Cover description:

Landsat thematic mapper mosaic of the Middle Rio Grande Basin. The four scenes used in the image were acquired in September 1993. Bands 1, 4, and 7 are displayed through blue, green, and red filters, respectively. The image has been output at 30-meter resolution by cubic convolution resampling to fit the North American Datum of 1983 (NAD83) in a Universal Transverse Mercator (UTM) projection. A terrain correction was included in the processing using USGS 1:24,000-scale Digital Elevation Model (DEM) data. Image compiled by the USGS Astrogeology Program, Flagstaff Field Center. See Mullins and Hare (1999) for a more complete description of the image.

Mullins, K.F., and Hare, T.M., 1999, Calibration, processing, and production of a Landsat thematic mapper mosaic of the Middle Rio Grande Basin Study area, *in* Bartolino, J.R., ed., U.S. Geological Survey Middle Rio Grande Basin Study—Proceedings of the Third Annual Workshop, Albuquerque, New Mexico, February 24–25, 1999: U.S. Geological Survey Open-File Report 99–203, p. 15–17.

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GROUND-WATER RESOURCES OF THE MIDDLE RIO GRANDE BASIN

By

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Foreword

In 1995, the agency primarily responsible for managing water resources in New Mexico, the Office of the State Engineer, declared the Middle Rio Grande Basin a “critical basin”; that is, a ground-water basin faced with rapid economic and population growth for which there is less than adequate technical information about the available water supply. This declaration was largely the result of studies of the ground-water resources of the Middle Rio Grande Basin by the New Mexico Bureau of Geology and Mineral Resources (formerly the New Mexico Bureau of Mines and Mineral Resources) and U.S. Geological Survey (USGS) in cooperation with the City of Albuquerque that showed conclusively that many aspects of the popular understanding of water resources of the basin were incorrect. The two most important conclusions of these studies were that there is significantly less ground water available for supply than previously thought and that the Rio Grande contributes less water to the Santa Fe Group aquifer system than was previously believed. Both conclusions have had and will continue to have major impacts on how water is used, allocated, and managed in the basin. However, these studies also revealed gaps in the understanding of the water resources of the basin. In an effort to fill some of these gaps, the USGS and other agencies began the Middle Rio Grande Basin Study, a 6-year effort to improve the understanding of the hydrology, geology, and land-surface characteristics of the Middle Rio Grande Basin.

An important aspect of the USGS mission is to provide information that describes the Earth, its resources, and the processes that govern the availability and quality of those resources. With reports such as this Circular, the USGS seeks to broaden public understanding of water resources and the processes that affect those resources. Our hope is that this improved understanding will contribute to another goal of the USGS: the use of this scientific information to enhance and protect our quality of life.

This Circular presents an overview of our current understanding of the water resources of the Middle Rio Grande Basin, with an emphasis on ground water. This report is written for a wide audience of people interested or involved in the use of water resources in the Middle Rio Grande Basin. It is intended to serve as a general educational document rather than a report of new scientific findings, though much of the information it contains is the result of new studies performed as part of the Middle Rio Grande Basin Study. This Circular, coupled with ongoing data collection and research, is the USGS contribution toward a sound scientific basis for water managers and policy makers to make informed decisions about the water resources of the basin with the goal of meeting current needs and assuring a sustainable supply for future generations.

Charles G. Groat
Director, U.S. Geological Survey

Acknowledgments

This report is not only the culmination of the 6-year Middle Rio Grande Basin Study, but also of the work of many preceding scientists and engineers. Some of the most notable scientists in the fields of geology and hydrology have worked in the Middle Rio Grande Basin at some point in their careers, including Kirk Bryan and C.V. Theis. The authors wish to acknowledge the contribution of all those who have contributed to the current understanding of the hydrogeology of the basin. The oft-quoted remark of Lucan (Marcus Annaeus Lucanus, A.D. 39–65) applies: "Pigmies placed on the shoulders of giants see more than the giants themselves."

Technical assistance (in the form of discussions and suggestions) was provided by S.K. Anderholm, J.W. Hawley, D.P. McAda, D.G. Woodward, and all the scientists who worked on the Middle Rio Grande Basin Study. Other nontechnical assistance was provided by L.V. Beal, R.A. Durall, and D.E. Straka.

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In addition to the U.S. Geological Survey, many other Federal, State, and local governments and agencies contributed resources to or cooperated in the characterization of the water resources, geology, and land surface of the Middle Rio Grande Basin. These governments and agencies include the City of Albuquerque, New Mexico Office of the State Engineer, New Mexico Bureau of Geology and Mineral Resources, Albuquerque Metropolitan Arroyo Flood Control Authority, Middle Rio Grande Council of Governments, Middle Rio Grande Conservancy District, Bureau of Reclamation, Pueblo of Cochiti, Pueblo of Isleta, Pueblo of Jemez, Pueblo of Laguna, Pueblo of San Felipe, Pueblo of Sandia, Pueblo of Santa Ana, Pueblo of Santo Domingo, Pueblo of Zia, City of Santa Fe, Village of Los Lunas, Bernalillo County, Santa Fe County, New Mexico Environment Department, Sandia National Laboratories, Los Alamos National Laboratory, U.S. Environmental Protection Agency, and the U.S. Army Corps of Engineers.

Final layout was prepared by A.J. Brogan with design input from R.J. Olmstead, illustration support from J.M. Evans and S.P. Clendening, and editorial review by M.A. Kidd, all of the U.S. Geological Survey, Denver, Colorado. Final versions of all figures were prepared by Alice and J.T. Springfield of Springfield and Springfield, Fort Collins, Colorado. All photographs are by J.R. Bartolino except as noted.

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Conversions

This Circular uses both inch/pound (U.S. customary) and International System of Units (SI metric) units. The conversion factors listed below are provided to convert between inch/pound and SI metric units, or different units in the same systems.

Measurement	Multiply	By	To Obtain
Length	inch	25.4	millimeter (mm)
	foot (ft)	0.3048	meter (m)
	mile (mi)	1.609	kilometer (km)
Area	square mile (mi^2)	2.590	square kilometer (km^2)
	acre (acre)	0.4047	hectare (ha)
Volume	acre-foot (acre-ft)	1,233	cubic meter (m^3)
	gallon	0.003785	cubic meter (m^3)
	cubic foot (ft^3)	0.02832	cubic meter (m^3)
Flow rate	cubic foot per second (ft^3/s)	0.2832	cubic meter per second (m^3/s)
	cubic foot per second (ft^3/s)	723.97	acre-foot per year (acre-ft/yr)
	cubic foot per second (ft^3/s)	448.83	gallon per minute (gal/min)
Hydraulic conductivity	foot per day (ft/d)	0.3048	meter per day (m/d)
Temperature	degree Fahrenheit (°F)	(°F–32)/1.8	degree Celsius (°C)
Tritium activity	tritium unit (TU)	3.24	picocuries per liter (pCi/L)
Magnetism	Tesla (T)	1	weber per square meter (Wb/m^2)
Gravity	gal (Gal)	1	centimeter per second squared (cm/s^2)

Electrical conductivity units are given in siemens (S), which is the preferred unit name under the International System of Units. It is numerically equivalent to the older term mhos.

Electrical resistivity can be converted to electrical conductivity (siemens per meter) by taking its inverse.

Vertical Datum

In this report, “sea level” refers to the National Geodetic Vertical Datum of 1929 (NGVD of 1929)—a geodetic datum derived from a general adjustment of the first-order level nets of the United States and Canada, formerly called Sea Level Datum of 1929.

Base Credits

All maps of the Middle Rio Grande Basin in this report are in Lambert Conformal Conic projection with standard parallels 33°00' and 45°00' north latitude, and central meridian 106°00' west longitude. The base for figure 3.1 was compiled from U.S. Department of Commerce, Bureau of Census TIGER/line Precensus Files, 1990, scale 1:100,000.

The base for the maps of the Middle Rio Grande Basin was compiled from several sources. The hydrography is from 1977–78 U.S. Geological Survey digital data, scale 1:100,000. Cultural features are from 1992 City of Albuquerque digital data, scale 1:2,400, and digitized from 1977–78 U.S. Geological Survey maps, scale 1:100,000. Other sources are noted on the maps themselves.

Executive Summary

The Middle Rio Grande Basin covers approximately 3,060 square miles in central New Mexico, encompassing parts of Santa Fe, Sandoval, Bernalillo, Valencia, Socorro, Torrance, and Cibola Counties. In this report, “Middle Rio Grande Basin” refers to the geologic basin defined by the extent of deposits of Cenozoic age along the Rio Grande from about Cochiti Dam to about San Acacia. In 2000, the population of the Middle Rio Grande Basin was about 690,000, or about 38 percent of the population of New Mexico (U.S. Census Bureau, 2001a, 2001b).

In 1995, the New Mexico Office of the State Engineer declared the Middle Rio Grande Basin a “critical basin”; that is, a ground-water basin faced with rapid economic and population growth for which there is less than adequate technical information about the available water supply. Though the basin had been intensively studied for a number of years, important gaps remained in the understanding of the water resources of the basin. In an effort to fill some of these gaps, the U.S. Geological Survey (USGS) and other Federal, State, and local agencies began the Middle Rio Grande Basin Study, a 6-year effort to improve the understanding of the hydrology, geology, and land-surface characteristics of the basin.

Characteristics of the Middle Rio Grande Basin

Much of the Middle Rio Grande Basin is classified as desert, with mean annual precipitation ranging from 7.6 inches at Belen to 12.7 inches at Cochiti Dam. Mean annual temperatures range from 54.0° F at Corrales to 56.5° F at Albuquerque and Belen (National Weather Service, 2002).

Scurlock (1998) listed eight main plant communities in the present-day Middle Rio Grande Basin and bordering mountains. They are, in a progression from near the Rio Grande to the mountaintops: riparian, desert grassland, plains-mesa grassland, scrublands, juniper savanna, pinyon-juniper woodlands, ponderosa pine, and subalpine and mixed coniferous forest. The vegetation of the riparian woodland (or bosque) has evolved significantly since the introduction of exotic species prior to 1900 and the construction of flood-control and bank-stabilization projects. During the last 60 to 70 years, the bosque has developed in an area that was formerly semibarren flood plain.

The Albuquerque area began to grow significantly during and after the Second World War. Postwar growth expanded the economic base of the area and led to a population increase in Albuquerque from about 35,000 to about 200,000 people between 1940 and 1960 (Reeve, 1961). This population growth led to increased pumping of ground water.

Geology

The Middle Rio Grande Basin lies in the Rio Grande rift valley, a zone of faults and basins that stretches from Mexico north to approximately Leadville, Colorado (about 150 miles north of the New Mexico border)—the modern Rio Grande follows this rift valley. The rift formed more than 25 million years ago and initially consisted of a succession of topographically closed basins. These closed basins filled with sediment from the adjacent mountain ranges, dune deposits from windblown sand, and volcanic deposits from local volcanic areas such as the Jemez Mountains. Flowing southward into and through the successive basins in the rift, the Rio Grande deposited river-borne sediment and established the through-flowing river seen today. About 3 million years ago the Rio Grande began to erode into sediment that it had deposited previously, suggesting that the river drained all the way to the Gulf of Mexico. Basin-fill deposits derived from all these sources (deposited in both open- and closed-basin conditions) are known as the Santa Fe Group and range from about 1,400 feet thick at the basin margins to approximately 14,000 feet in the deepest parts of the Middle Rio Grande Basin. The Santa Fe Group, in addition to younger alluvial deposits along the Rio Grande, makes up the Santa Fe Group aquifer system.

Each of the different settings in which sediment was deposited in the Middle Rio Grande Basin (such as mountain-front alluvial fans, rivers and streams, or sand dunes) resulted in a unique type of sedimentary deposit. These deposits are a complex mixture of different sediment types and grain sizes that change rapidly in the vertical and horizontal directions. Some of these deposits make better aquifer material than others, resulting in variations in the quantity and quality of water produced from wells installed in different locations.

Faults throughout the basin further increase the complexity of the aquifer system. Ground-water flow can be restricted across faults by offsetting units of different permeability or enhanced along faults by the presence of fractured rock. Over time, such fractures may become barriers to flow because of the precipitation of chemical cements in the fractures.

Surface, airborne, and borehole-geophysical techniques have been used to improve the understanding of the geologic framework of the Santa Fe Group aquifer system. Such properties as magnetism, gravity, electrical properties, and natural radioactivity have allowed scientists to better define the boundaries of the aquifer system, faults, and areas underlain by a more permeable aquifer material.

Geologic information collected for the Middle Rio Grande Basin Study has been incorporated into a new conceptualization of the composition of the aquifer system. This improved understanding has been formalized into a three-dimensional geologic model that is the basis for a new ground-water-flow model of the basin.

Surface Water

In the Middle Rio Grande Basin, the surface- and ground-water systems are intimately linked through a series of complex interactions. These interactions can make it difficult to recognize the boundary between the two systems, and changes in one often affect the other. The most prominent hydrologic feature in the basin is the Rio Grande, which flows through the entire length of the basin, generally from north to south. The fifth longest river in North America, its headwaters are in the mountains of southern Colorado. Flow in the Rio Grande is currently (2002) regulated by a series of dams and storage reservoirs. The greatest flows occur in late spring as a result of snowmelt and for shorter periods during the summer in response to rainfall. Historically, the Rio Grande has flowed year-round through much of the basin, except during severe drought. Within the basin, tributary steams, wastewater-treatment plants, flood-diversion channels from urban areas, and a large number of arroyos and washes contribute flow to the river.

The inner valley of the Rio Grande contains a complex network of irrigation canals, ditches, and drains. During irrigation season, water is diverted from the river at four locations in the basin and flows through the Rio Grande inner valley in a series of irrigation canals and smaller ditches for application to fields. This water recharges ground water, is lost to evaporation, is transpired by plants, or is intercepted by interior drains and returned to the river. Besides the Rio Grande, the inner-valley surface-water system also contains 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. The drains then carry this ground water back to the Rio Grande.

Estimated and measured annual surface-water inflow into the Middle Rio Grande Basin is about 1,330,000 acre-feet (for water years 1974–2000) and measured annual surface-water outflow is about 1,050,000 acre-feet (for water years 1974–2000). Currently (2002), the primary consumptive use by humans of surface water in the Middle Rio Grande Basin is irrigation in the inner valley of the Rio Grande. Other water is consumed by reservoir evaporation, recharge to ground water, and evapotranspiration by riparian vegetation. Other nonconsumptive uses include recreation, esthetics, and ceremonial use by Native Americans.

Ground Water

The Santa Fe Group aquifer system is divided into three parts: the upper (from less than 1,000 to 1,500 feet thick), middle (from 250 to 9,000 feet thick), and lower (from less than 1,000 to 3,500 feet thick). In places, the upper part and(or) the middle part of the aquifer has eroded away. Much of the lower part may have low permeability and poor water chemistry; thus, ground water is mostly withdrawn from the upper and middle parts of the aquifer. Only about the upper 2,000 feet of the aquifer is typically used for ground-water withdrawal. Ground water from the Santa Fe Group aquifer system is currently the sole source of water for municipal supply, domestic, commercial, and industrial use in the Middle Rio Grande Basin.

The depth to water in the Santa Fe Group aquifer system varies widely, ranging from less than 2 feet near the Rio Grande to about 1,180 feet in an area west of the river beneath the West Mesa. Effects of ground-water pumping are not evident on the earliest ground-water-level maps of the Middle Rio Grande Basin (1936 conditions). However, a ground-water-level map showing more recent conditions (winter 1994–95) shows well-defined cones of depression in the Albuquerque and Rio Rancho areas and marked distortion of water-level contours across the Albuquerque area. Water levels in a network of 255 wells are being measured to monitor further water-level changes.

Water enters the Santa Fe Group aquifer system in four main settings: mountain fronts and tributaries to the Rio Grande, the inner valley of the Rio Grande, the Rio Grande, and subsurface basin margins. Water entering the aquifer in the first three settings is usually termed recharge, whereas water entering the basin in the subsurface is typically termed underflow.

Ground water discharges from the Santa Fe Group aquifer system in several ways: pumpage from wells, seepage into the Rio Grande and riverside drains, springs, evapotranspiration, and subsurface outflow to the Socorro Basin. If ground-water pumpage from an aquifer exceeds recharge, water levels in the aquifer decline, as has been observed in the Middle Rio Grande Basin. These declining water levels can have adverse effects that influence the long-term use of the aquifer, including deterioration of water quality, water-well problems, and land subsidence.

Ground-Water Chemistry

A useful approach to characterizing ground-water chemistry in the Middle Rio Grande Basin is to divide the basin into 13 zones, or regions, of different water-chemistry characteristics. The median concentrations of two constituents (chloride and sulfate) exceed the U.S. Environmental Protection Agency (USEPA) secondary standards for drinking water in several zones. Arsenic concentrations in ground water exceeded the USEPA primary standard (finalized in 2001) of 0.010 milligram per liter (mg/L) of arsenic in one zone.

Most of the ground water in the basin is not very susceptible to contamination because the depth to water in most areas is greater than 100 feet. Deposits in the inner valley of the Rio Grande, however, are more susceptible to contamination because the depth to water is generally less than 30 feet. There are four Superfund sites, three RCRA (Resource Conservation and Recovery Act of 1976) sites, and about 700 former and present leaking underground-storage-tank sites in the Middle Rio Grande Basin.

Ground-Water-Flow Modeling

Several ground-water-flow models of the Middle Rio Grande Basin have been developed. The most recent (2002) is a USGS model that incorporates new hydrogeologic data collected since 1995 (McAda and Barroll, 2002). The model encompasses the entire thickness of the Santa Fe Group in order to simulate probable flow paths in the lower part of the aquifer. Model simulations show that (1) prior to installation of the riverside drains along the Rio Grande, the river was losing flow, though currently (2002) the drains intercept much of this flow and divert it back into the river; (2) the Rio Grande and riverside drains are so closely related, especially during the nonirrigation season, that they function as one system; (3) 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; (4) in much of the Santa Fe Group aquifer system throughout the basin, water removed from storage is partially replaced during the nonirrigation season; and (5) mountain-front recharge to the Santa Fe Group aquifer system is less than amounts estimated by previous models.

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. However, it does provide water-resource managers a more accurate and powerful tool than previous models to evaluate the potential effects of management decisions.

Chapter 1: Common questions about water resources in the Middle Rio Grande Basin

This report summarizes the current (2002) understanding of water resources in the Middle Rio Grande Basin. The basin provides the water supply for the City of Albuquerque and other growing communities in the basin (with a combined population of about 690,000), as well as water for agricultural, industrial, and other uses. The goal of the Middle Rio Grande Basin Study is to provide the most complete scientific understanding of the hydrologic system in the region as a foundation for water-management policy. The goals of this report are to give the reader a better understanding of the major components of the hydrologic system and how the components interact, describe some of the scientific contributions of the Middle Rio Grande Basin Study, and describe how a ground-water-flow model is constructed and how it can be used to aid water-management decisions.

How much water do we have?

The answer to this question depends on our understanding of the natural hydrologic system as well as legal constraints on the management of water resources in the Middle Rio Grande Basin. Though scientists cannot definitively estimate how much available water remains in the aquifer system, Chapter 4, “The hydrologic system of the Middle Rio Grande Basin” (p. 41), describes the water resources in the basin and issues that affect the management of those resources.

City of Albuquerque production well Leyendecker no. 1.

How much water do we use?

Water use by municipalities can be quantified with some certainty; however, a large number of production wells in the Middle Rio Grande Basin are not metered, and irrigation use can only be estimated. The “Water use in the basin” section on page 60 describes what is known about water use in the basin.

How long will our supplies last?

Santa Fe Group sediments exposed near Bernalillo. Such deposits form some of the most productive zones of the aquifer.

A definitive estimate of how long water supplies of suitable quality and quantity will last in the Middle Rio Grande Basin is not possible. The answer depends on future population growth rates and water demand, new technologies for producing or recharging water, newly available sources of water, and the environmental, economic, and social changes we are willing to accept in using ground and surface water. Currently, water is being withdrawn from the aquifer faster than it is being recharged or replaced; thus, ground-water levels are declining. Such ground-water use will eventually deplete the aquifer because there is a finite volume of water in the aquifer. As a result, Albuquerque is currently (2002) planning to use surface water to help create a sustainable water supply. Chapter 4, “The hydrologic system of the Middle Rio Grande Basin” (p. 41), discusses what is known about water supplies in the basin, and the “Effects of ground-water withdrawals” section (p. 85) describes the possible effects of declining water levels in the aquifer.

How effective are water conservation efforts in the area?

The City of Albuquerque reduced its water use by 23 percent between 1995 and 2000, with a stated goal of a total reduction of 30 percent by 2005 (City of Albuquerque Public Works Department, 2000). The Middle Rio Grande Conservancy District is currently considering ways to increase irrigation efficiency (Shah, 2001). By reducing water use, less ground water is pumped from the aquifer, and more remains available for future use. The “Water use in the basin” section on page 60 describes what is known about water use in the basin.

How rapidly are ground-water levels declining?

Ground-water levels are declining in many parts of the Middle Rio Grande Basin; the water table has declined more than 160 feet since 1945 in some areas. The “Ground-water-level declines” section on page 47 describes what is known about predevelopment and current conditions.

Is municipal and(or) industrial pumping lowering ground-water levels outside major metropolitan areas?

