also known to have occurred in Deming, New Mexico, Las Vegas, Nevada, the Tucson-Phoenix areas, and elsewhere in south-central Arizona. Subsidence in various areas of the Nation is likely responsible for annual losses of hundreds of millions of dollars as a result of structural damage and flooding of lowered land surfaces (Galloway, Jones, and Ingebritsen, 1999).

In the Middle Rio Grande Basin, three methods are being used to check for the onset of land subsidence related to ground-water withdrawals. In the Albuquerque area, a high-precision survey network consisting of 44 benchmarks was established in 1993, using both existing survey markers and new markers installed for the study. By periodically resurveying this network of benchmarks, changes in their elevations can be detected. Repeat survey techniques originated in the 19th century; however, advances in survey instrumentation have improved measurement efficiency and accuracy. The **G**lobal **P**ositioning **S**ystem (GPS), which uses timed microwave signals from satellites to determine location and elevation, can be used to survey a network of benchmarks with accuracies typically on the order of 0.4 to 0.8 inch. The Albuquerque subsidence network was surveyed with GPS in 1993 and 1994 but GPS did not detect land subsidence greater than 0.5 inch (C.E. Heywood, U.S. Geological Survey, written commun., 1995).

In 1994, the Montaño borehole extensometer was installed to a depth of 1,035 feet in northern Albuquerque about 0.6 mile east of the Rio Grande. A borehole extensometer is a vertical strain gage that detects compression and expansion of an aquifer system (fig. *J.1*). A borehole extensometer is constructed by drilling a straight, vertical hole to a depth below the zone of the aquifer system to be measured. The hole is cased with steel pipe containing slip-joints, which allow the casing to deform vertically with the surrounding aquifer system. A smaller diameter pipe is suspended inside this well casing and allowed to rest lightly on the bottom of the well. Because the length of the extensometer pipe does not change, it moves upward relative to the land surface as the aquifer system compresses. The displacement of the top of the extensometer pipe with respect to a surface datum (benchmark) is accurately measured with an electronic strain gage and analog recorder. Currently (2002), the extensometer has not detected land subsidence greater than 0.5 inch (Heywood, 1998; Galloway, Jones, and Ingebritsen, 1999).

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Both the GPS network and the extensometer monitor land subsidence at discrete locations in the Middle Rio Grande Basin. **In**terferometric **S**ynthetic **A**perture **R**adar (InSAR), a fairly recent development in the Earth sciences, complements these techniques by mapping the spatial distribution of land-surface elevation changes. In standard **S**ynthetic **A**perture **R**adar (SAR) mapping, which has been used for mapping topographic features on the Earth and other planets, the distance to the land surface from the radar antennae on a satellite or aircraft is determined from the round-trip traveltime of the radar waves. The InSAR process compares two SAR images of the same area made at different times and generates an image of the land-surface displacements (an interferogram) that have occurred between the two SAR scenes. With InSAR it is possible to detect land-surface changes of 0.2 to 0.4 inch over an image pixel (about 17,000 to 69,000 square feet) from satellite imagery (Galloway, Jones, and Ingebritsen, 1999).

InSAR analysis of part of the Middle Rio Grande Basin for five periods between July 1993 and September 1999 detected land subsidence and uplift in several areas in Albuquerque and Rio Rancho (C.E. Heywood, D.L. Galloway, and S.V. Stork, U.S. Geological Survey, written commun., 2001). One interferogram (fig. *J.2*) shows a maximum of about 0.6 inch of land subsidence in several areas of Albuquerque and about 2 inches in an area near Rio Rancho well 16, which produced 250 to 290 acre-feet of water per month from September 1994 through September 1995. The subsequent interferogram shows land-surface uplift (or rebound) in these areas. The sequence of five interferograms, in conjunction with water-level data, shows elastic, and possibly inelastic, aquifer-system deformation in the Middle Rio Grande Basin.

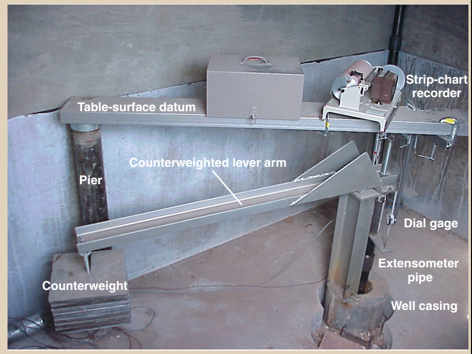

Figure J.1.*—Surface instrumentation of the Montaño extensometer. The top of the well casing is on the right; a counter-weighted lever arm balances 80 percent of the weight of the extensometer pipe. A table suspended between piers anchored 15–20 feet below land surface provides the surface datum; a strip-chart recorder rests on this table. Displacements between the extensometer pipe and the table-surface datum are measured with an electronic strain gage, the strip-chart recorder, and a dial gage.*

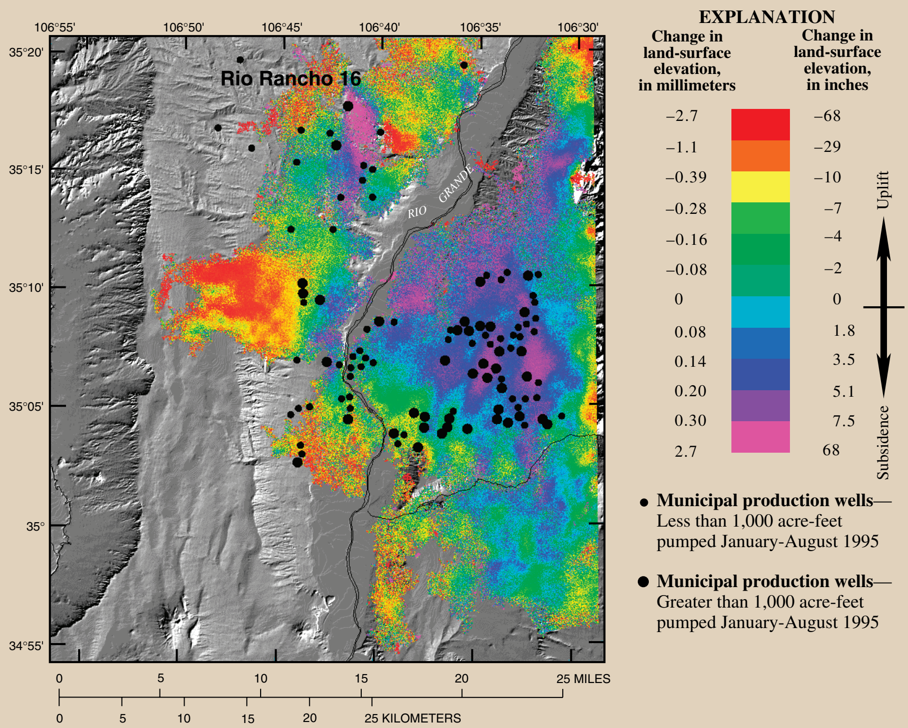

Figure J.2.*—Interferometric Synthetic Aperture Radar (InSAR) image of the Albuquerque area, July 2, 1993–September 3, 1995. Maximum subsidence of 2 inches is shown in the Rio Rancho area by purple and blue. The linear boundaries of subsidence features are parallel to and in the approximate locations of mapped faults in the area. In the Albuquerque area, maximum subsidence is about 0.4 to 0.6 inch and is also shown by purple and blue. Municipal wells are shown as black dots sized according to January–August 1995 production.*