Currently (2002), the largest ground-water-level declines in the Middle Rio Grande Basin are focused around municipal-supply wells. Eventually the effects of pumping will propagate outward from the wells and cause water-level declines in areas away from pumping centers. The "Ground-water-level declines" section beginning on page 47 shows ground-water-level maps of the basin during different years.

Have ground-water-level declines triggered land subsidence?

Some localized subsidence has occurred in the Albuquerque area, though this is probably related to the draining of swampy areas and not to ground-water pumping. The "Subsidence" section on page 86 and Box *J* on page 88 describe this subsidence, discuss the potential for widespread subsidence due to aquifer depletion, and show how scientists are studying the issue.

How will water chemistry affect the use of ground water?

Several factors potentially can affect water quality (and thus the suitability of water for a particular use) in the Middle Rio Grande Basin: natural conditions, human-induced contamination, and pumping effects. Chapter 6 on page 91 discusses what is known about ground-water chemistry in the basin.

Rio Grande Conveyance Channel at San Marcial and USGS streamflow-gaging station. Completed in 1958, the channel has helped New Mexico meet its Rio Grande Compact obligations.

How much water in the basin is appropriated?

Under the terms of the Rio Grande Compact, water in the Rio Grande is fully appropriated between Colorado, New Mexico, Texas, and Mexico. Within the Middle Rio Grande Basin, water rights have not yet been adjudicated, though the New Mexico Office of the State Engineer considers the surface flows of the Rio Grande to be fully appropriated. The "Water appropriation" section on page 69 discusses the appropriation of water in the basin.

How much water can be pumped from the aquifer system using the present infrastructure?

This also is a difficult question to answer because much of the necessary information is unavailable. Wells have a limited life because of corrosion and mechanical deterioration; thus, any well will eventually need to be replaced. In addition, declining ground-water levels will necessitate the deepening of existing wells or construction of new, deeper wells. Water-level declines are dependent on ground-water withdrawals, which in turn are affected by population increases, conservation measures, and the use of additional sources of municipal water supply. The possible effects of declining water levels in the aquifer are discussed in the "Effects of ground-water withdrawals" section on page 85.

A USGS technician measures flow in the Jemez River below Jemez Dam. Such measurements are critical to understanding ground-water/surface-water interaction.

How interrelated are the ground-water and surface-water systems?

As knowledge of the hydrology of the Middle Rio Grande Basin improves, so has the understanding of how the ground-water and surface-water systems interact. The current understanding of this interaction and the techniques used in the Middle Rio Grande Basin Study are discussed in Chapter 5 on page 71, Box *H* on page 78, and the "What the ground-water-flow model tells us about the hydrologic system of the basin" section on page 110.

Chapter 2: The Middle Rio Grande Basin

Physical characteristics

The Middle Rio Grande Basin covers approximately 3,060 square miles in central New Mexico, encompassing parts of Santa Fe, Sandoval, Bernalillo, Valencia, Socorro, Torrance, and Cibola Counties (fig. 2.1). In this report, "Middle Rio Grande Basin" refers to the geologic basin defined by the extent of deposits of Cenozoic age along the Rio Grande from about Cochiti Dam to about San Acacia. This basin lies almost entirely within the Rio Grande Valley and is equivalent to the Albuquerque Basin of Thorn, McAda, and Kernodle (1993) and Kernodle, McAda, and Thorn (1995). The extent of the Middle Rio Grande Basin has been defined many different ways in different reports; no standard or convention seems to apply.

The Middle Rio Grande Basin lies in an asymmetric, elongated valley along the Rio Grande. The basin encompasses the inner valley, or flood plain, of the Rio Grande and the surrounding terrain that slopes from surface-drainage divides toward the river. The eastern boundary of the basin is largely mountainous, with merging alluvial fans and stream terraces leading downslope to the Rio Grande. The basin surface west of the Rio Grande has only isolated mountains and volcanoes and generally slopes up to a rolling divide to the Rio Puerco (this surface is known as the Llano de Albuquerque). Both active and vegetated sand dunes and dune fields are found throughout the basin.

Alluvial fans are the open-fan or cone-shaped masses of sediment deposited by streams at canyon mouths along a mountain front. *Terraces* are the step-like benches that parallel a stream and represent different climatic and geologic episodes in the stream's history. *Sand dunes* are mounds of loose windblown sediment ranging in height from inches to hundreds of feet. They are heavily influenced by climate, and their movement can be slowed or stopped by the growth of vegetation on their surfaces (Jackson, 1997).

The Rio Grande inner valley is the area adjacent to the Rio Grande underlain by alluvium of Quaternary age of the most recent cut-and-fill episode of the river. In the basin, the inner valley ranges from approximately 0.5 to 5 miles wide and is incised into older Quaternary alluvium and Santa Fe Group sediments. The inner valley corresponds to the flood plain of the pre-flood-control era (1971).

Alluvium is a general term for sediment deposited by a stream or other running water. Typically, a late Cenozoic age is implied (Jackson, 1997).

Elevation in the Middle Rio Grande Basin ranges from about 4,650 feet above sea level on the Rio Grande at San Acacia to about 8,000 feet on the flanks of the Manzano and Sandia Mountains. However, peaks in the adjacent Jemez, Sandia, and Manzano Mountains are greater than 10,000 feet above sea level, with the highest being Redondo Peak in the Jemez Mountains at 11,254 feet.

Climate

One of the definitions scientists use to define a desert is "a region with a mean annual precipitation of 10 inches or less, and so devoid of vegetation as to be incapable of supporting any considerable population" (Jackson, 1997). By using this definition, much of the Middle Rio Grande Basin may be classified as a desert.

Precipitation generally increases with elevation, and because the elevations of the basin and surrounding mountains span nearly 7,000 feet, Scientists currently understand the Earth to be about 4.7 billion years old. To facilitate the study of rocks and their features, geologists have divided this *geologic time* into a hierarchical system of units characterized by distinct assemblages of rock types and fossils. The time prior to most of the fossil record is known as the Precambrian era, which encompasses the period from 4,700 to 570 million years before the present (Ma). The remaining time until the present is divided into three eras: the Paleozoic (approximately 570 to approximately 240 Ma), Mesozoic (approximately 240 to 66 Ma), and Cenozoic (66 Ma to present) (Press and Siever, 1986; Hansen, 1991; Jackson, 1997).

Era	Period	Epoch	Age estimates, in millions of years
Cenozoic	Quaternary	Holocene	Present – 0.010
		Pleistocene	0.010 – 1.6
	Tertiary	Pliocene	1.6 – 5
		Miocene	5 – 24
		Oligocene	24 – 38
		Eocene	38 – 55
		Paleocene	55 – 66
Mesozoic	Cretaceous		66 – 138
	Jurassic		138 – 205
	Triassic		205 – 240
Paleozoic	Permian		240 – 290
	Pennsylvanian		290 – 330
	Mississippian		330 – 360
	Devonian		360 – 410
	Silurian		410 – 435
	Ordovician		435 – 500
	Cambrian		500 – 570

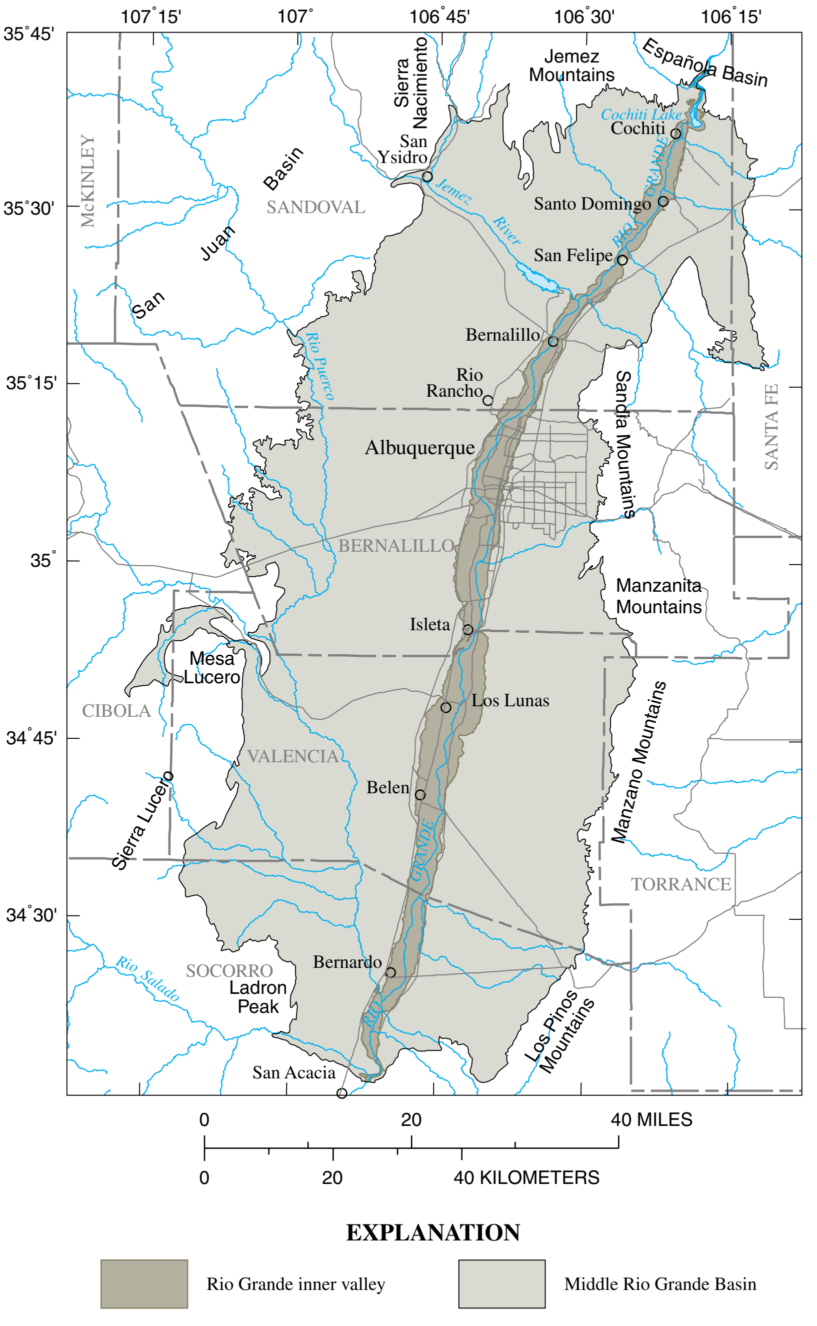

Figure 2.1.—*Major physiographic features of the Middle Rio Grande Basin.*

climate in the basin ranges from arid to humid, though climate over most of the basin is semiarid (based on modified Thornwaite climate types by Tuan, Everard, and Widdison [1969]). The climate is characterized by sunshine and low humidity: Albuquerque receives 77 percent of the possible annual sunshine, and its average annual relative humidity at 5:30 p.m. is 32 percent (Tuan, Everard, and Widdison, 1969).

The National Weather Service has seven weather stations in the Middle Rio Grande Basin with at least 10 years of record (table 2.1). The Sandia Crest station has also been included as representative of conditions in the mountains surrounding the basin. Locations of the weather stations are shown in figures 2.2 and 2.3.

Average annual temperatures at weather stations in the basin range from 54.0° F at the Corrales station to 56.5° F at the Belen station. At the Sandia Crest station, the average annual temperature is 37.6° F. The coldest month in the basin is January, with average temperatures ranging from 33.5° F at the Cochiti Dam station to 35.1° F at the Albuquerque WSFO station. The warmest month is July, with average temperatures ranging from 74.4° F at the Corrales station to 78.5° F at the Belen station. January and July average monthly temperatures are 20.0 and 56.9° F, respectively, at the Sandia Crest station. Average monthly temperatures for the seven weather stations in the basin and Sandia Crest are shown in figure 2.2 (National Weather Service, 2002).

Moisture in storms is derived mainly from the Gulf of Mexico (Tuan, Everard, and Widdison, 1969). July and August are typically the wettest months, though the rainy season may be considered to extend from July through October; 45 to 62 percent of annual precipitation falls during these 4 months (National Weather Service, 2002). Average annual precipitation ranges from 7.6 inches at Belen to about 23.0 inches at Sandia Crest. Average monthly precipitation is shown in figure 2.3. Precipitation in the

Many different formal climate classification systems have been developed, each with its own terminology and basis of classification. However, the two most commonly used classification systems are Thornwaite climate types (based on a ratio of precipitation to evaporation) and Köppen climate types (based on temperature and precipitation). Various authors have modified these two classification systems to meet local, more specific conditions (Gates, 1972).

Table 2.1.—National Weather Service weather stations in the Middle Rio Grande Basin and Sandia Crest station

[National Weather Service (2002). WSFO, Weather Service Field Office; —, still in operation]

Station name	Station number	Latitude	Longitude	Elevation (feet above sea level)	Dates in operation	
					Starting date	Ending date
Albuquerque WSFO	290234	35° 03'N	106° 36'W	5,310	01/01/14	—
Belen	290846	34° 40'N	106° 46'W	4,800	11/01/41	05/31/76
Bernalillo 1 NNE, new	290903	34° 26'N	106° 49'W	5,045	02/01/24	08/31/82
Bernardo	290915	34° 25'N	106° 50'W	4,735	08/01/33	—
Cochiti Dam	291982	35° 38'N	106° 20'W	5,560	02/01/75	—
Corrales	292100	35° 14'N	106° 36'W	5,015	10/06/82	—
Los Lunas 3 SSW	295150	34° 46'N	106° 45'W	4,840	07/01/23	—
Sandia Crest	298015	35° 13'N	106° 27'W	10,680	02/16/53	04/30/79

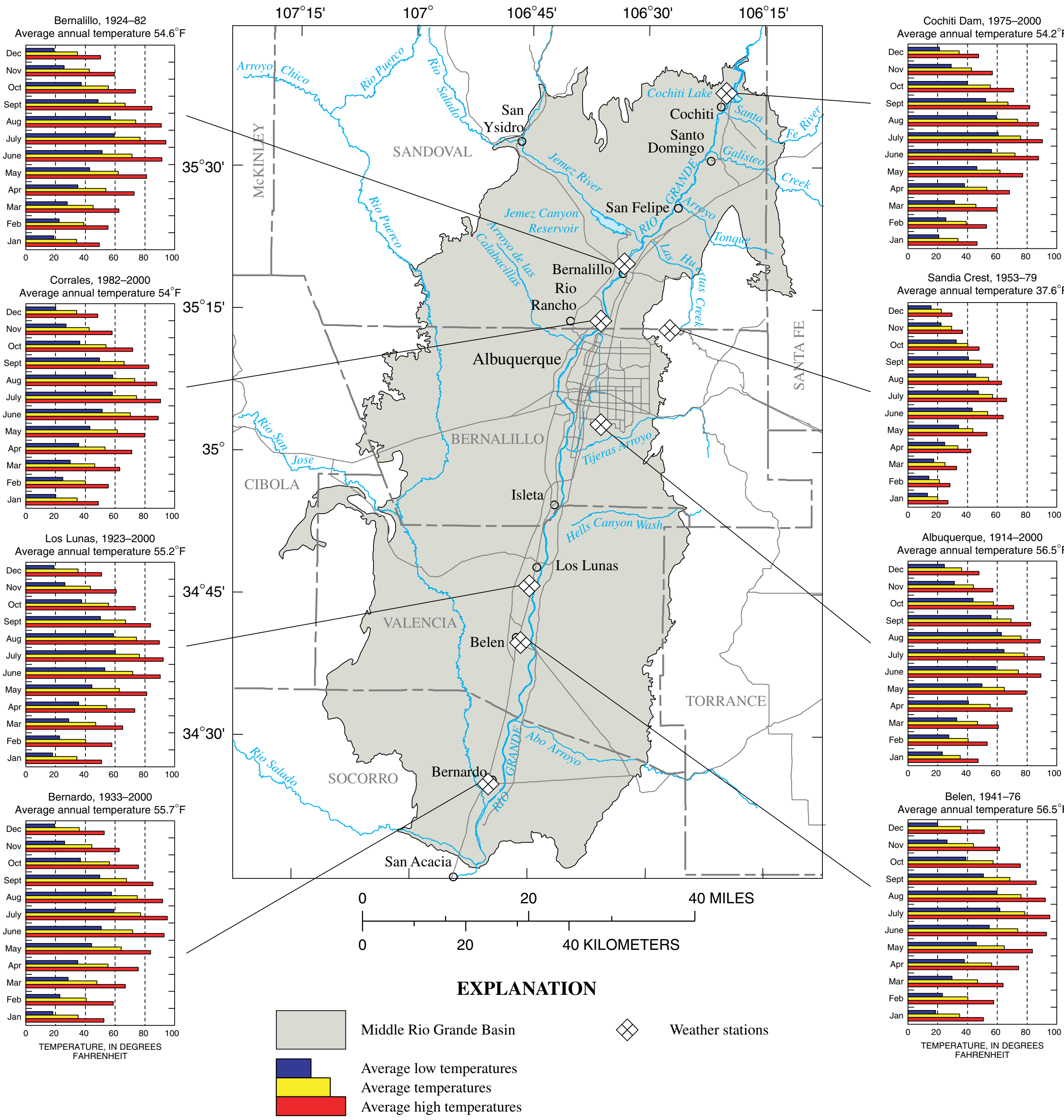

Figure 2.2.*—Average monthly temperatures for selected National Weather Service stations in and near the Middle Rio Grande Basin.*

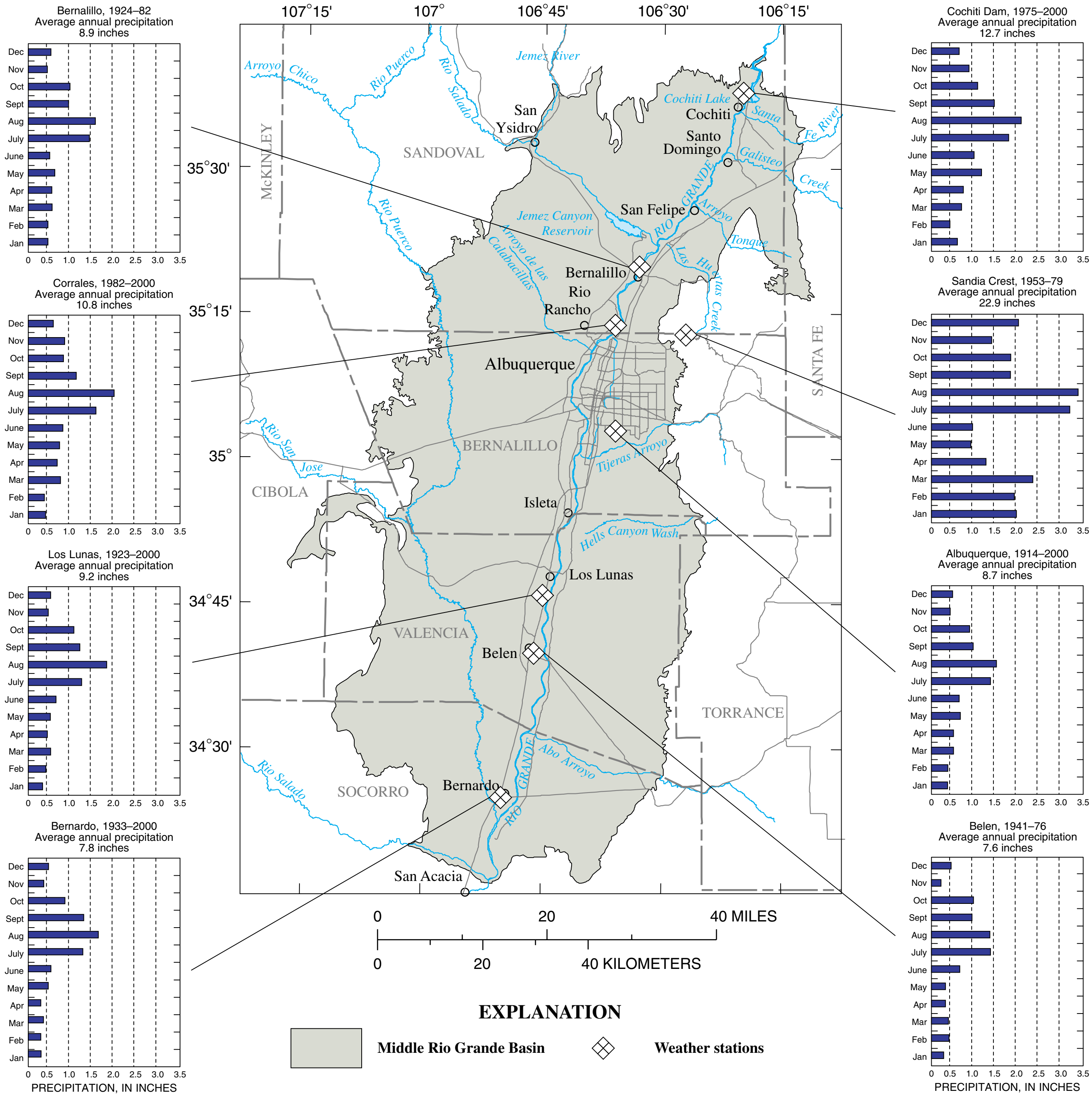

***Figure 2.3.—**Average monthly precipitation for selected National Weather Service stations in and near the Middle Rio Grande Basin.*

The Rio Grande bosque at Paseo del Norte in northern Albuquerque. The tree in the left foreground is a Russian olive and the tallest trees on the opposite bank are cottonwoods.

basin comes from local thunderstorms due to orographic or convective uplift in the summer months and from frontal storms due to the interaction of large masses of air in the winter months (Bullard and Wells, 1992). Because thunderstorms can be localized and short lived, precipitation in the basin can be extremely variable from year to year and place to place.

Evaporation occurs from open water and moist soil; transpiration occurs from plants. Because open bodies of water generally compose a fairly small percentage of the area of continental interiors, hydrologists usually group the combined water loss from evaporation and transpiration into evapotranspiration. Many factors influence evapotranspiration rates, including temperature, windspeed, amount of solar radiation, and humidity. Annual potential evapotranspiration was estimated by Gabin and Lesperance (1977) to be 41.19 inches at Bernalillo, 47.58 inches at Albuquerque, 42.29 inches at Los Lunas, 45.25 inches at Belen, and 39.97 inches at Bernardo. At all these sites, annual potential evapotranspiration is at least four times greater than annual precipitation.

As documented by tree ring and other data, drought has repeatedly occurred in the Southwestern United States at irregular intervals during the past several thousand years, though the complex climatic interactions responsible for triggering and sustaining drought remain poorly understood (National Drought Mitigation Center, 1995). The two most recent major droughts in the Southwest were during 1942–56 and 1976–77 (Thomas and others, 1963; Matthai, 1979). Though the effects of drought on surface-water supplies are usually immediate and obvious, effects on ground-water supplies may not be. In addition to reducing recharge to ground water, drought often forces surface-water users to replace or augment their supplies by pumping from wells.

Periodic water-temperature fluctuations in the eastern equatorial Pacific Ocean, termed El Niño and La Niña, can influence episodes of drought in the Southwestern United States (Conlan and Service, 2000). El Niño conditions are characterized by warmer ocean temperatures and tend to cause an increase in moisture in the Southwest. La Niña conditions are characterized by cooler ocean temperatures and tend to cause drier conditions in the Southwest. Research into these phenomena has increased since the mid-1970's; however, understanding remains incomplete, and patterns and effects cannot yet be predicted with much certainty. For additional information on the climate of the Middle Rio Grande Basin, the reader is referred to Tuan, Everard, and Widdison (1969), Gabin and Lesperance (1977), Scurlock (1998), Scurlock and Johnson (2001), and the National Weather Service (2002).

Major vegetation types

For the present-day Middle Rio Grande Basin and surrounding mountains, Scurlock (1998) defined eight main plant communities, listed in a progression from near the Rio Grande to the mountaintops: riparian, desert grassland, plains-mesa grassland, scrublands, juniper savanna, pinyon-juniper woodlands, ponderosa pine, and subalpine and mixed coniferous forest. Dick-Peddie (1993) further divided the scrubland in the basin into three separate plant communities: Great Basin desert scrub, plains-mesa sand scrub, and montane scrub. Martin (1986) used still another classification system.

The riparian woodland (or bosque) is highly prized for recreation and is protected as the Rio Grande State Park through much of the Albuquerque area. Today, the bosque consists of native species of cottonwood (*Populus deltoids* ssp. *wislizeni*) and willow (*Salix* sp.), as well as introduced exotic species, mainly Russian olive (*Elaeaganus angustifolia*) and tamarisk or salt cedar (*Tamarix pentandra* and *Tamarix chinensis*). Currently (2002) the bosque covers the flood plain of the river between the levees; when the Spanish arrived in the 16th century, however, the flood plain supported scattered stands of predominantly cottonwood and willow (Bogan, 1998; Scurlock, 1998). The construction of flood-control projects since 1925 has stabilized the channel of the Rio Grande and eliminated the periodic flooding now considered necessary for cottonwood reproduction (Finch and others, 1995). Though reduced cottonwood reproduction is an issue, the largest factor in the change in composition of the bosque was the introduction of the exotic species prior to 1900 (Campbell and Dick-Peddie, 1964).

The bosque assumed its present character fairly recently, as can be seen in the photographs shown in figure 2.4. In the past 60 to 70 years, the bosque has developed in an area that was formerly semi-barren flood plain. A similar change can be seen in two oblique aerial photographs in a report by Ground-Water Science, Inc. (1995).

From a water-resources perspective, the bosque is of importance because it is composed largely of phreatophytes. Along the Rio Grande, the amount of riparian vegetation has increased (Ground-Water Science, Inc., 1995); therefore, it is probable that more water is required to maintain the dense vegetation of the bosque today than was required for the scattered stands of cottonwood and willow that existed in the past. Ground-Water Science, Inc. (1995) estimated that evapotranspiration from riparian vegetation and evaporation from open water account for about two-thirds of surface-water consumptive use in the basin.

The remaining plant communities in the Middle Rio Grande Basin are of less interest from a hydrologic standpoint. Most have been altered by human activities such as grazing, fire suppression, and logging, as well as natural factors such as climatic variation (Scurlock, 1998). Detailed descriptions of these plant communities are in Dick-Peddie (1993) and Scurlock (1998).

Phreatophytes are plants that extend their roots to the water table. A phreatophyte acts as a pump by transporting ground water (in the Middle Rio Grande Basin, the source often is ultimately the river) upwards to be transpired from leaf surfaces. Tamarisk, willows, Russian olive, and cottonwood are all phreatophytes. In the past, phreatophyte-control projects were conducted along streams such as the Pecos River to enhance streamflow (Welder, 1988). The mixed success of these efforts, changing esthetic values, and threatened and (or) endangered-species issues have curtailed such efforts.

A

B

Figure 2.4.*—Photographs looking west across the Rio Grande toward the Albuquerque volcanoes. Photograph (A) was taken in the early 1930's (courtesy of the Middle Rio Grande Conservancy District). Photograph (B) was taken in 1994 at the same location (courtesy of Gary Daves, City of Albuquerque Public Works Department).*

In 1992, turf grasses in urban areas, such as this golf course, were the second most abundant crop (in terms of planted acreage) in Bernalillo County, after alfalfa.

Farming in the Middle Rio Grande Basin is important for several reasons. Water use by irrigated agriculture in the basin is several times that of urban use, and because irrigated agriculture predates substantial urban growth in the basin, most senior water rights are held by irrigators. As part of its Middle Rio Grande Basin Water Assessment study, the Bureau of Reclamation developed crop-acreage estimates and cropping patterns for the basin, by county, from June 1992 aerial photography (Kinkel, 1995). These estimates were then compared to New Mexico Office of the State Engineer and New Mexico State University estimates. The Bureau of Reclamation estimates indicate that nine main crop types were being cultivated in the basin, including pasture. The most abundant crop type was alfalfa, composing 42 to 62 percent of the cultivated area in each county. The remaining crop types each covered less than 30 percent of the total crop area (Kinkel, 1995).

Another irrigated "crop" is turf grass in residential yards, parks, golf courses, and other urban land. In 1992, turf grasses in urban areas were the second most abundant crop (in terms of planted acreage) in Bernalillo County, after alfalfa. In Sandoval, Socorro, and Valencia Counties, turf-grass acreage composed a very minor percentage of total irrigated acreage (Kinkel, 1995). Nevertheless, Ground-Water Science, Inc. (1995) estimated that turf grasses in the Middle Rio Grande Basin transpired about 12,000 acre-feet of water in 1990.

Human activities and water resources

Water-resource managers and scientists use the term *acre-feet* to describe a particular volume of water. One acre-foot is the amount of water it takes to cover 1 acre 1 foot deep in water. Though the term had its origins in describing irrigation diversions, it is used in referring to any large volume of water. One acre-foot is equivalent to 43,560 cubic feet or about 325,829 gallons.

More than 10,000 years of human settlement along the Rio Grande has been documented (Ware, 1984). By the 10th century, primitive irrigation systems had been developed in parts of New Mexico (Bullard and Wells, 1992), and by the early to mid-1300's, most of the "major, historic" pueblos in the Rio Grande drainage had been founded (Scurlock, 1998). As the pueblos developed the water resources along the Rio Grande, populations began to abandon smaller villages and consolidate into the larger pueblos. The habitation of these pueblos was largely dependent on water, and they were often abandoned permanently or temporarily during drought (Scurlock, 1998).

Spanish settlement in New Mexico began in 1598 with a settlement at San Juan Pueblo and spread into the Middle Rio Grande Basin as far south as Isleta Pueblo by the 1620's. Bernalillo was founded in 1700, Albuquerque in 1706, and Tomé (between Los Lunas and Belen) in 1739. The Spanish began development of the current irrigation system, patterned after the community irrigation ditches (or acequias) of the pueblos (Wozniak, 1987). This acequia system was a successful means of assuring access to irrigation water and replenishing topsoil and nutrients depleted by farming. The Spanish continued to develop the irrigation system along the Rio Grande throughout the colonial period (Scurlock, 1998). Early settlers dug shallow wells in unconsolidated river alluvium for domestic use (Kelly, 1982).

Acequia is the Spanish word for irrigation ditch. It can also refer to a community-owned or maintained irrigation system, which is maintained by an acequia association.

Most of New Mexico passed into the possession of the United States in 1848 with the Treaty of Guadalupe-Hidalgo. In the 1850's, farms increased in number, size, and value in the Middle Rio Grande Basin as a result of the increasing number of Anglo farmers who introduced new crops, farming techniques, and equipment, including barbed wire and the steel plow. The arrival of the Santa Fe Railroad and other rail lines around

1880 accelerated the influx of Anglo settlers. Albuquerque’s population was 1,307 in 1880 (Ground-Water Science, Inc., 1995). Territorial legislation was enacted to protect existing irrigation systems, farms, and irrigation rights; subsequent Federal legislation stimulated irrigation development in the region. Irrigated acreage probably peaked sometime in the early 1890’s, after which “droughts, sedimentation, aggradation of the main channel, salinization, seepage, and waterlogging” caused total acreage to decline (Wozniak, 1996). By 1889, the Rio Grande did not flow downstream from Albuquerque for 4 months of the year (Wozniak, 1996). Increased irrigation diversion of the Rio Grande upstream in the San Luis Valley of Colorado was responsible for at least some of these problems (Wozniak, 1996). During this period, most of the water for domestic use came from hand-dug wells (Scurlock, 1998).

The Albuquerque skyline from the west. (Courtesy of R.A. Durall, USGS.)

The municipal water-supply system for Albuquerque started as a private utility with a few shallow wells around the time the city incorporated in 1885 (Daves, 1994; Ground-Water Science, Inc., 1995). Daves stated that the first municipal-supply well for Albuquerque was completed in 1875. By 1904, there were several wells more than 200 feet deep (the deepest well was 710 feet deep) and one 65-foot-diameter dug well (Lee, 1907). The public sewage system began discharging untreated effluent into the Rio Grande in 1891–92; rudimentary treatment of the effluent began in 1919 (Ground-Water Science, Inc., 1995).

Prior to the First World War, Albuquerque became a regional trade and railway center serving the largely agricultural economy in the Middle Rio Grande Basin. By 1910, the city had a population of 11,200 (Ground-Water Science, Inc., 1995). Following the First World War, further development of the automobile and the opening of U.S. Route 66 in 1926 reinforced Albuquerque’s status as a regional trade and tourism center (Reeve, 1961). Bernalillo, Los Lunas, and Belen also experienced growth around their railroad depots, though at a slower rate than Albuquerque (Ground-Water Science, Inc., 1995).

The Albuquerque area began to grow significantly during the Second World War, and postwar growth led to a population increase in Albuquerque from about 35,000 to about 200,000 people between 1940 and 1960 (Reeve, 1961). After an infrastructure redesign in 1948, an expanding network of municipal-supply wells supported the water needs of this growing population (Ground-Water Science, Inc., 1995), though little thought was given to monitoring or characterizing the ground-water resources of the basin. In about 1950, several Albuquerque municipal-supply wells were pumped dry, leading one of the major figures in the science of hydrogeology, C.V. Theis, to make the rather pointed remark, “What happened was that the city got a notice from its bank that its account was overdrawn and when it complained that no one could have foreseen this, only said in effect that it had no bookkeeping system” (Theis, 1953). These and other ground-water-supply problems led to the first efforts to understand the hydrogeology of the Middle Rio Grande Basin. Nevertheless, most people in the basin continued to believe that the aquifer beneath Albuquerque contained a volume of freshwater equivalent to one of the Great Lakes (Niemi and McGuckin, 1997).

Scientific studies completed in the early 1990’s (such as Hawley and Haase, 1992; Thorn, McAda, and Kernodle, 1993; and Kernodle, McAda, and Thorn, 1995) provided a much more comprehensive understanding of the ground-water system of the Middle Rio Grande Basin and showed conclusively that Albuquerque was withdrawing water from the aquifer faster than the water was being replenished (City of Albuquerque

Name a great American city on a large body of water: Albuquerque.
Each year the Rio Grande Basin, an underground lake larger than Lake Superior, yields over 30 billion gallons to the City’s wells serving 109,000 residential and commercial Albuquerque customers. At the projected rate of growth, the City’s present water rights holdings will allow Albuquerque to tap this vast underground lake well into the twenty-first century.
—Paid advertisement, *Albuquerque Living* magazine, October 1984.

Public Works Department, 1997b). This led the City of Albuquerque to revise its water-use strategy and actively encourage water-use conservation and move toward the direct use of native Rio Grande water and San Juan-Chama Project water diverted into the Rio Grande upstream from the city (Brown and others, 1996; City of Albuquerque Public Works Department, 1997b; Niemi and McGuckin, 1997). (The San Juan-Chama Project is discussed on page 67.)

In 2000, the population of the Middle Rio Grande Basin was about 690,000 or about 38 percent of the population of New Mexico. The steady population increase in New Mexico, Albuquerque, and the Middle Rio Grande Basin since 1900 is listed in table 2.2. Other than the growth of Albuquerque as a percentage of the population of New Mexico, the most interesting aspect of these data is the decrease in 2000 of Albuquerque's population as a percentage of the population in the Middle Rio Grande Basin.

The population increase in the Middle Rio Grande Basin has led to the urbanization of irrigated agricultural land in the inner valley of the Rio Grande, as well as an increase in population in other communities in the basin including Rio Rancho, Los Lunas, Belen, Corrales, and Bernalillo. Currently (2002), residential development in response to economic growth in the Middle Rio Grande Basin is occurring primarily west and northwest of Albuquerque, in and east of the Los Lunas-Belen area, and outside the basin in the east mountain area (east of the Sandia, Manzanita, and Manzano Mountains). Secondary residential development is occurring on the north and south margins of Albuquerque, as well as on plots of vacant land within the Albuquerque city limits. A land-use and land-cover map of the Middle Rio Grande Basin in the early 1980's is shown in figure 2.5.

Table 2.2.—Population in New Mexico, Albuquerque, and the Middle Rio Grande Basin, 1900–2000

[Data from Thorn, McAda, and Kernodle, 1993; Ground-Water Science, Inc., 1995; Famighetti, 1997; U.S. Census Bureau, 2001a, 2001b; --, no data]

Year	Population			Percentage of population		
	New Mexico	Albuquerque	Middle Rio Grande Basin	Middle Rio Grande Basin/ New Mexico	Albuquerque/ Middle Rio Grande Basin	Albuquerque/ New Mexico
1900	195,310	6,238	--	--	--	3.2
1910	327,301	11,200	--	--	--	3.4
1920	360,350	15,160	--	--	--	4.2
1930	423,317	26,570	--	--	--	6.3
1940	531,818	35,400	--	--	--	6.7
1950	681,187	96,800	--	--	--	14
1960	951,023	201,200	--	--	--	21
1970	1,017,055	244,500	314,900	31	78	24
1980	1,303,302	332,900	419,000	32	80	26
1990	1,515,069	384,600	563,600	37	68	25
2000	1,819,046	448,600	690,000	38	65	25

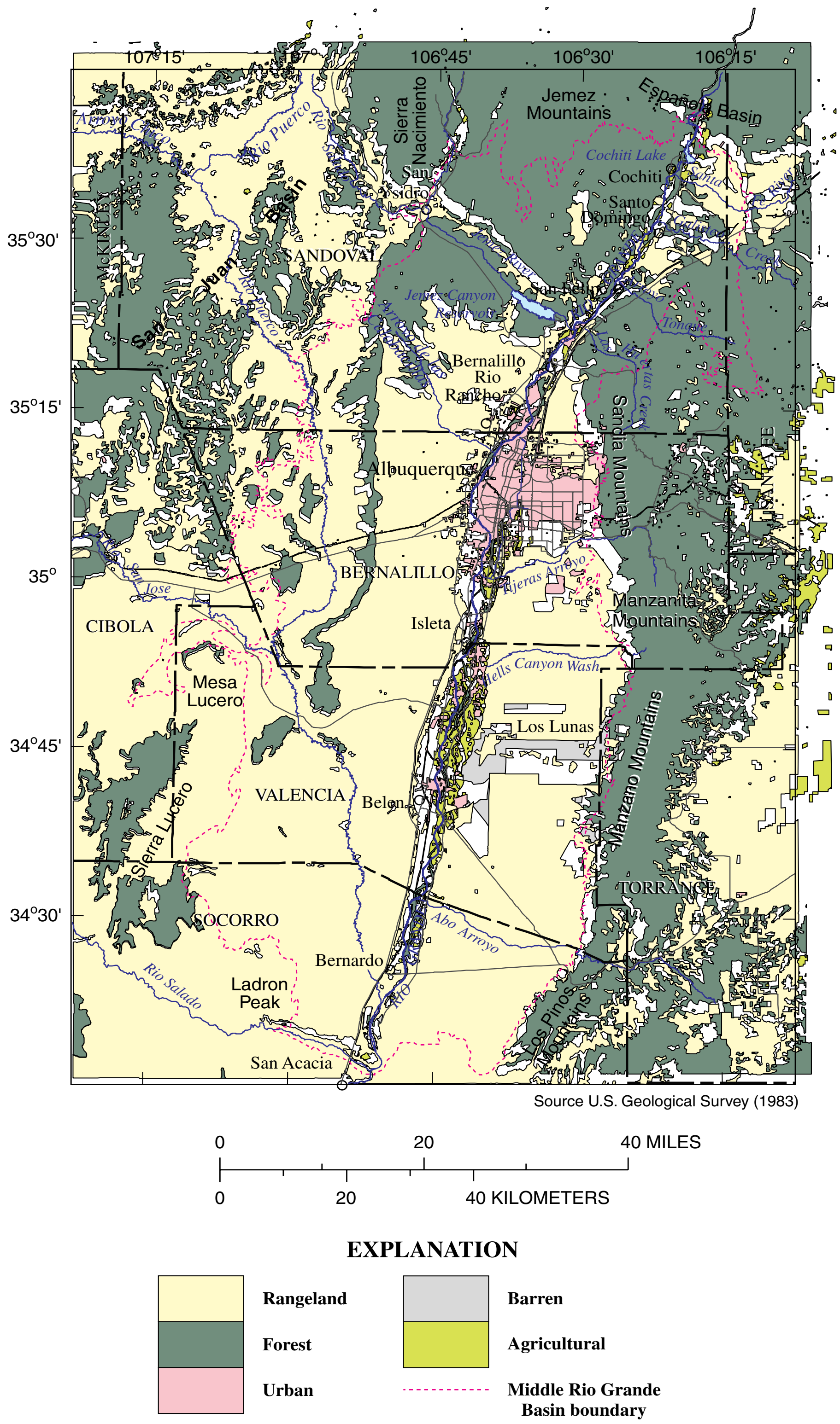

Figure 2.5.*—Generalized land use and land cover in the Middle Rio Grande Basin in the early 1980's. This is currently (2002) the most recent land-use and land-cover map of the entire basin.*

A

Landscape change modeling

David J. Hester[1] and Mark R. Feller[1]

The landscape changes that result from the growth of metropolitan areas are one subject of the USGS Land Cover Characterization Program. By using historical maps, aerial photography, and satellite imagery, scientists construct databases showing how urban land use has changed over several decades. These databases are then used to analyze how urbanization has affected the landscape as well as to model urban growth and land-use change to project future growth patterns and changes under different scenarios (U.S. Geological Survey, 1999).

The extent and characteristics of an urban area and its infrastructure are the result of differing social, economic, and environmental conditions. Understanding the factors that have contributed to shaping an urban area is essential for gaining an insight into the processes that will influence its growth and change in the future. Such an understanding can then be used to construct computer simulations (models) for projecting urban-landscape change in the future.

In the Albuquerque area, human-induced land changes were characterized by mapping the shape and extent of Albuquerque's urban area as it evolved over time (table A.1 and figs. *A.1* and *A.2*). Although Albuquerque has grown both on vacant land within developed areas (infill development) and on the fringes of developed areas (new development), the long-term trend was greater dispersed development, leading to an increase in the size of the urban area (urban expansion).

Table A.1.—Urban growth in Albuquerque, 1935–2050. Projections for 2050 are based on SLEUTH model output

[--, not applicable]

Year	Urban area (acres)	Percent growth	
		Cumulative, since 1935	Since previous period
1935	4,372.2	--	--
1951	15,397.9	252	252
1973	49,746.1	1,038	223
1991	84,889.3	1,842	71
2050	124,608.5	2,750	47

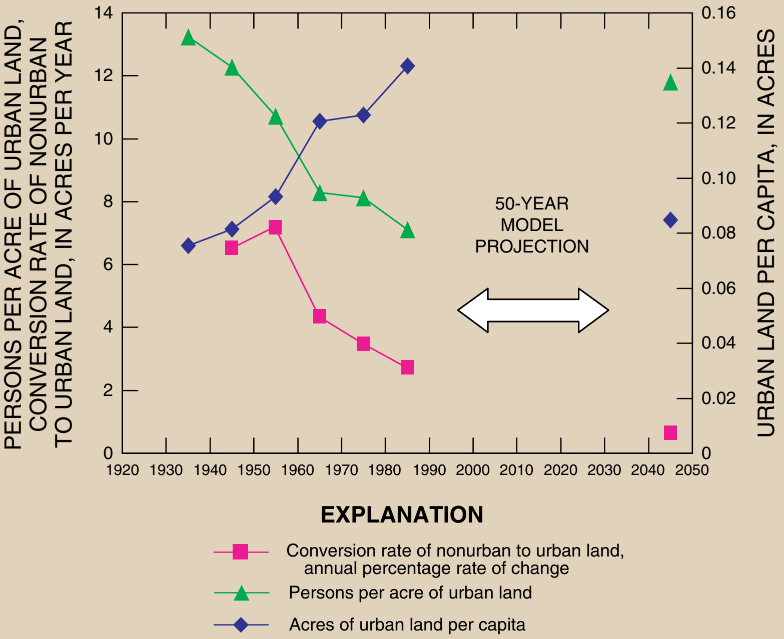

Figure A.1.*—Changes in urban characteristics for Albuquerque, 1935–2050. Projections for 2050 are based on University of New Mexico Bureau of Business and Economic Research population estimates.*

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[1]U.S. Geological Survey, Denver, Colorado.

Assuming that redevelopment (the transition of an existing or prior land use into another land use category) did not contribute to the total urban area, the amount of urban land in the Albuquerque area per person (shown as acres of land per capita in fig. *A.1*) approximately doubled from 1940 to 1990.

As part of the Middle Rio Grande Basin Study, the USGS modeled the Albuquerque area using the **S**lope, **L**and Use, **E**xclusions, **U**rban, **T**rans-portation, and **H**illshade (SLEUTH) urban-growth model developed by the University of California-Santa Barbara (U.S. Geological Survey, U.S. Environmental Protection Agency, and University of California-Santa Barbara, 2001). The SLEUTH model is used to estimate the probability of an area becoming urbanized by using a database of contemporary land-surface characteristics (such as the current extent of urban lands, land-surface slopes likely to develop, lands excluded from development, and probable effects of the existing road network on future land-use patterns). For the Albuquerque area, simulations projected the urbanized area extent in 2050. This 50-year projection was chosen to correspond with the FOCUS 2050 Regional Plan of the Middle Rio Grande Council of Governments (Middle Rio Grande Council of Governments, 2000).

Because conditions in 1935 and 1991 are known (fig. *A.2, A* and *B*), model runs simulating the period 1935–91 were used to adjust model parameters in order to match the known conditions in 1991 (model calibration). Once a composite score indicated the "best" combination of variables, a projection between 1991 and 2050 was run. The resulting projection is shown in figure *A.2, C*. If the trend of dispersed development in the Albuquerque area continues until 2050, approximately 125,000 acres of the Middle Rio Grande Basin landscape will be urbanized, with a resulting population density of 11.8 persons per urban acre (fig. *A.1*).

The goal of landscape-change modeling is to provide accurate scientific information such as basic data (such as historical and contemporary landscape characteristics), projections (such as the 2050 simulated urban landscape that was forecast using SLEUTH), and perspectives (such as "land-surface characterization" analyses calculated from historical, contemporary, and future landscapes that can be used to analyze urbaniza-tion trends, rates, patterns, and densities) to help managers form sound policies for guiding sustainable growth. Because the Albuquerque area is surrounded by numerous boundaries with Federal and pueblo lands and because the availability of water may ultimately be limited, decisions on growth can only be improved by realistic projections of growth patterns and changes based on scientific methods.

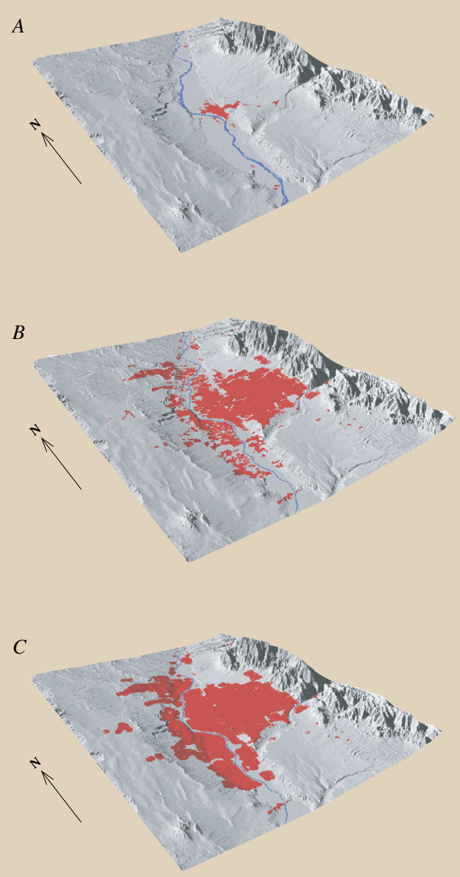

Figure A.2.—*Urban area in the vicinity of Albuquerque in (A) 1935, (B) 1991, and (C) 2050 projected using the SLEUTH model.*

Chapter 3: Geology of the Santa Fe Group aquifer system

The Santa Fe Group aquifer system, which supplies the ground-water resources for the Albuquerque metropolitan area and surrounding communities within the Middle Rio Grande Basin, is composed chiefly of sand and silt with lesser amounts of clay and gravel. Most of the sediment was transported into subsiding fault-bounded basins of the Rio Grande Rift by ancient streams and rivers that drained the surrounding regions. Additional deposition was a result of windblown sediment (eolian deposits), intermittent streams, and downslope creep from mountain uplifts. Because these geologic processes have been active in the Middle Rio Grande Basin for millions of years, the Santa Fe Group locally is thousands of feet thick. The varied processes and the available sediment combine to form a complex, three-dimensional framework of truncated and overlapping sedimentary units of contrasting hydrologic properties. (See Box *B*.)

An *aquifer* is defined as “a rock unit that will yield water in a usable quantity to a well or spring” (Heath, 1983). An *aquifer system* is two or more aquifers that are separated (at least locally) by impermeable rock units but function together as an aquifer with regional extent. The impermeable or low-permeability rock units that bound aquifers are *confining beds*.

The Rio Grande Rift

The geologic processes at work in this part of New Mexico have guided and controlled formation of the Santa Fe Group aquifer system. More than 25 million years ago, tectonic forces operating on the western North American continent began to pull apart the brittle upper crust, and the continent began to spread and extend toward the Pacific Ocean basin (Chapin and Cather, 1994; Pazzaglia and others, 1999). In New Mexico and Colorado, these forces created a more-or-less continuous north-south structural zone called the Rio Grande Rift (fig. 3.1). This rift formed in northern Mexico and southern New Mexico and slowly continued to split and extend toward the north as the Colorado Plateau block on the west separated from the North American continental interior block on the east. Since its inception, the floor of the rift has subsided, sporadically and unevenly, to local depths greater than 14,000 feet as the continental crust east and west of the rift continues to slowly pull apart (Grauch, Gillespie, and Keller, 1999).

The Rio Grande Rift is a zone of faults and sediment-filled basins extending along its length. Some faults appear to follow ancient lines of weakness in the brittle crust that are related to older geologic events, but many of the faults cut through older rock along new, crosscutting traces. These faults caused pieces of the brittle crust to pull apart and slide past each other; blocks on the inside of the rift zone generally dropped down under the influence of gravity relative to (uplifted) blocks on the outside edges of the rift. In this way, the rift has created a series of valleys along its length that have influenced the flow of streams and sediment deposition. Faulting, uplift, volcanic activity, subsidence, and deposition rates have varied through time in the rift. Nonetheless, the overall geologic processes have remained fairly constant. Geologic and geophysical data show that the rift consists of numerous discrete structural basins that mark the locations where faulting and subsidence rates and displacements have been greatest overall (see Box *C*).

Rock units may be classified and mapped on the basis of many different criteria including lithology, magnetic polarity, age, and depositional environment. The most common method is to classify rock strata of about the same age and similar physical characteristics into *formations*. Formations may be subdivided into *members* and *beds* or aggregated into *groups*. By convention, the formal name of the unit is a geographic feature near the type exposures (or outcrops) of the rock unit. Geologic maps typically portray the surface extent and structure of such stratigraphic units. However, young unconsolidated deposits are generally mapped and classified primarily by depositional environment and material properties.

A *rift* is an elongated valley in the Earth’s crust that forms in response to the crust extending or spreading apart. The Rio Grande Rift forms one of the great rift valleys of the world, on a scale similar to the East African rift and the Lake Baikal rift in Russia.

B

Structural, sedimentologic, and climate effects on the Middle Rio Grande Basin aquifer system

James C. Cole[1] and Byron D. Stone[2]

The interplay of faulting and sedimentation within the Rio Grande Rift has controlled major aspects of aquifer geometry. Basin-fill sediment thickens substantially toward the center of the basin. Outcrop and drill-hole studies show that basin-fill sediments thicken abruptly across major faults, indicating that faults were active while sediment was accumulating (fig. *B.1*). Rising fault blocks were eroded, and the detritus was deposited on the sinking fault blocks in a process that recycled older sediment within the rift or stripped material off the rift-flank mountain ranges. The rising and falling fault blocks also shifted the internal stream drainage in the subbasins and caused various depositional environments (such as river channel, overbank flood plain, alluvial fan, and pediment) to migrate laterally over time (Cather and others, 1994; Stone, 2001). In this dynamic setting, the types of sediment that accumulated across the rift basins were highly varied, and the location of their deposition changed as the basin filled. Erosion on the uplifted blocks created breaks in the sedimentary record that make it difficult to correlate sequences of strata from one location to another.

The Middle Rio Grande Basin consists of three discrete subbasins distinctly separated by zones where the rocks underlying the basin-fill sediment (basement rocks) are high (fig. 3.2). Each subbasin has a unique structural and depositional history. Drainage was internal to each subbasin during the early history of the rift valley, as indicated by the type of sediment

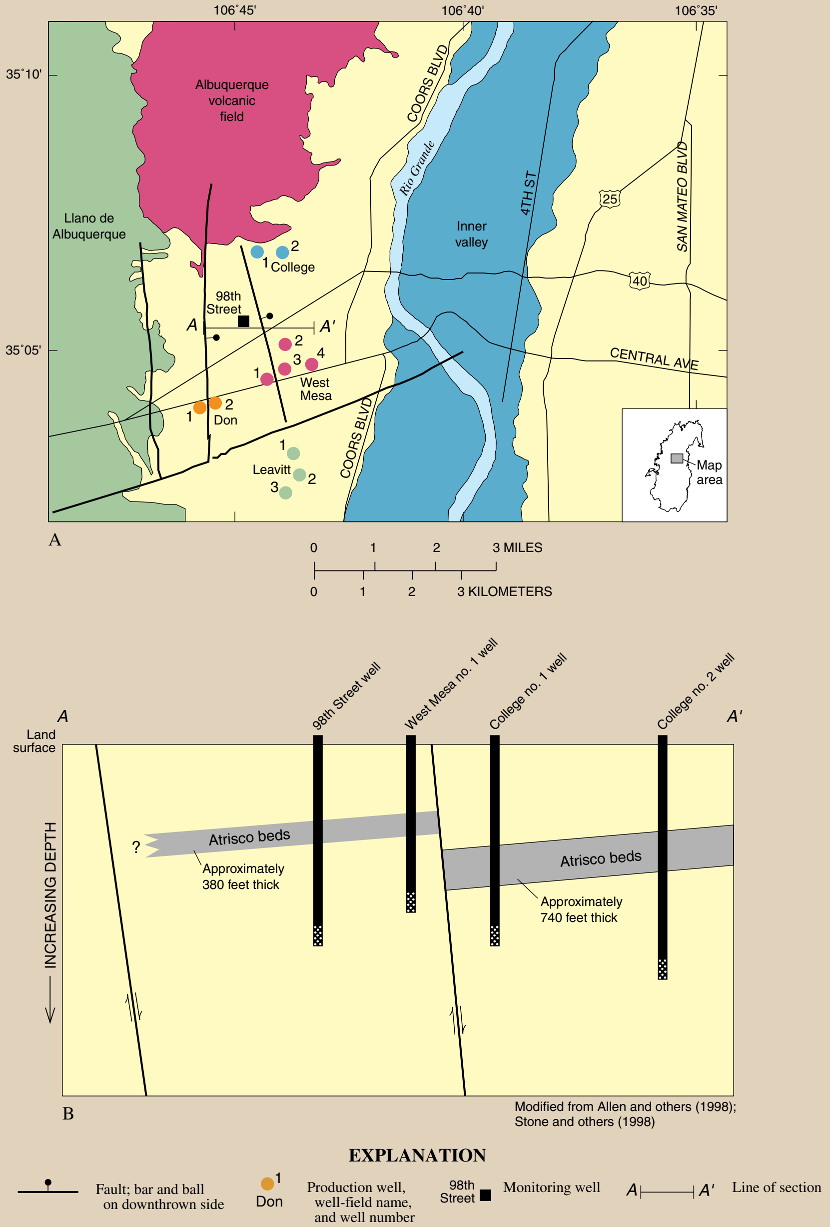

Figure B.1.—*Generalized section showing substantial thickening of the Atrisco silt- and clay-rich beds in the downthrown fault block east of the 98th Street well location (A) and index map (B). All wells except the 98th Street well are projected to the line of section, parallel to the northwest-trending fault trace.*

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deposited; thus, no continuous hydrostratigraphic deposit in the deeper parts of the Santa Fe Group aquifer system extends across all three subbasins.

The youngest sediments that were deposited during roughly the last 5 million years can be traced across the buried basement highs and the deep subbasin centers. These deposits differ from the older rift-fill deposits in ways that reflect significant changes in rift history and climate. First, these younger deposits are thinner (for a specific interval of time), indicating that the rates of subsidence began decreasing at least 5 million years ago. Second, the younger deposits are more tabular in form across all three subbasins and show less variation in thickness across faults, indicating that faulting was less active during deposition. Some subhorizontal younger sedimentary layers were deposited above erosion surfaces on top of inclined older deposits, consistent with a decline in the rate of tilting. Third, the younger deposits are only more than a few hundred feet thick along the central axis of the subbasins (Hawley, Haase, and Lozinsky, 1995; Connell, Allen, and Hawley, 1998), showing that active faulting and subsidence occurred in a much narrower part of the rift than earlier in the rift's history. These younger deposits show that the supply of sediment was greater than subsidence; thus, stream deposition was able to fill the separate subbasins to form a connected, broad basin (Cather and others, 1994; Chapin and Cather, 1994; Pazzaglia and others, 1999).

The youngest sedimentary deposits also consist of coarser grained materials than most of the earlier rift-fill deposits. Coarse sand and pebble to cobble gravel are common in the younger deposits, indicating that streams transporting these materials had greater discharge and flowed at greater velocities. The change from fine- to coarse-grained sediment is evident on a regional scale and is consistent with regional and world evidence that rainfall and runoff increased substantially beginning about 5 million years ago (Krantz, 1991; Thompson, 1991). These younger deposits locally are productive zones of the aquifer in the Middle Rio Grande Basin, but they compose only a small percentage of the rift-fill deposits and are not laterally extensive. These deposits are currently being eroded in the Rio Grande drainage.

Rift faults remain active today and continue to influence sedimentation. Outcrops along the western and northern basin margins show sequences of alluvial and windblown sediment that are thickest on top of the tilted, downdropped blocks of faults (Koning, Pederson, and Pazzaglia, 1998; Connell, Koning, and Cather, 1999). The sediment accumulated next to the fault scarp and developed a calcareous soil as the surface stabilized. Subsequent faulting buried the calcareous soil beneath another layer of sand and silt, which then developed its own calcareous soil zone (Wright, 1946; Machette, 1978; Stone, 2001). More than 10 buried soil zones are preserved in some locations (Wright, 1946), which indicate repeated offsets across young rift faults (Personius, Machette, and Kelson, 1999).

Figure B.2.*—Oblique aerial photograph of outcrops in the upper Santa Fe Group sediment adjacent to the Zia fault in the northern Calabacillas subbasin. The prominent whitish zone is a buried calcareous soil that was buried by yellowish, windblown silt deposited following downdropping on the Zia fault. (Courtesy of J.C. Cole.)*

C

How well information is used to understand the hydrogeology of the basin

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Subsurface geologic information about an aquifer is obtained primarily from wells. Studies of sites where the aquifer crops out on the surface provide some geologic information, but such outcrops are often unsaturated and of limited extent. Consequently, geologic and hydrogeologic data used to characterize aquifers at depth are routinely obtained from petroleum exploration and water wells. Such subsurface data are typically obtained during the drilling and construction of wells and include (1) characteristics of rock cuttings removed by the drill bit and used to reconstruct the general sequence and composition of the rocks in the subsurface (lithology); (2) drillers' notes of drilling conditions, including drilling rate; (3) measurements of the physical properties of the rock and fluids using borehole geophysical logging tools; (4) hydraulic conductivity as estimated from hydraulic tests; and (5) ground-water chemistry. Abundant geophysical-log data and lithologic descriptions have been obtained for wells in the Albuquerque-Rio Rancho metropolitan area and have been used to interpret hydrogeologic conditions of the Santa Fe Group aquifer system in the Middle Rio Grande Basin (Connell, Allen, and Hawley, 1998).

A USGS hydrologist using geophysical-logging equipment at the Del Sol Divider monitoring well.

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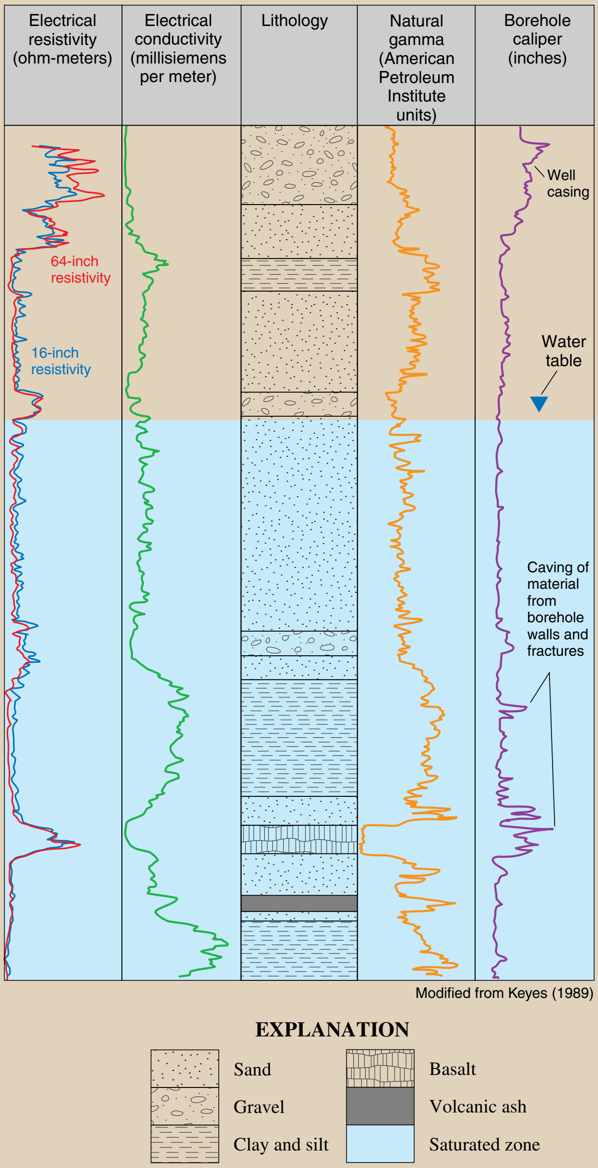


Figure C.1.*—Hypothetical responses of various borehole geophysical tools to alluvial deposits of contrasting texture and saturation and to volcanic rock units.*

The most common drilling method is mud rotary, which uses a thick drilling fluid to carry rock fragments to the surface after they are broken from the bottom of the hole by a spinning drill bit. Examination of these cuttings provides information about the mineralogy and general grain size of the deposit; however, fine-grained cuttings (clay, silt, and fine sand) often are suspended by the drilling fluid and are washed out of the sample, which tends to bias cutting descriptions toward the coarser fragments (medium- to coarse-grained sand and gravel). Borehole-geophysical logs measure the physical properties of the rock surrounding the well and provide essential qualitative and quantitative information about aquifers that cuttings cannot provide. Geophysical logs provide critical data on the fine-grained materials as well as information about features that affect ground-water movement. The most common geophysical logs in the Albuquerque area are of electromagnetic properties, natural gamma radioactivity, and borehole diameter (caliper).

Two types of geophysical logs that are measures of the response of fluid in the rock surrounding the borehole to an induced electromagnetic field are electrical (or resistivity) and induction logs. In freshwater aquifers, these logs are good indicators of the percentage of clay minerals in the deposit because moist clays conduct electricity much better than freshwater alone (Kwader, 1985). Thus, sand and gravel units are poor conductors of electric current because they contain few clays, and clay- or silt-rich units tend to be better conductors (fig. *C.1*).

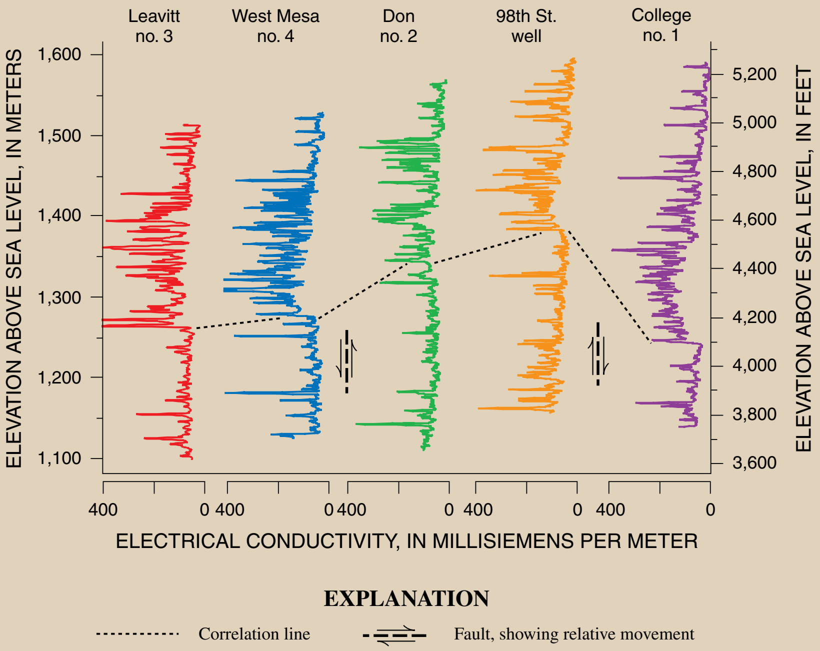


Figure C.2.*—Correlation of electrical-conductivity logs among Albuquerque well fields west of the Rio Grande. The dashed line indicates a rather abrupt boundary between overlying, fine-grained clayey sand and sand (high electrical conductivity) and underlying, medium-grained sand (lower electrical conductivity). Variations in the elevation of this boundary are interpreted to reflect tilted bedding and faults, especially between the 98th Street well and the College no. 1 well. See figure B.1A for a location map of the wells. The order of presentation is from well to well, not strictly south to north.*

The most common radioactivity log measures natural gamma-ray production in the rock surrounding the borehole and is used to determine rock type. The log measures the natural radioactive decay of potassium, uranium, and thorium in feldspar, mica, and clay minerals. The amount of decay correlates with clay-mineral content because clays are generally rich in potassium, resulting in higher measurements (fig. *C.1*). In the Santa Fe Group, gamma-ray logs also respond to deposits of volcanic origin and ash beds that contain potassium, uranium, and thorium. Therefore, using only the gamma-ray log, these volcanic deposits can be misinterpreted as clay-rich beds; such mistakes can be avoided by using other geophysical logs or by evaluating the cuttings description. Another type of radioactivity log measures the response of the rock to a source of neutrons and is used to determine bulk density and porosity,

Caliper logs show the shape and size of the borehole and delineate zones of loose and caving rock or sediment caused by weak cementation (such as unconsolidated gravel and sand) or breakage by faults (fig. *C.1*). Caliper logs are also used to correct and interpret other log data for variations in the distance between the borehole sensor and the surrounding rock.

Evaluation of geologic and hydrogeologic information for wells involves a systematic approach that uses all available lithologic, geophysical, and geochemical information for a given borehole or well field (Keyes, 1989). With multiple wells, distinctive geophysical features can be identified and correlated areally. An example in the Santa Fe Group aquifer system is a prominent clay-rich interval in western Albuquerque identified by a sharp change in electrical conductivity. The base of this unit was correlated for several miles between different well fields (fig. *C.2*) (Hawley and Haase, 1992; Allen and others, 1998). Such correlations aid in understanding the hydrogeology of the Santa Fe Group aquifer system (Connell, Allen, and Hawley, 1998).

Lithology is the term used by Earth scientists to describe the physical and mineralogical characteristics of a rock (Jackson, 1997). Common lithologic names may denote a specific type of rock, for example, sandstone, basalt, or granite, or may denote the general mode of rock formation, for example, sedimentary, volcanic, or intrusive. *Strata* are layers or beds of sedimentary rock (Jackson, 1997).

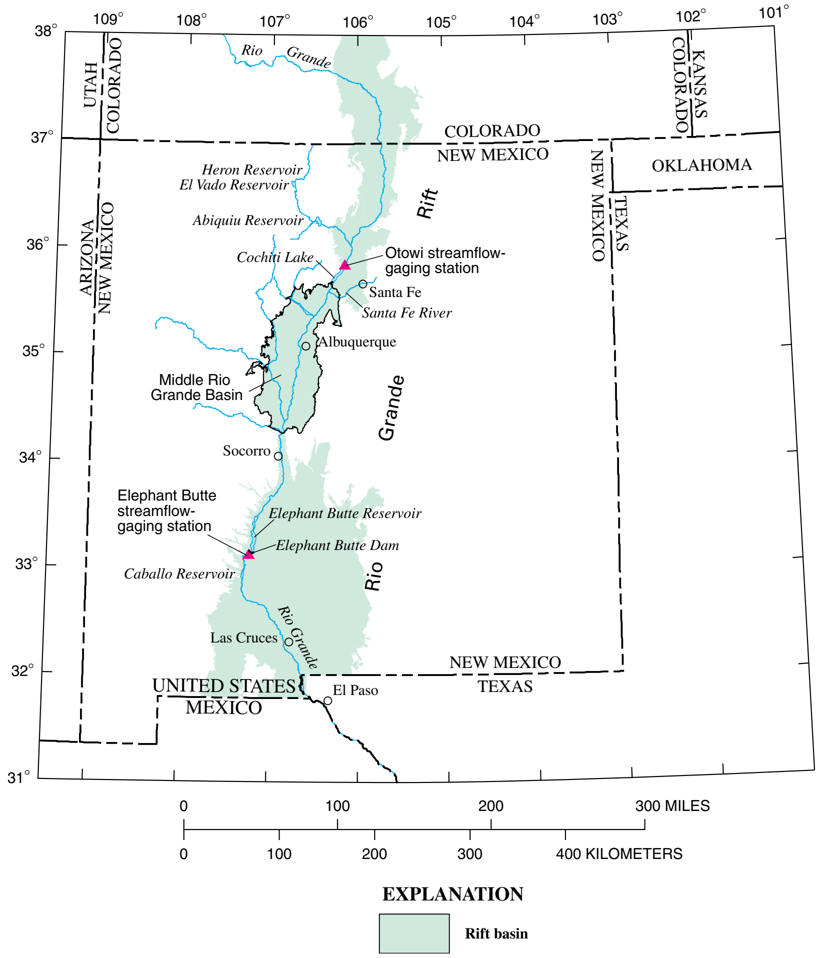


Figure 3.1.*—Location of the Middle Rio Grande Basin and the Rio Grande Rift.*

The Middle Rio Grande Basin consists of three discrete subbasins, separated by northwest-trending structural benches (fig. 3.2). Each subbasin contains more than 14,000 feet of rift-fill deposits in its deepest part, but structural benches and upthrown blocks separate these three subbasins where the sediment is as thin as 3,000 feet (Stone, 2001). Detailed geologic mapping and geophysical logs and cores obtained from petroleum-exploration wells show that the stratigraphic record for the lower and middle parts of each subbasin is distinct (Cole and others, 1999), indicating that the drainage system for each subbasin evolved differently in response to its unique structural history. Abundant fine-grained sediment and local lakebed deposits indicate that each subbasin drained internally during the early history of the Rio Grande Rift. Consequently, no major hydrostratigraphic unit extends across all three subbasins in the deeper parts of the aquifer system.

Rift processes also have influenced the types of sediment transported into the Rio Grande Rift basins. The faulting and mountain uplift that have occurred along the rift have changed the topography and slope, and these changes have influenced the ability of streams to carry sediment toward the valleys. Rift-margin uplifts expose additional rock material to weathering and erosion and increase the supply of sediment to be transported by streams, wind, and gravity-driven processes. Changes in topography also have caused changes in local climate (especially precipitation) that affect weathering, streamflow, and sediment transport. The Rio Grande Rift has experienced widespread and diverse volcanic activity through time, and molten material has exploited weaknesses in the rift-faulted crust to rise from depth and erupt at the surface. Volcanic processes have provided new source areas for sediment, produced landforms that alter topography and drainage, and affected climate and vegetation patterns in the region of the Middle Rio Grande Basin.

The rift has altered river processes in the Middle Rio Grande Basin and has affected deposition (see Box *B*). Rivers in more geologically stable settings typically are in equilibrium and neither erode nor deposit much sediment but simply transport it through the basin. Faulting and subsidence in the Rio Grande Rift, however, have repeatedly produced sags and swales where the river has deposited sediment to maintain its gradient.

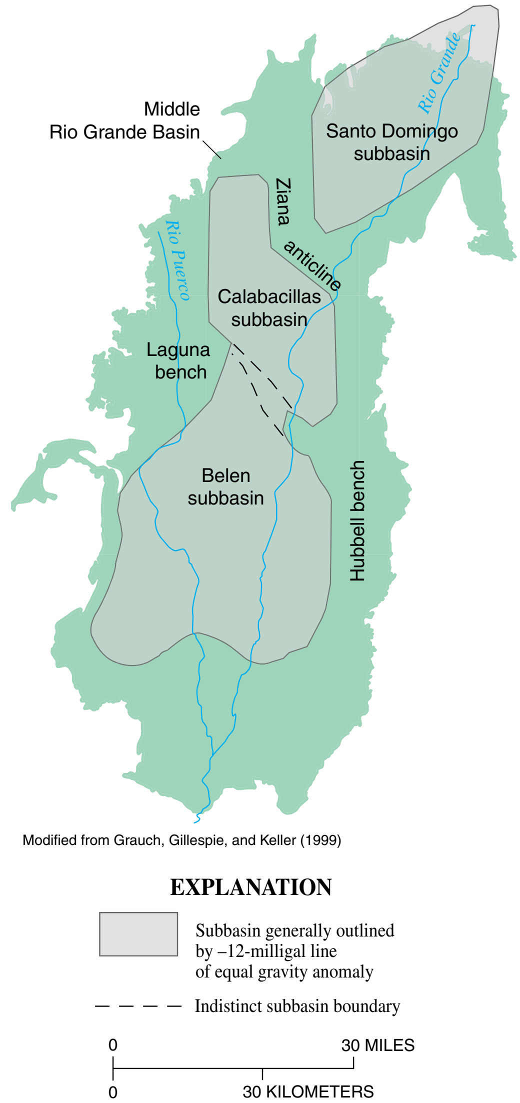


Figure 3.2.*—Simplified structural features of the Middle Rio Grande Basin. Features are defined on the basis of gravity surveys, structural models of other authors, and geologic mapping.*

Faults mark parts of the Earth's crust that have broken and where the two sides have slid past each other across the break (Jackson, 1997). This relative motion can be vertical, horizontal, or a combination. Not all faults are exposed at the land surface, either because younger deposits overlie the faults or because the break at depth did not propagate to the surface through the intervening rock. The gaping fault cracks depicted in popular movies are rare and are called *fissures* if they remain open (Jackson, 1997).

Geologic processes that shaped the aquifer system

The dynamic setting of the Rio Grande Rift has produced a complex geologic framework for ground water. The river and stream networks that deposited most of the sediment shifted across the landscape through time in response to tectonic uplift and subsidence and to climate change. The sediments deposited by running water typically are quite variable because of the very different depositional settings that form side by side (for example, main or axial channels, natural levees, and flood plains). Such sedimentary deposits commonly interfinger in complicated three-dimensional patterns, rather than form continuous tabular beds (fig. 3.3). In addition, faults that have been displaced after these sediments were buried have also offset the deposits (fig. *B.1A*). Chemical alteration, compaction, fracturing, and cementation over time have affected the hydrologic character of the sedimentary deposits in the Middle Rio Grande Basin to varying degrees.

The type of deposit and the distribution of sediment depend on the transport medium (water, wind, gravity, or ice), the energy of the transportation process, and the depositional environment. Depositional environments that have existed in the rift during deposition of the Santa Fe Group aquifer system are principally of five types: fluvial (sediment deposited by rivers and streams), alluvial-colluvial (sediment deposited on slopes and along mountain fronts), eolian (wind-transported sediment deposited in dunes), lacustrine (sediment deposited in lakes), and volcanic (molten rock erupted from vents in the form of lava flows or volcanic ash). Fluvial deposits are highly variable because the grain size and mixture of the sediment depend on the velocity and turbulence of the streamflow and on the amount of erosion and redeposition before burial and preservation. Main-

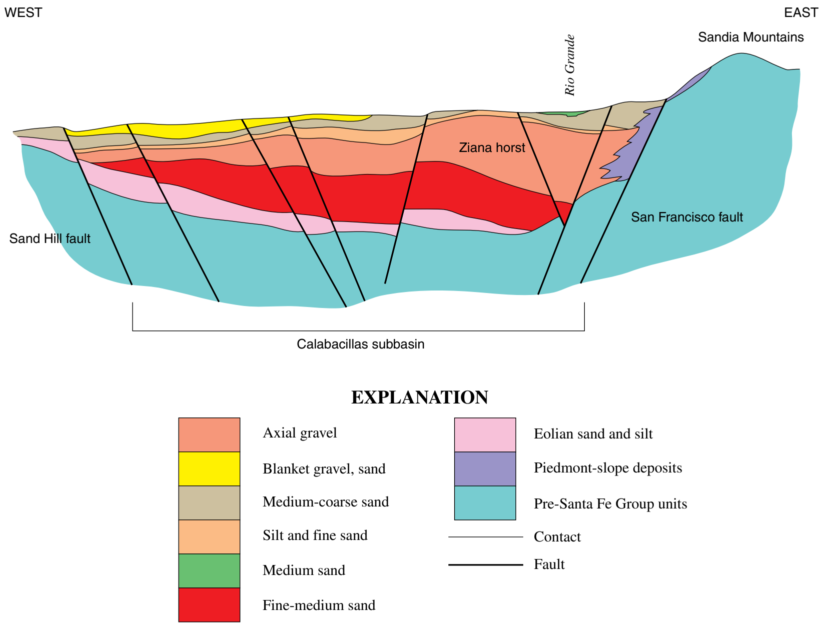


Figure 3.3.*— *East-west geologic section through the Calabacillas subbasin illustrating general relation of faults and sedimentary units.

channel deposits tend to be coarser grained because the fine-grained sediment is carried away by the current, whereas overbank flood deposits on the margins of a river valley typically contain more silt and clay because of reduced current velocity. Alluvial-colluvial deposits that form near mountain fronts are composed of sediment ranging in size from boulders to sand and silt. In eolian deposits, the sediment grains typically are uniform in size and well rounded, and pore spaces are well connected. Lacustrine deposits consist of very fine grained sand, silt, and clay, and often, evaporitic salts. Volcanic rocks have highly variable hydraulic properties depending on the kind of deposit and the extent of alteration following deposition (such as fracturing).

Ground water moves through the pore spaces between the grains and through fractures in the deposit. Unconsolidated deposits consisting primarily of medium- to coarse-grained sand or gravel have interconnected larger pore spaces that allow water to move freely in the deposit and, thus, make highly productive aquifers. Deposits containing a mixture of grain sizes (fine to coarse) have less pore space because finer grains fill the pore spaces between larger grains, thus reducing the interconnection between pore spaces. Deposits consisting of a high percentage of silt and clay have large proportions of pore spaces, but the pore spaces are smaller and interconnection is poor. Thus, water does not move freely in these deposits, and these deposits typically form confining units in an aquifer system. The interconnection of pore spaces in volcanic deposits is commonly due to fracturing after the rock has cooled.

Main-channel deposits tend to make more productive aquifers because of their coarse-grained size, whereas overbank deposits are likely to form confining units because of their fine-grained size. The poorly sorted range of grain sizes in alluvial-colluvial deposits typically make moderate to poor aquifers. Because of their uniform grain size, eolian deposits generally make very productive aquifers. Fine-grained lacustrine deposits tend to form confining units.

Sedimentary particles are generally described according to their grain size. The classification system used is called the Modified Wentworth Scale (Ingram, 1989).

Largest diameter (inches)	Smallest diameter (inches)	Size-class name	Deposit name
161.3	10.1	Boulders	Gravel
10.1	2.52	Cobbles	Gravel
2.52	0.08	Pebbles	Gravel
0.08	0.002	Sand	Sand
0.002	0.0002	Silt	Silt
0.0002	0.00001	Clay	Clay

How the basin has changed over geologic time

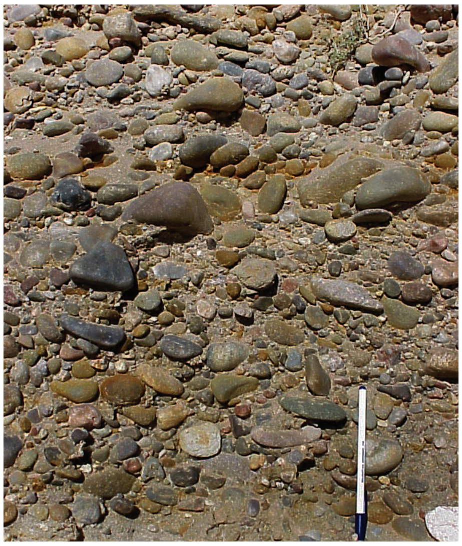
The early history of the Rio Grande Rift and the Middle Rio Grande Basin is not well known because much of the geologic record is buried. However, several lines of evidence show that the basin has responded to significant changes in tectonic conditions, volcanic activity, and climatic conditions. Each of these changes has influenced the ground-water environment to varying degrees.

Gravity data (see Box *D*) are most useful in defining the structural trends of the deeper and, therefore older, parts of the Middle Rio Grande Basin. Along the western margin of the central subbasin (Calabacillas) of the Middle Rio Grande Basin, the entire basin-fill sequence is only about 1,400 feet thick, but several miles to the east rocks deposited over the same span of time are more than 14,000 feet thick (Tedford and Barghoorn, 1999). The subbasins are bounded by steep gravity gradients (probably caused by buried faults) that trend toward the northwest and the north. These trends indicate that tectonic forces were oriented differently in the early stages of rift formation than they are today, when the most conspicuous faults trend toward the north.

The Jemez Mountains. Volcanic activity in this area was the source of many of the volcanic deposits in the northern part of the Middle Rio Grande Basin.

Regional volcanic activity has accompanied faulting within the Rio Grande Rift, but the eruptions have varied considerably over space and time. Early volcanic eruptions occurred primarily south of the Middle Rio Grande Basin near Socorro and north of the basin near Santa Fe (fig. 3.1). These early volcanic rocks were eroded to form some of the first basin-fill sediments in the Socorro and Santa Fe areas. Volcanic deposits are generally missing in the central part of the Middle Rio Grande Basin, with the exception of thin ash beds that formed as a result of distant eruptions. Volcanic deposits are abundant in the northern part of the basin as a result of eruptions from volcanoes in the Jemez Mountains. Basalt flows are also common in several areas of the basin; most erupted during the last 4 million years. With the exception of an area southwest of Albuquerque, most basalt flows are within the upper, unsaturated part of the Santa Fe Group and have little effect on ground-water resources.

Climate in the Southwestern United States has changed significantly during the time of sedimentation of the Rio Grande Rift (fig. 3.4). Variations in precipitation and aridity have affected vegetation and streamflow and thus the amount of erosion and sediment transported into and within the Middle Rio Grande Basin. Eolian deposits are common in the lower part of the Santa Fe Group in the northwestern part of the basin, indicating that a warm, arid climate existed until about 15 to 14 million years ago. The dominantly fluvial parts of the middle portions of the Santa Fe Group indicate a more temperate climate, but streamflows probably were not large because most deposits consist of fine-grained sand and silt. Beginning about 5 million years ago, rift-fill deposits across much of the basin became notably coarser grained, indicating that the climate became wetter, which led to more upland erosion, increased stream discharge, and the transport of coarse gravel into the central parts of the valley. This sedimentological change is consistent with independent climatic, isotopic, and paleobotanical evidence that rainfall and runoff increased significantly during the early Pliocene (about 5 million years ago) along with a general



Typical gravels deposited by the through-flowing Rio Grande.

cooling of the climate that preceded late Pliocene glaciations, which began as early as 2.8 to 2.7 million years ago (Thompson, 1991).

Sometime after 2.7 million years ago (late Pliocene), the first through-flowing Rio Grande in the Albuquerque area was formed, and it began to erode the rift-fill deposits laid down by smaller streams in closed-basin settings (Cole, 2001). This erosion indicates that the Rio Grande drainage system became connected southward through Socorro to lower elevations in other closed basins near Las Cruces and in northern Mexico (Gile, Hawley, and Grossman, 1981). This ancestral Rio Grande continued to intermittently erode into the rift-fill deposits in response to Pleistocene climatic fluctuations (Dethier, 1999) and in response to final connection to the Gulf of Mexico after about 700,000 years before present (Gile, Hawley, and Grossman, 1981).

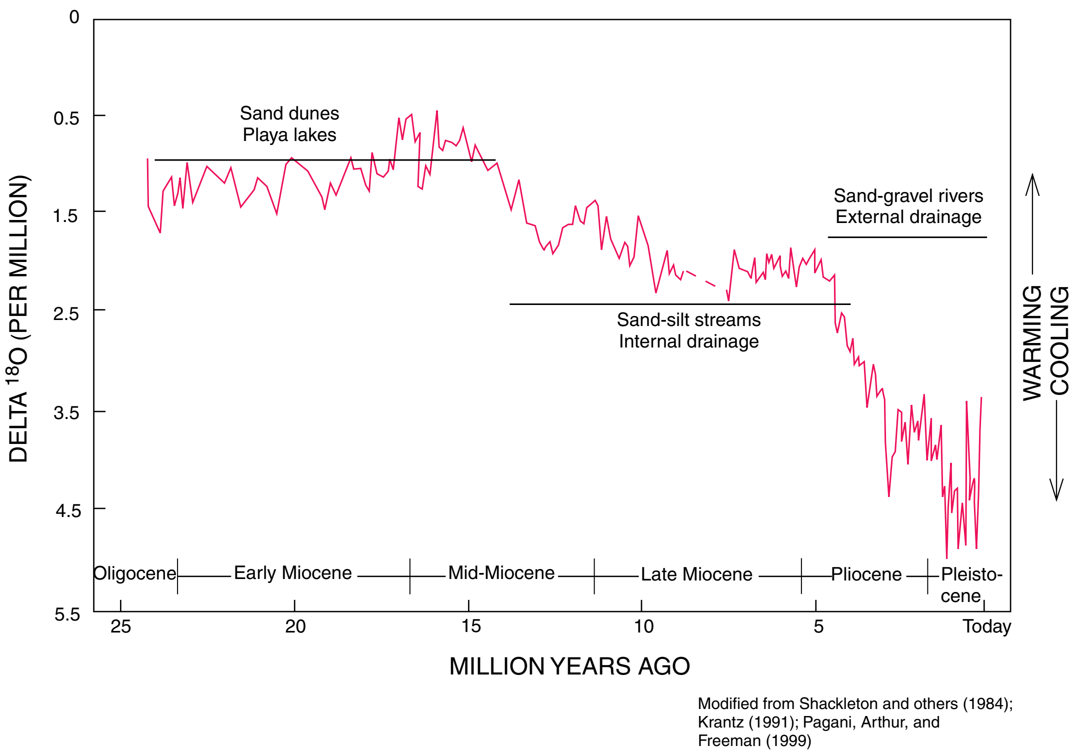


Figure 3.4.*—Variation of oxygen isotope composition of shells from bottom-dwelling micro-organisms in the Pacific and Atlantic Oceans during the last 25 million years. The oxygen isotope composition varies according to the temperature of seawater and reflects long-term climatic conditions (as indicated on the right side). Generally warm conditions existed until about 15 million years ago, roughly when the sedimentary record in the Rio Grande Rift indicates a change from sand dunes and playa-lake environments to braided stream systems. Significant cooling began about 5 million years ago, about when coarse sand and cobble-boulder gravel appeared prominently in the rift-fill deposits.*

Three-dimensional form of the aquifer system today

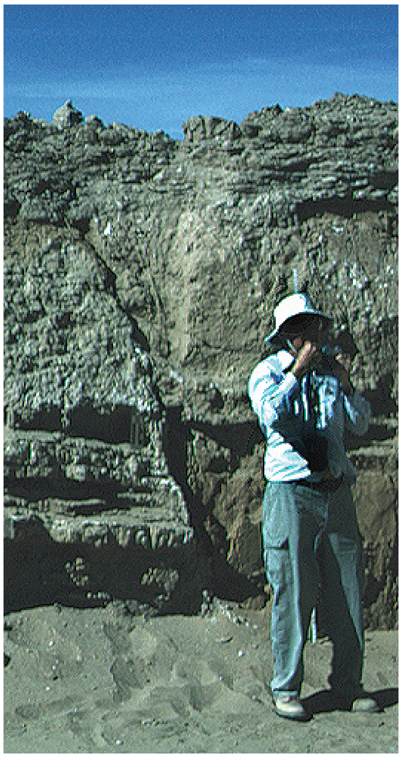
The structure of the aquifer system within the Middle Rio Grande Basin today is complex. The major hydrostratigraphic units in the aquifer are tabular and wedge-shaped bodies that are truncated and displaced by numerous faults (fig. 3.3). Few of the major units are present continuously throughout all three subbasins, and most pinch out against the subsurface basement blocks that separate the subbasins. These major units are hundreds to thousands of feet thick, extend over tens of square miles, and primarily consist of unconsolidated and partially cemented deposits that interfinger in complex arrangements. The diverse rock types and intricate interbedding relations mean that the hydrologic characteristics of these units can be defined only in general terms.

A *hydrostratigraphic unit* is a body of rock or sediment distinguished and characterized by its hydrologic characteristics (Seaber, 1988).

Some of the greatest geologic complexity in the system is near the basin margins. Tectonic uplift of mountain ranges adjacent to the Rio Grande Rift has caused erosion and the formation of alluvial-fan deposits, chiefly next to the Sandia and Manzano Mountains on the east and Ladron Peak on the southwest. Persistent volcanic eruptions in the Jemez Mountains north of the basin produced thick deposits of volcanic rocks and transported volcaniclastic debris (fragments of volcanic rock) in that area. Most of the western margin of the rift basin has remained fairly stable through time. Deposits on the western margin are thin and are separated by breaks in deposition, representing times when the east-flowing streams neither eroded nor deposited sediment in the basin.

The hydrostratigraphic units of particular interest for ground-water resources in the Middle Rio Grande Basin are the coarse-grained sand and gravel facies that compose some of the most productive aquifer materials in the basin. These Pliocene (5 to 1.6 Ma) and younger deposits reflect deposition by streams and rivers during a period of significantly greater precipitation and increased streamflow in the last 5 million years as well as integration of the through-flowing Rio Grande drainage after about 2.7 million years ago. These medium to coarse sand and pebble deposits form an irregular sheetlike zone that blankets the western and northern parts of the basin. The unit is locally several hundred feet thick below the water table, primarily in a broad band that follows the modern Rio Grande (Hawley, Haase, and Lozinsky, 1995).

Effect of faults on the aquifer system



The East Paradise fault zone. Faults can affect ground-water movement by enhancing or retarding flow.

Most faults in the Middle Rio Grande Basin trend in a north-south direction, although northeasterly trending faults are common in the northern (Santo Domingo) part of the basin. Faults have two principal effects on the aquifers and confining units, the first resulting from displacement and the second from the altered physical nature of the fault zone itself.

The lateral continuity of a hydrostratigraphic unit is broken where the displacement across a fault is greater than the thickness of the unit. For example, a highly permeable deposit might be faulted against low-permeability silt- and clay-rich deposits that restrict ground-water flow across the fault zone. Such a juxtaposition can lead to large changes in water-table elevation across the fault, as is observed in the Albuquerque area across the Isleta and West Sandia faults (Thorn, McAda, and Kernodle, 1993). Lesser displacements may not completely truncate a permeable unit but may reduce flow within the unit.

Fault displacement also affects the thickness of similar units in the adjoining fault blocks. Units of the same age tend to be thicker on the downthrown side of faults because faulting was more or less continuous with deposition (see fig. *B.1*). The downthrown block may have a thicker unit because more sediment is deposited on this block over time or because erosion removed material from the upthrown block. Faulting during deposition also can alter depositional facies along the fault scarp and change the hydrologic character of the deposits (see Box *B*; Cather and others, 1994).

Physical changes within the fault zone can alter the local hydrologic environment (Caine, Evans, and Forster, 1996). Faults can increase the number and extent of fractures in the rock medium and can disaggregate loosely consolidated deposits, resulting in enhanced permeability along the fault zone. In contrast, intense shearing along the core of the fault zone can grind rock fragments into fine-grained fault gouge (a soft, clayey material) that has lower permeability than the rock on either side of the fault zone. Thus, fault zones may become either conduits or barriers for horizontal ground-water movement at various places along their extents.

In addition, increased permeability along a fault zone can enhance movement of ground water in contact with freshly broken rock. Ground water can have chemical reactions in fault zones as a result of enhanced movement, and mineral constituents may dissolve and (or) reprecipitate as cement. Carbonate and silica cements are common along some of the major fault zones in the Middle Rio Grande Basin (Mozley and Goodwin, 1995).

Permeability refers to the general ability of a rock unit to transmit fluid (Jackson, 1997). It is a function of how well the pores in a rock unit are connected. Because different fluids such as petroleum or brines are found in rocks, the permeability can change depending on the fluid. For this reason, hydrologists use a water-dependent permeability called hydraulic conductivity, which is discussed on page 58.

Contribution of geophysical data to understanding the aquifer system

Surface outcrops can provide only a general guide to the lithologic and hydrologic characteristics at depth; thus, various geophysical methods are used to gain information about subsurface conditions (see Box *D*). These methods rely on indirect measurements of rock properties. The most commonly used techniques are based on measurements of density, magnetization, natural radioactivity, or electrical conductivity. Geophysical data have been collected in the Middle Rio Grande Basin by equipment towed behind aircraft, lowered into deep boreholes, or transported across the land surface.

Density-based techniques, also called gravity methods, are conducted by measuring minor variations in the strength of the Earth's gravitational force. Local variations in the gravity field primarily reflect variations in the density of rock, sediment, and pore fluids. In the Middle Rio Grande Basin, gravity methods have been especially useful in defining the buried margins of the subbasins and in estimating the thickness of low-density deposits of the aquifer system.

Magnetic methods measure minor differences in the Earth's magnetic field strength from place to place. Local variations primarily reflect the concentration and type of minor magnetic minerals in different rock and soil materials but in some cases may also reflect an intrinsic magnetic field contained in the rock itself. Some of the most magnetic materials in the Middle Rio Grande region are the ancient granitic and metamorphic rocks that are exposed in the mountain uplifts around the margins of the basin. Most of these materials typically are barriers to ground-water movement. Buried young (Cenozoic age) volcanic rocks throughout the basin are also strongly magnetic. The magnetic data obtained from airborne surveys across much of the study area have been extremely useful in locating these rock units and in identifying faults that offset aquifer units (see Box *D*).

Earth materials contain minor amounts of naturally occurring radioactive elements, the most common of which are potassium, uranium, and thorium. Sophisticated versions of the Geiger counter can be towed behind an airplane or lowered down a borehole to measure variations in the concentrations of these elements. The borehole tool has been extremely useful in subsurface exploration of aquifer properties because it is sensitive to the potassium content of clay-rich layers and some volcanic materials (see Box *C*).

Measurements of electrical conductivity rely on sensing differences in the way Earth materials and pore fluids conduct electricity. The methods are varied, but the results can help define important properties of the ground-water system. In the Middle Rio Grande Basin Study, these methods have been most useful in identifying zones or layers rich in clay (good electrical conductor, poor aquifer properties) and zones rich in medium- to coarse-grained sand and gravel (poor electrical conductor, good aquifer properties).

Most people are familiar with the magnetic field of the Earth and its effect on a compass needle. Periodically, however, the Earth's magnetic field reverses *magnetic polarity,* which would cause a compass needle to point the opposite direction. As some rocks are deposited (or heated above 870°F and cooled), some iron minerals align with the Earth's magnetic field, thus preserving the magnetic polarity at the time of deposition or cooling. Because the reversals have not occurred at regular or uniform intervals, a paleomagnetic history can be used to date a sequence of rocks (Press and Siever, 1986).

A converted Spanish transport plane used for airborne time-domain electromagnetic surveys in the Middle Rio Grande Basin. The wires wrapped around the plane compose the transmitting antenna.

D

How geophysical methods have been used to understand the subsurface

V.J.S. Grauch,[1] Brian D. Rodriguez,[1] and Maryla Deszcz-Pan[1]

Different rock units and the fluids contained in them can be characterized by their physical properties, such as density, magnetization, and electrical resistivity. Geophysicists use indirect methods to measure the differences in underground physical properties; these methods provide information about the subsurface without well information (though some well information is needed for the calibration of geophysical data). For example, measuring the variations in the Earth's gravity or magnetic field at different places provides information about the density or magnetization of the subsurface deposits. Measuring the effects of an electric current transmitted through the ground gives clues to the electrical resistivity, a measure of how well or how poorly the subsurface deposits and their fluids conduct electricity.

In the Middle Rio Grande Basin, several different geophysical methods were used to determine specific aspects of the subsurface hydrogeology, three of which are listed in table D.1. The gravity geophysical method was used to estimate the total thickness of the Santa Fe Group deposits, which are less dense than the underlying and surrounding bedrock. The mapping provided a base for the geologic model of the Santa Fe Group aquifer system (fig. *D.1*). Aeromagnetic surveys can detect faults that offset water-bearing units in the Santa Fe Group and can be used to map the extent of buried igneous rocks, which have different hydraulic properties than the surrounding sedimentary deposits (fig. *D.2*). When correlated with lithologic and geophysical borehole logs, the airborne time-domain electromagnetic method can be used to determine changes in the electrical resistivity of the Santa Fe Group with depth that are related to variations in grain size and hydraulic properties.

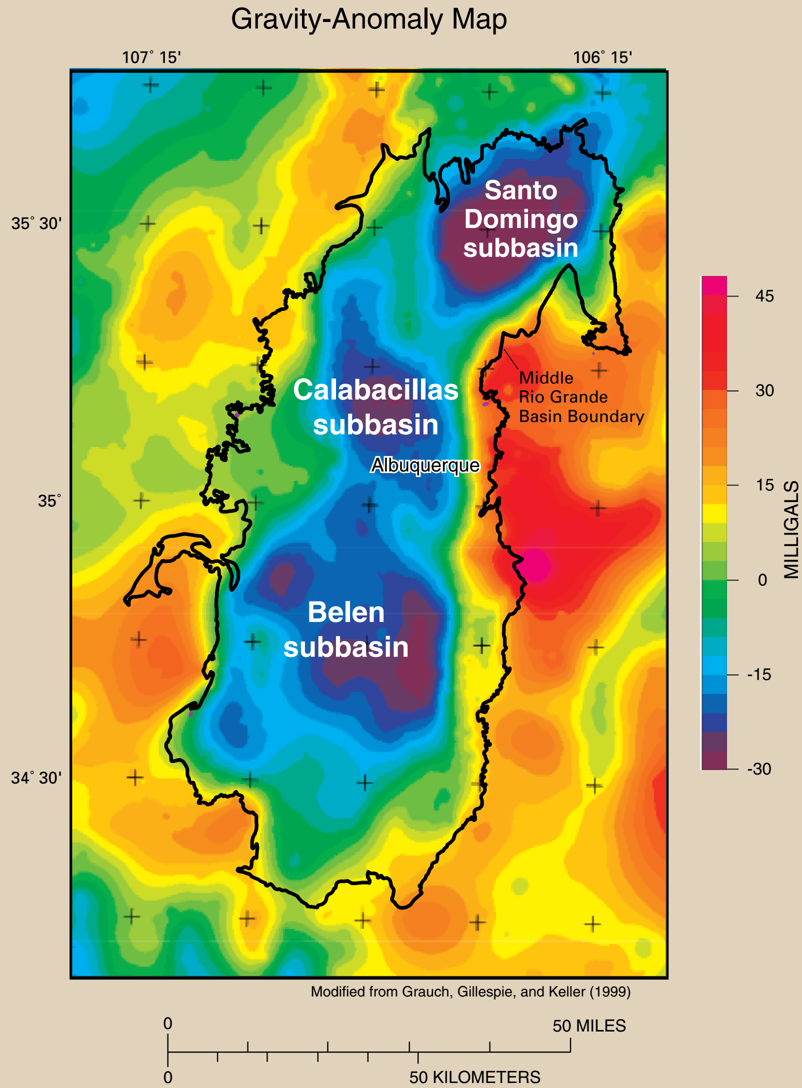


Figure D.1.—*Gravity data for the entire Middle Rio Grande Basin and surrounding area. The Santa Fe Group has much lower density than the surrounding bedrock, producing low values (shown in blue and purple) on the gravity-anomaly map .*

[1]U.S. Geological Survey, Denver, Colorado.

Table D.1.—Brief description of the geophysical methods used and the hydrogeologic features delineated by each

Geophysical method	Geophysical measurement	Associated physical property	Type of geophysical map and units	Hydrogeologic features delineated
Gravity	Ground measurements of variations in the Earth's gravity field	Bulk-rock density	Gravity-anomaly map in milligals	Thickness of the Santa Fe Group
Aeromagnetic	Airborne measurements of variations in the Earth's magnetic field	Total rock magnetization	Aeromagnetic anomaly map in nanoTeslas	Faults within the Santa Fe Group and buried igneous rocks
Time-domain electromagnetic	Airborne monitoring of the time-varying effects of shutting off an electric current induced in the Earth	Electrical resistivity (inverse of electrical conductivity)	Electrical-resistivity maps for different depth slices in ohm-meters	Grain-size variations within the Santa Fe Group

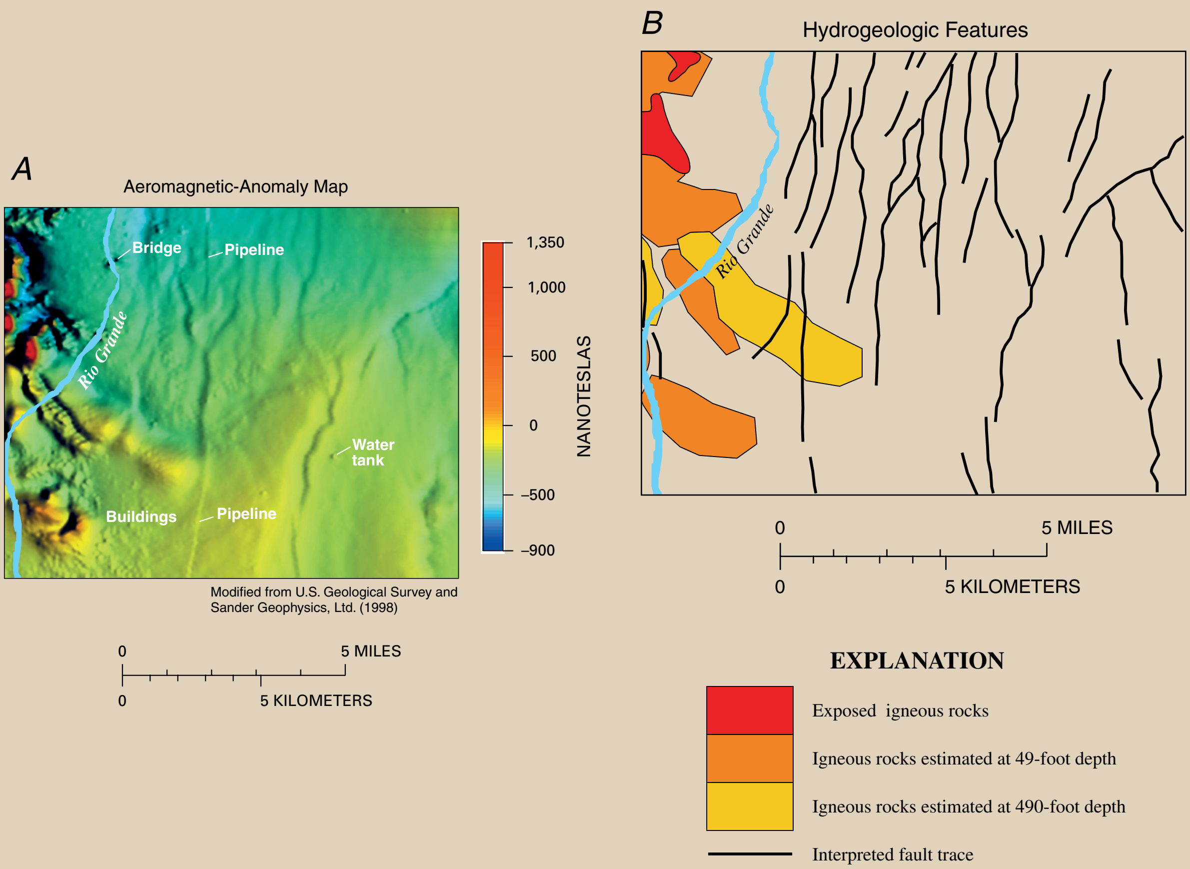


***Figure D.2.**—Aeromagnetic-anomaly map of an area south of Albuquerque (A) and simplified map of important hydrogeologic features (B). Many geologic features and manmade structures can be seen on the anomaly map (A), which is displayed in color and shaded as though it were a relief map illuminated from the east. The most important hydrogeologic features expressed in the aeromagnetic map are faults and igneous rocks, depicted on the simplified map (B). Depths to the buried igneous rocks were estimated by analysis of the aeromagnetic data. Note the shallow, buried igneous rocks near the Rio Grande that probably affect ground-water flow.*

E

Knowledge gained from the 98th Street well core

Mark R. Stanton[1] and James C. Cole[1]

In 1996, the USGS, in cooperation with the City of Albuquerque, drilled a 1,560-foot well into the Santa Fe Group aquifer system to obtain information about the conditions within the aquifer at depth and to establish a reference point that could be correlated with other wells. The well is located near the intersection of 98th Street and Interstate Highway 40 immediately west of Albuquerque (see fig. *B.1A* for a location map). A continuous core collected during drilling provided samples of the undisturbed sediment that composes the aquifer. A number of studies were performed to characterize these continuous-core samples. Other information collected from this well (some of which is described here) allowed reinterpretation of previous work from other wells in the basin and consequently improved the accuracy of the geologic framework.

Geologic characterization of the Santa Fe Group aquifer system within the Middle Rio Grande Basin relies primarily on subsurface information collected from wells. As discussed in Box *C*, the information obtained from these wells is based chiefly on rock fragments recovered during drilling (cuttings), on geophysical logs that measure physical properties of the rock and fluids, and on hydrologic tests to determine aquifer properties. Because core samples are continuous pieces of aquifer material, they allow correlation between the geophysical-log responses and the grain-size and bedding characteristics as well as an improved interpretation of aquifer tests based on detailed knowledge of the variation in these hydrologic properties.

The types of sediments penetrated in the well and two geophysical logs from the borehole are shown in figure *E.1* (the lowermost 60 feet of the borehole were not logged or described). Drilling penetrated an upper zone of about 100 feet of gravel and coarse sand that was deposited by high-discharge stream networks flowing eastward into the valley during the Pliocene Epoch (Connell, Allen, and Hawley, 1998; Stone and others, 1998). This unit has large values of hydraulic conductivity and is an important ground-water source farther east where it is saturated beneath Albuquerque.

Beneath this coarse uppermost unit is a zone of about 700 feet of mostly silty fine sand, silt, and clay that were deposited by lower energy drainage systems of the ancestral Rio Puerco and Jemez River (Stone and others, 1998). The bottom part of this zone is conspicuously red and clay rich and is referred to as the Atrisco member of the Santa Fe Group (Connell, Allen, and Hawley, 1998). The Atrisco member appears to be laterally continuous between several wells in the central part of the basin and may restrict ground-water flow because of its low permeability.

The lowermost 700 feet of the 98th Street well is mostly fine- to medium-grained sand with discontinuous layers of pebble gravel, silty clay, coarse sand, and sandstone (fig. *E.1*). Like the silty sands above the Atrisco member, these sediments were also interpreted as deposits of east-flowing, low-energy streams.

The specific time of deposition of any of the sediments could not be established because no datable materials were found (for example, volcanic ash or pollen). Detailed measurements of magnetic polarity of the core indicated that most of the lower section was deposited during a period of normal magnetic polarity, although no unique correspondence to normal periods of the Earth's magnetic polarity time scale could be detected (Hudson and others, 1998). On the basis of several possible correlations with the magnetic polarity time scale, most of the sediment below the uppermost coarse unit probably was deposited in a relatively short span of geologic time, possibly less than a few million years.

Geochemical analyses of core samples and ground water were conducted to determine the occurrence and concentrations of arsenic in Santa Fe Group sediments (Stanton and others, 1998a; 1998b). Core samples from selected depths were processed to isolate four geochemically different sediment fractions. Analyses of these fractions indicated that most of the arsenic was contained in the iron-oxide fraction of sediment that was probably deposited with clay minerals and silt-sized rock fragments. The most likely sources of these materials are the weathering of naturally occurring arsenic-rich volcanic rocks in the Jemez Mountains and Precambrian crystalline rocks in parts of the Sangre de Cristo Range (north of the Middle Rio Grande Basin in north-central New Mexico). Chemical treatment of some of the core sediment demonstrated that most of the arsenic in the deposits is not soluble in ground water of the Santa Fe Group aquifer system. No water sample collected from the 98th Street well contained more than 0.042 mg/L of total arsenic, though this isolated value is greater than the 2001 Federal drinking-water standard of 0.010 mg/L of arsenic (Stanton and others, 1998a). (See Chapter 6 for more information on water chemistry in the aquifer system.)

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[1]U.S. Geological Survey, Denver, Colorado.

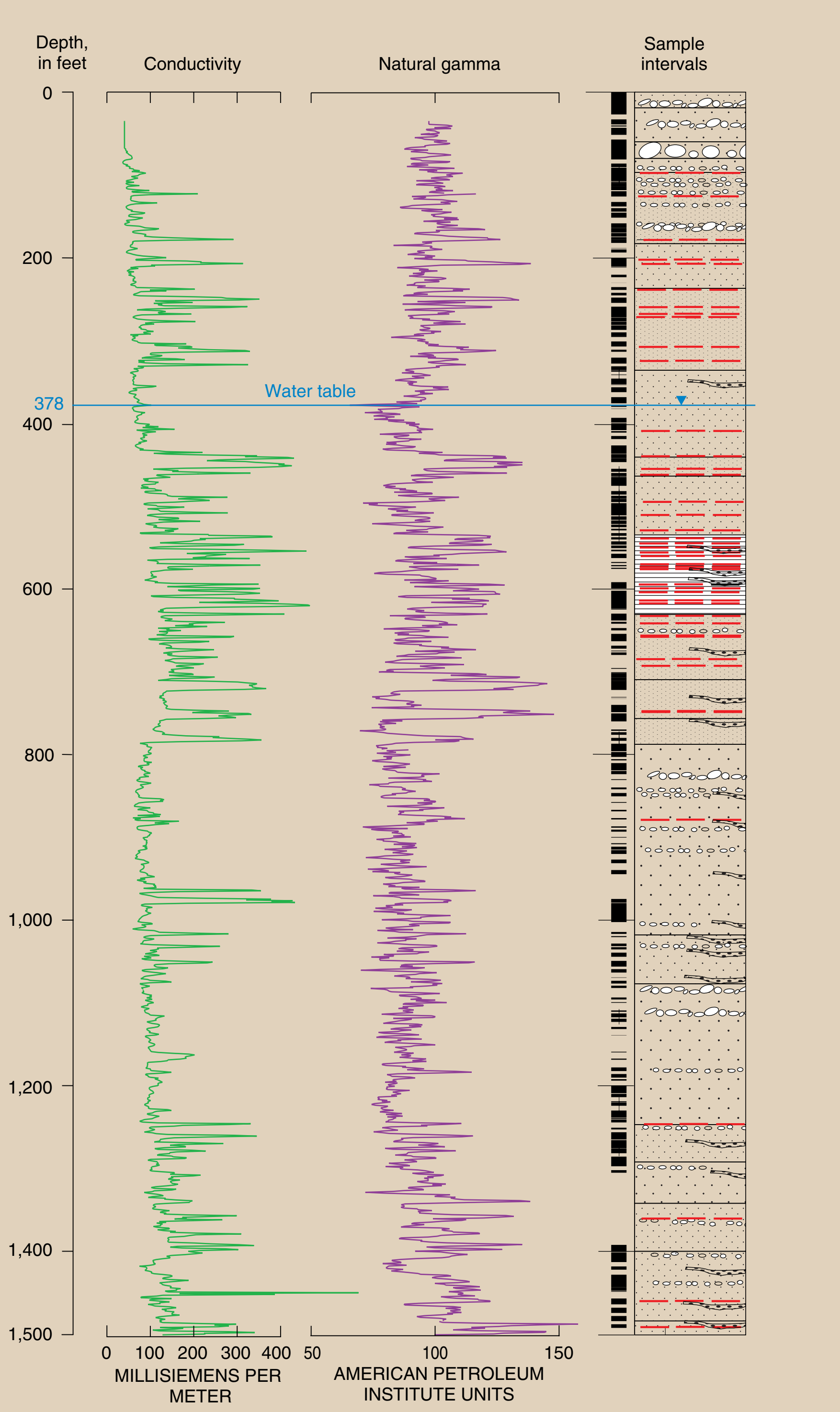
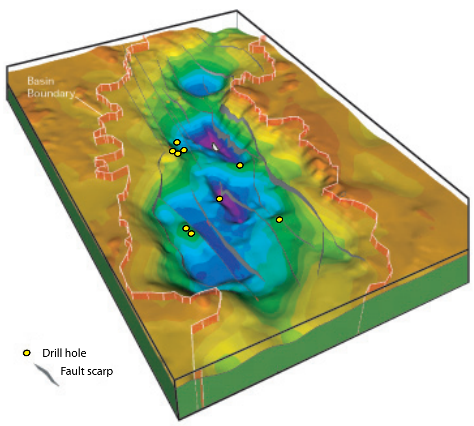


***Figure E.1.**—Lithology and geophysical logs of the 98th Street well.*

Modified from Stone and others (1998)

A USGS drilling rig collecting core at the 98th Street well.

How the geologic model represents current interpretation of basin structure and stratigraphy



Perspective view of the southern part of a model of the Middle Rio Grande Basin showing the base of the Santa Fe Group aquifer system. The model was derived from gravity data and constrained by information for the deep drill holes shown as yellow circles. (Courtesy of V.J.S. Grauch, USGS.)

The combined geologic and geophysical studies in the Middle Rio Grande Basin over a 6-year period (1995–2001) have produced considerable new information about the geologic framework of the Santa Fe Group aquifer system. The three-dimensional geologic model that forms the basis of the new ground-water-flow model embodies the major elements of this refined understanding of the Rio Grande Rift and its basin-fill deposits (Cole and others, 1999; Cole, 2001).

Major structural elements of the basin are currently (2002) better known and located than elements used in previous ground-water-flow models. Interpretation of the regional gravity data (see Box *D*; Heywood, 1992; Grauch, Gillespie, and Keller, 1999) has shown that the major subbasins are bounded at depth by northwest-trending faults, that the principal basin-bounding fault beneath Albuquerque is very near the Sandia Mountains uplift, and that the Belen subbasin is quite complex. These findings improve the preexisting structural framework model of Russell and Snelson (1994), on which the ground-water-flow model of Kernodle, McAda, and Thorn (1995) was based. The new aeromagnetic data provide detailed information about faults that offset aquifer units (see Box *D*) and allow for more accurate analysis of hydrologic relations among wells in adjacent fault blocks.

The stratigraphy of the basin-fill deposits that compose the aquifer system has always been difficult to define, largely because of the complex relation between rock units resulting from the interplay of faulting, climate, and deposition (see Box *B*). The current geologic model improves on previous concepts by recognizing that distinct stratigraphic assemblages were deposited over the same time period, but more or less independently, in the three subbasins (Santo Domingo, Calabacillas, and Belen) (fig. 3.2). This new geologic model includes numerous major faults that were identified and precisely located by the mapping and aeromagnetic surveys, and regional information about the thickness of rift-fill sediment based on calculations from the gravity data. In addition, the model accurately portrays laterally discontinuous and wedge-shaped units, particularly for the middle and deeper parts of subbasins where fault activity had the greatest effect on the composition and geometry of the aquifer system.

Chapter 4: The hydrologic system of the Middle Rio Grande Basin

In discussions of the water resources of an area, the hydrologic system is commonly split into two components for convenience: surface water and ground water. However, in the Middle Rio Grande Basin, as in most other locales, the surface- and ground-water systems are intimately linked through a series of complex interactions. These interactions often make it difficult to recognize the boundary between the two systems. In this report, the surface- and ground-water systems are described separately, though one of the goals of the report is to show that they are both parts of the hydrologic system of the Middle Rio Grande Basin and that changes in one often affect the other.

The Rio Grande is the only river I ever saw that needed irrigation. –attributed to Will Rogers

As defined earlier, in this report "Middle Rio Grande Basin" refers to the geologic basin defined by the extent of deposits of Cenozoic age along the Rio Grande from about Cochiti Dam to about San Acacia. This definition includes nearly the entire ground-water basin; however, the extent of the surface-water basin is delimited topographically by drainage divides and is consequently somewhat larger than the ground-water basin.

Surface-water system

The most prominent hydrologic feature in the Middle Rio Grande Basin is the Rio Grande, which flows through the entire length of the basin, generally from north to south. The fifth longest river in the United States, its headwaters are in the mountains of southern Colorado. The Rio Grande is the largest river in New Mexico, with a drainage area of 14,900 square miles where it enters the Middle Rio Grande Basin. It gains about 12,900 square miles of drainage area as it flows through the basin; much of that gain is from the Rio Puerco drainage basin.

Though flow in the Rio Grande is currently (2002) regulated by a series of dams and storage reservoirs, now, as historically, the greatest flows tend to occur in late spring as a result of snowmelt and for shorter periods during the summer in response to rainfall. Historically, the Rio Grande has flowed year-round through much of the basin, "except for those periods of severe, extended drought" (Scurlock, 1998).

Within the Middle Rio Grande Basin, tributary streams, wastewater-treatment plants, flood-diversion channels from urban areas, and a large number of arroyos and washes contribute flow to the Rio Grande. Among the major tributaries are the Santa Fe River, Jemez River, Rio Puerco, and Rio Salado. Of these four tributaries, only the Santa Fe River is perennial, and most of its flow is treated effluent from the City of Santa Fe wastewater-treatment plant. The cities of Bernalillo, Rio Rancho, Albuquerque, Los Lunas, and Belen discharge treated effluent directly into the Rio Grande. Two main flood-diversion channels, the North Floodway and South Diversion Channels, east of the Rio Grande intersect many smaller arroyos and divert the flow to the river at outlets north and south of Albuquerque. Among the major ephemeral arroyos that are tributary to the Rio Grande are Galisteo Creek, Arroyo Tonque, Las Huertas Creek, Arroyo de las Calabacillas, Tijeras Arroyo, Hells Canyon Wash, and Abo Arroyo (fig. 4.1).

Ephemeral streams are those that flow occasionally, usually in direct response to precipitation. *Perennial* streams are those that flow year-round from either upstream flow or the contribution of ground water.

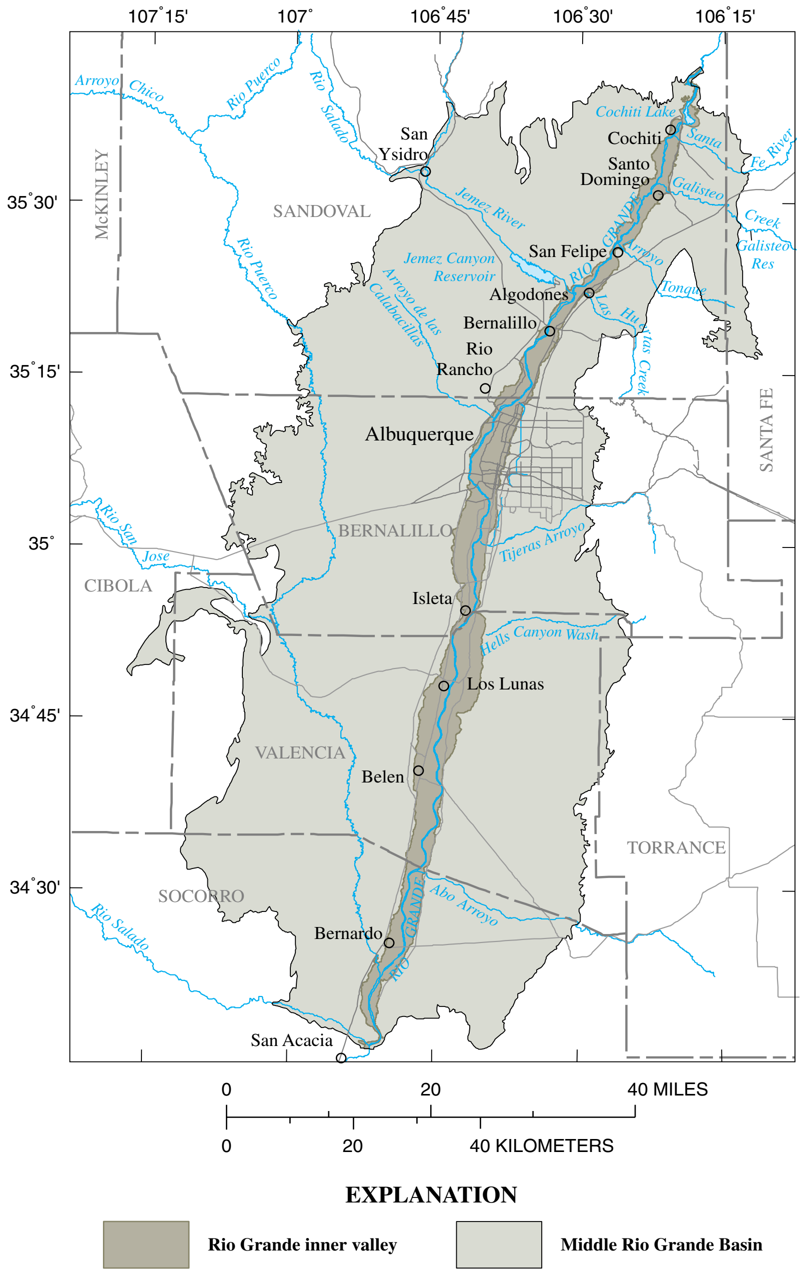


Figure 4.1.—*Major surface-water features of the Middle Rio Grande Basin.*

Three major reservoirs are in the Middle Rio Grande Basin: Cochiti Lake, Jemez Canyon Reservoir, and Galisteo Reservoir. Cochiti Lake is located in Sandoval County on the Rio Grande at its confluence with the Santa Fe River and began filling in 1973. In 1981, the reservoir capacity was 596,400 acre-feet. Though originally authorized for flood and sediment control, the authorization was subsequently modified to establish a permanent pool of 50,000 acre-feet for wildlife and recreational purposes. In addition, because the construction of Cochiti Lake destroyed a Middle Rio Grande Conservancy District irrigation diversion structure, irrigation water is now diverted at the dam. Approximately 5,900 acre-feet of water is lost to evaporation annually from Cochiti Lake. The reservoir is operated and maintained by the U.S. Army Corps of Engineers (Bullard and Wells, 1992).

Jemez Canyon Reservoir is located in Sandoval County on the Jemez River approximately 2.5 miles upstream from its confluence with the Rio Grande. The dam was finished in 1953 and is authorized to be operated solely for flood and sediment control; thus, there is no provision for maintenance of a permanent pool, and lake level consequently fluctuates over a wide range. Jemez Canyon Reservoir has a capacity of 102,700 acre-feet and is operated by the U.S. Army Corps of Engineers (Bullard and Wells, 1992).

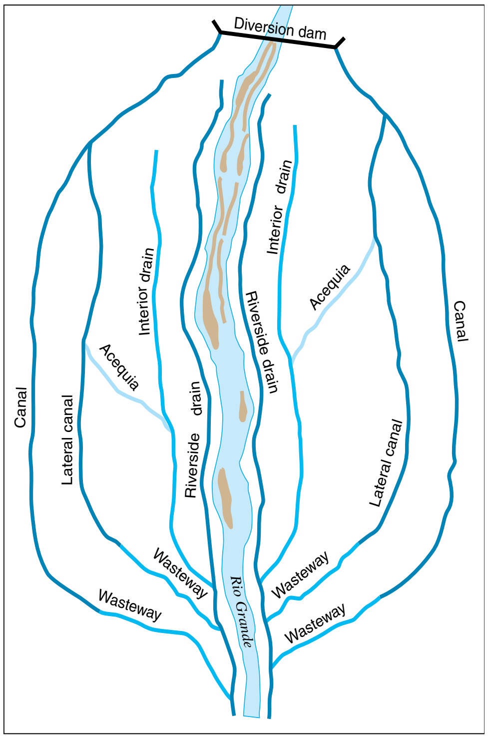
A third reservoir, Galisteo Reservoir, is located in Santa Fe County on Galisteo Creek, approximately 12 miles upstream from its confluence with the Rio Grande. The reservoir was authorized for flood and sediment control, and the dam was finished in 1970. Though empty most of the time, the reservoir has a capacity of 88,900 acre-feet and also is operated by the U.S. Army Corps of Engineers (Bullard and Wells, 1992).

A number of small flood-retention dams in the Albuquerque-Rio Rancho area are operated by the Albuquerque Metropolitan Arroyo Flood Control Authority (AMAFCA) and the Southern Sandoval County Arroyo Flood Control Authority (SSCAFCA). These dams were constructed for the downstream reduction of peak flows and contain water for only short periods following precipitation.

The inner valley of the Rio Grande contains a complex network of irrigation canals, ditches, and drains that has evolved from the original acequia system. The Middle Rio Grande Conservancy District administers this irrigation system and diverts Rio Grande water at four points in the basin: Cochiti Dam, Angostura, Isleta, and San Acacia (which serves an irrigation area downstream from the basin). During irrigation season, water is diverted from the river and flows through the Rio Grande inner valley in a series of irrigation canals and smaller ditches for application to fields. This water recharges ground water, is lost to evaporation, is transpired by plants, or is intercepted by interior drains or wasteways and returned to the river. Figure 4.2 is a schematic showing the generalized inner valley irrigation network (Bullard and Wells, 1992; Kernodle, McAda, and Thorn, 1995; Anderholm, 1997).

The other main component of the inner-valley surface-water system is a network of riverside drains, which are deep canals that parallel the river immediately outside the levees. They are designed to intercept lateral ground-water flow from the river, thus preventing waterlogged conditions in the inner valley. The riverside drains then carry this intercepted ground-water flow back to the Rio Grande. Within the basin, riverside drains and levees are usually present on both banks of the river, except where bluffs adjoin the river.

Several different types of conveyance channels (fig. 4.2) make up the irrigation system in the Middle Rio Grande Basin. *High-line canals* run along the hills bordering the inner valley at relatively shallow grades. *Low-line canals* run along the valley floor. *Laterals* are somewhat smaller and usually have a heading in a canal. *Acequias* (or *ditches*) are the smallest channels. *Wasteways* and *drains* return unused or excess irrigation water to the river (Bullard and Wells, 1992).



Modified from Bullard and Wells (1992)

***Figure 4.2.**—Schematic diagram of the inner valley irrigation network in the Middle Rio Grande Basin.*

Surface-water quantity

Streamflow-gaging stations are the means by which hydrologists monitor the flow of water in streams and rivers. Gaging stations typically consist of a shelter that encloses a recorder to monitor water height (or stage). A correlation (known as a rating curve) can be made between stage and discharge by periodically measuring the streamflow rate (or discharge) of the stream and comparing it to the stage. An increasing number of recorders in gaging stations broadcast their stage data in real time or near real time by satellite or telephone. These data are used to automatically calculate discharge, and the discharge is then made available over the Internet. This streamflow information is useful not only for resource management and flood warning but also for recreational purposes such as fishing and boating. New Mexico streamflow information can be found on the Internet at http://nm.water.usgs.gov.

The North Floodway at Paseo del Norte in northern Albuquerque.

Information collected from streamflow-gaging stations can be used to estimate how much water is flowing through the surface-water system of the Middle Rio Grande Basin. Currently (2002) 38 USGS streamflow-gaging stations are being operated in or adjacent to the Middle Rio Grande Basin; 37 gaging stations have been operated in the past but have been discontinued (fig. 4.3). The sites with gaging stations include the Rio Grande and other streams tributary to the Rio Grande, irrigation canals and drains, arroyos and washes, and reservoirs. In addition to streamflow information, some of these gaging stations provide information about water chemistry and reservoir levels in the basin.

Table 4.1 shows surface-water inflows into and outflows from the Middle Rio Grande Basin for both the period of record for selected gaging stations or sites and for 1974–2000 (1974 is the first full water year in which flows in the Rio Grande were regulated by Cochiti Dam).

Streamflow in arroyos and washes is by definition ephemeral, and measuring ephemeral streamflow is problematic. For this and other reasons, most of the arroyos and washes tributary to the Rio Grande are not gaged; thus, the amount of water they contribute to the Rio Grande is an estimate. Streamflow in Galisteo Creek and Tijeras Arroyo is measured close enough to their confluence with the Rio Grande that their contribution to the flow of the Rio Grande is known. Streamflow in Abo Arroyo is also measured; however, the gaging station (Abo Arroyo near Blue Springs) is located where the arroyo enters the basin many miles upstream from the Rio Grande. This gaging station was installed to estimate recharge to ground water at the basin margin, and because many flows recorded at this station infiltrate or evaporate before they reach the Rio Grande, measurements are not a reliable indicator of Abo Arroyo's contribution to Rio Grande flow, though it is included in table 4.1. The North Floodway and the South Diversion Channels in Albuquerque were designed to convey ephemeral flow to the Rio Grande, but the North Floodway now flows continuously at about 1 to 5 cubic feet per second in its lower reaches. The flow is the result of return flow from turf-grass irrigation and the City of Albuquerque's practice of discharging municipal-well water to arroyos during the first few minutes of operation (Ground-Water Science, Inc., 1995).

Treated sewage effluent contributes a volume of water to the Rio Grande. Because this water was originally withdrawn from the aquifer system rather than the river, it is counted as tributary inflow. The major municipalities in the basin have sewage-treatment plants: Bernalillo, Rio Rancho, Albuquerque, Los Lunas, and Belen. All discharge at least part of their treated effluent to the Rio Grande. Rio Rancho discharges a limited volume of its effluent into the Albuquerque system. Both Albuquerque and Rio Rancho use some of the treated effluent for turf-grass irrigation. Areas of the basin not served by a sewage system use septic tanks, cesspools, or open-pit toilets for waste disposal (Ground-Water Science, Inc., 1995).

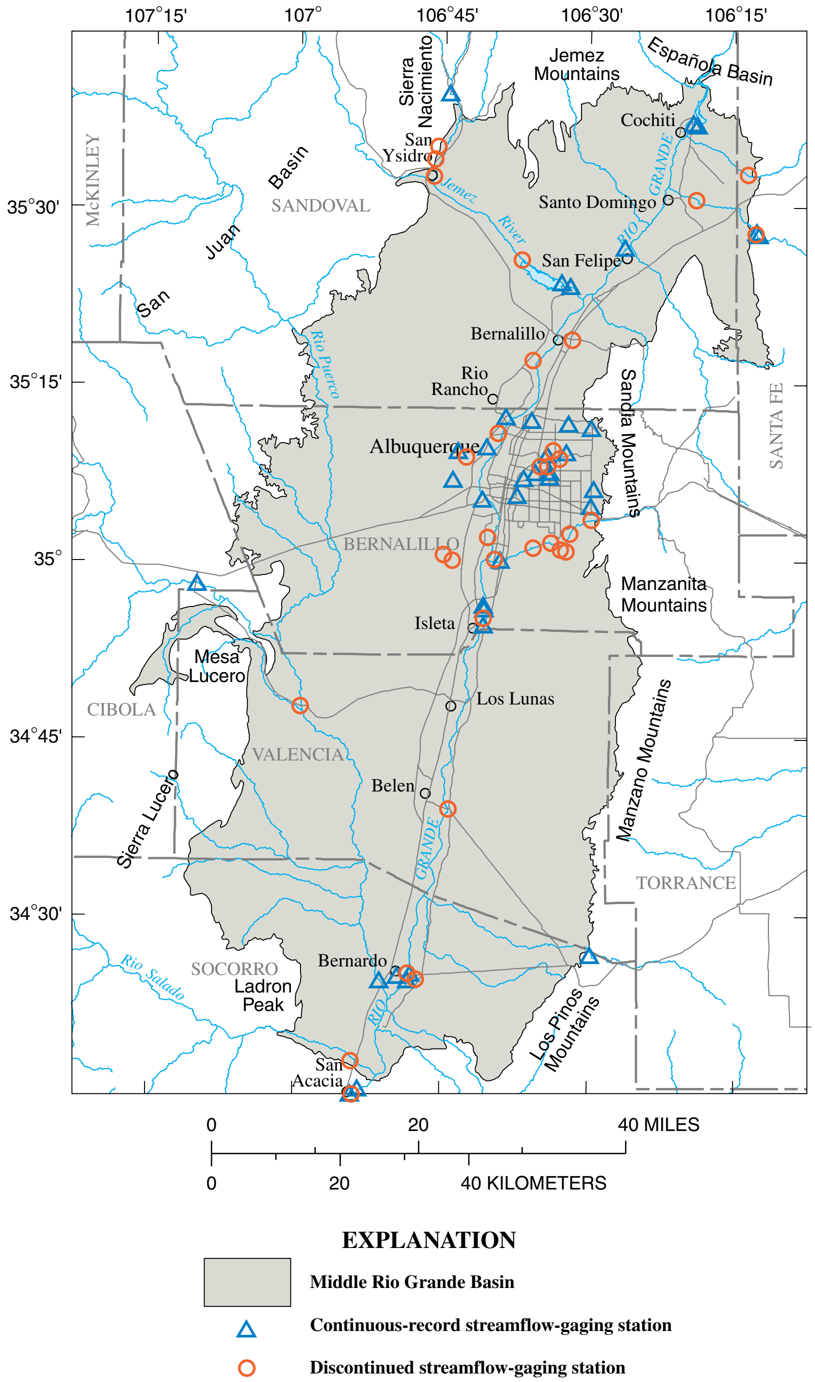


Figure 4.3.*—Current and discontinued streamflow-gaging stations in and adjacent to the Middle Rio Grande Basin.*

Water year describes the 12-month period from October 1 through September 30 of the following year. The water year is designated by the calendar year in which it ends. Thus, the 12 months ending on September 30, 2002, are water year 2002.

Cubic feet per second is the unit of measurement used to report discharge in the United States. Discharge is an instantaneous measurement of the volume of water that passes a given point in a set amount of time. One cubic foot of water is equivalent to 7.48 gallons.

Table 4.1.—Mean annual surface-water inflows into and outflows from the Middle Rio Grande Basin. Streamflow of the Santa Fe River above Cochiti Lake gaging station is not included in total inflow because it is included in streamflow for the Rio Grande below Cochiti Dam station. Streamflow for the Jemez River below Jemez Canyon Dam gaging station is not included in total inflow because it is downstream from the Jemez River near Jemez gage

[--, no data; period of record is in water years unless otherwise indicated]

Station name (station number) and period of record	Annual mean streamflow			
	Water years 1974–2000		Period of record	
	Cubic feet per second	Acre-feet per year	Cubic feet per second	Acre-feet per year
Inflow to the Middle Rio Grande Basin				
Rio Grande at Cochiti (08314500); 1924–70	--	--	[1,2] 1,300	[1,2] 945,000
Rio Grande below Cochiti Dam (08317400); 1970–present	1,460	1,060,000	[3] 1,430	[3] 1,030,000
Sili main canal (at head) at Cochiti (08314000); 1954–present	47.6	34,400	35.7	25,800
Cochiti east side main canal at Cochiti (08313500); 1954–present	84.2	61,000	66.9	48,400
Galisteo Creek below Galisteo Dam (08317950); 1970–present	5.62	4,070	[2] 6.15	[2] 4,450
Jemez River near Jemez (08324000); 1936–41, 1949–50, 1951–52, 1953–present	86.0	62,200	77.8	56,300
Santa Fe River above Cochiti Lake (08317200); 1970–99	[2] 11.7	[2] 8,500	[2] 11.3	[2] 8,160
Jemez River below Jemez Canyon Dam (08329000); 1936–39, 1943–present	[4] 72.1	[4] 52,200	[2] 63.6	[2] 46,000
Abo Arroyo near Blue Springs (08331660); 1996–present	[3] 17.1	[3] 4,670	[3] 17.1	[3] 4,670
North Floodway Channel near Alameda (08329900); 1968–89, 1990–present [seasonal record 1968–89]	11.8	8,510	10.5	7,630
South Diversion Channel above Tijeras Arroyo near Albuquerque (08330775); 1988–present	0.83	601	0.83	601
Tijeras Arroyo near Albuquerque (08330600); 1952–68, 1974–present [annual maximum only 1952–68; seasonal record 1974–98]	0.68	492	0.68	492
Rio San Jose at Correo (08351500); 1943–94	9.97	7,220	[4] 11.3	[4] 8,190
Rio Puerco near Bernardo (08353000); 1940–present	30.4	22,000	[3] 41.9	[3] 30,400
Rio Salado near San Acacia (08354000); 1947–84	[5] 8	[5] 5,900	[6] 14	[6] 10,400
Inflow from treated sewage effluent				
Town of Bernalillo wastewater-treatment plant, 1985–2000	[7] 0.7	[7] 530	[7] 0.7	[7] 530
City of Rio Rancho wastewater-treatment plant, 1985–2000	[7] 2.5	[7] 1,780	[7] 2.5	[7] 1,780
City of Albuquerque wastewater-treatment plant, 1985–2000	[7] 80.4	[7] 58,200	[7] 80.4	[7] 58,200
Village of Los Lunas wastewater-treatment plant, 1985–2000	[7] 0.9	[7] 659	[7] 0.9	[7] 659
Town of Belen wastewater-treatment plant, 1985–2000	[7] 1.3	[7] 938	[7] 1.3	[7] 938
Total inflow into the Middle Rio Grande Basin				
Total streamflow and sewage effluent measured	**1,830**	**1,330,000**	**1,790**	**1,290,000**
Outflow from the Middle Rio Grande Basin				
Rio Grande Floodway at San Acacia (08354900); 1964–present	1,100	793,000	[8] 801	[8] 580,000
Rio Grande Conveyance Channel at San Acacia (08354800); 1958–present	230	167,000	[8] 345	[8] 250,000
Socorro Main Canal North at San Acacia (08354500); 1936–present	125	90,400	[3,8] 117	[3,8] 84,500
Total outflow from the Middle Rio Grande Basin				
Total streamflow measured	**1,450**	**1,050,000**	**1,260**	**914,000**

[1] U.S. Geological Survey (1971).
[2] Not included in total inflow because of other downstream station or replacement.
[3] Ortiz, Lange, and Beal (2001).
[4] Borland and Ong (1995).
[5] Thorn, McAda, and Kernodle (1993).
[6] Denis, Beal, and Allen (1985).
[7] Upper Rio Grande Water Operations Model (2002).
[8] Period of record values are for water years 1964 through 2000.
Data not footnoted were retrieved directly from the USGS National Water Information System database.

Ground-water system

Most water-bearing units of the Middle Rio Grande Basin are unconsolidated deposits of the Santa Fe Group. Post-Santa Fe Group deposits (basin and valley fill) of Quaternary age formed during the last 1.6 million years. These deposits are present on mountain slopes, in the incised valley of the Rio Grande, and along flood plains of tributaries to the Rio Grande. They are locally used as aquifers, although the deposits are generally saturated only in flood plains or the inner valley of the Rio Grande. Because the Santa Fe Group and basin and valley-fill deposits are hydraulically connected, they are commonly grouped together as the Santa Fe Group aquifer system, following the informal usage of Thorn, McAda, and Kernodle (1993). Though the aquifer is under confined conditions locally, it is considered to be an unconfined aquifer as a whole. (For ground-water-flow modeling, the upper part of the aquifer system is treated as unconfined and the lower part as confined.)

The geology of the Santa Fe Group aquifer system was described in detail in the previous chapter. To review, the thickness of the Santa Fe Group in the Middle Rio Grande Basin ranges from about 1,400 feet at the basin margins to approximately 14,000 feet in the center of the basin (Lozinsky, 1988; Hawley and Haase, 1992; Grauch, Gillespie, and Keller, 1999). The Santa Fe Group is divided into three parts: upper (less than 1,000 to 1,500 feet thick), middle (250 to 9,000 feet thick), and lower (less than 1,000 to 3,500 feet thick). In places, either the upper part or the upper and middle parts have eroded away. Because of the depositional history of the Santa Fe Group, much of the lower part may make a poor aquifer. For this and economic reasons, ground water is withdrawn mostly from the upper and middle parts; only about the upper 2,000 feet of the aquifer is used for ground-water withdrawal. The depth to water in the aquifer system varies widely, from less than 2 feet near the Rio Grande to as much as 1,180 feet in an area west of Albuquerque.

In an *unconfined* aquifer, the water level (water table) is free to rise and fall. The pressure is atmospheric at the water table. An aquifer bounded above and below by confining beds and completely filled with water under pressure is known as a *confined* aquifer (or an artesian aquifer) (Lohman and others, 1972; Heath, 1983; Jackson, 1997).

The ground-water level in a well completed in an unconfined aquifer rises to the level of the top of the saturated zone, or water table. In a well completed in a confined aquifer, the ground-water level in the well rises to an elevation higher than the top of the aquifer, but not necessarily to the land surface. Differences in the ground-water levels in multiple wells completed at different depths in a single location indicate the general direction of vertical flow within an aquifer (Heath, 1983). See Box *F* for a discussion of ground-water-level maps and flow.

Ground-water-level declines

The main method by which ground-water managers and scientists track changes in the volume of water in an aquifer is comparing changes in ground-water levels in wells. These data are typically shown as ground-water-level maps or hydrographs. Box *F* describes how ground-water scientists use water levels to study an aquifer.

The earliest ground-water-level maps of the Middle Rio Grande Basin were of 1936 conditions (Theis, 1938). Theis' detailed maps are limited to the inner valley of the Rio Grande between the Jemez River and a few miles north of San Marcial. No effects of ground-water pumping in the basin can be seen on these maps.

Bexfield and Anderholm (2000) constructed the most complete ground-water-level map of predevelopment conditions in the Middle Rio Grande Basin (fig. 4.4) using a number of sources. As expected for predevelopment conditions, no effects of ground-water production in the basin are evident. On the basis of shapes of the ground-water-level contours, the river reach between Corrales and Belen appears to be losing water from the river into the aquifer. This losing reach during predevelopment conditions was probably not due to ground-water production but may in fact indicate evapotranspiration from vegetation in the inner valley or, as geochemical data suggest, long-term water movement into the Santa Fe Group aquifer system.

The terms *steady-state* or *predevelopment* conditions refer to the hypothetical, unchanging state of the aquifer prior to ground-water production. It is the starting point that ground-water-flow models use to assess the effect of ground-water development. However, because ground-water-level measurements are seldom available for the early years of aquifer development and because natural climatic fluctuations affect water levels, predevelopment conditions are often speculative. Commonly, the earliest water-level measurements are assumed to represent predevelopment conditions.

F

Ground-water-level maps and how they are used to understand the aquifer

Laura M. Bexfield[1]

A ground-water-level map is an essential tool to achieve a thorough understanding of a ground-water-flow system. This kind of map generally is used to indicate the elevation and shape of the water table. A carefully constructed map can be used to infer many distinct characteristics of a ground-water-flow system that are particularly important for the accurate construction of ground-water-flow models and the interpretation of hydrologic and geochemical data.

A ground-water-level map is constructed by measuring the depth to water in as many similarly constructed wells as possible. The part of an aquifer where all the rock openings and pores between sediment grains are completely filled with water is known as the saturated zone (fig. *F.1*). In an unconfined aquifer, such as the Santa Fe Group aquifer system, the upper surface of the saturated zone, the water table, is free to rise and fall. The water table is mapped using water-level measurements collected from wells that are open to the aquifer at or just below the water table. The measurements of depth to water obtained from these wells must be referenced to the same datum (commonly defined relative to sea level). For any particular well, a measuring point is defined as the elevation of the point from which the depth to water is always measured. After the depth to water in the well is measured, the value obtained is subtracted from the elevation of the measuring point to obtain the elevation of the water table above (or below) sea level (fig. *F.1*). When water-table elevations are plotted on a map of well locations, the values can be contoured to indicate the configuration of the water table (fig. *F.2*). Because the position of the water table varies in response to changes in the quantities of water entering and leaving the aquifer, a ground-water-level map should use only measurements from a time interval during which such changes are expected to be minimal.

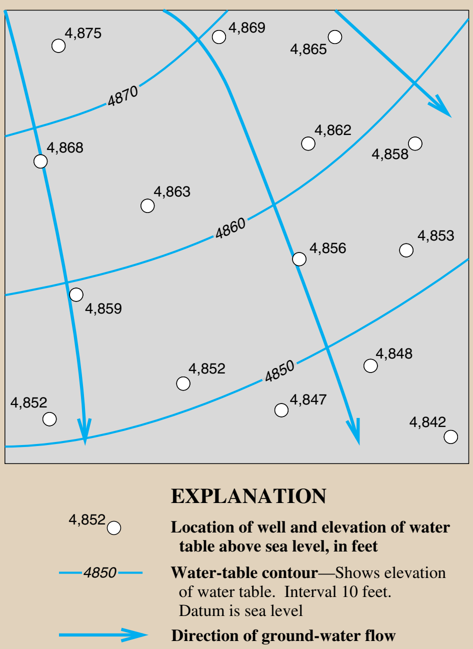


Figure F.1.*—Information needed to determine water-table elevations and to calculate hydraulic gradients.*

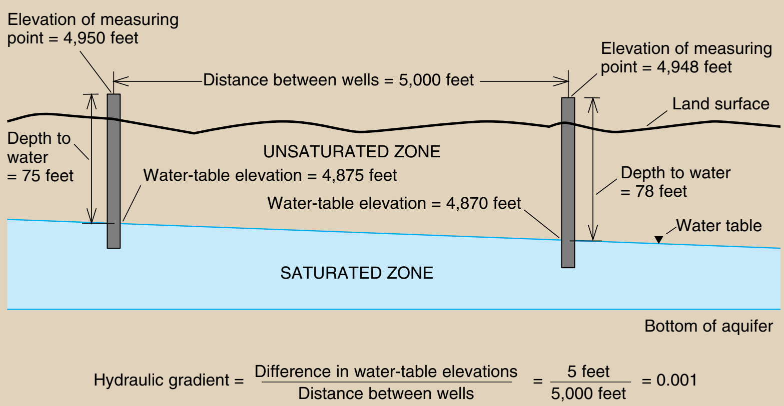


Figure F.2.*—Hypothetical well locations, water-table elevations, water-table contours, and approximate directions of ground-water flow.*

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

One of the most common uses of a ground-water-level map is to infer the direction of ground-water flow in the aquifer. Water generally flows from areas of higher hydraulic head (higher water-table elevations) to areas of lower hydraulic head (lower water-table elevations) along the path of the steepest gradient. Lines drawn perpendicular to the water-table contours approximate the direction of ground-water flow (fig. *F.2*). Flow lines delimited in this manner are not exact because they assume that the aquifer is isotropic (that is, aquifer materials allow water to move with equal efficiency in all directions), which is often not the case, and because they do not reflect the vertical component of ground-water movement (Domenico and Schwartz, 1990). However, such flow lines generally are reasonably representative of ground-water-flow directions, particularly in the upper part of the aquifer. Changes in flow directions through time can be determined by comparing ground-water-level maps constructed using water-level measurements from different time periods. Flow directions may change as the result of sustained ground-water pumping, which can lower water levels both locally and regionally.

Areas where water recharges to and discharges from the aquifer can be inferred from the configuration of water-table contours. The water table slopes from areas of recharge to areas of discharge. Where water-table contours bend across a stream channel to form a "V" pointing downstream, the stream is losing water to (recharging) the aquifer and ground-water flow is away from the stream (fig. *F.3*). Conversely, where the contours bend to form a "V" pointing upstream, the aquifer is discharging water to the stream and ground-water flow is toward the stream. If there is no deflection of the water-table contours across a stream channel, there may be little or no interaction between the stream and the aquifer or the type of interaction may not be determined from the available data.

The spacing of water-table contours with a defined contour interval also provides important information about the hydraulic gradient of the aquifer, which is the difference in the elevation of the water table over a known horizontal distance (fig. *F.1*), and is a necessary component in determining how fast ground water moves through the aquifer. Differences in the hydraulic gradient (spacing in the water-table contours) across an area of interest generally indicate differences in the physical properties of the aquifer. For example, a flatter hydraulic gradient (greater spacing between contours) often indicates an area of larger aquifer thickness or greater hydraulic conductivity, which is a measure of the ability of aquifer materials to transmit water.

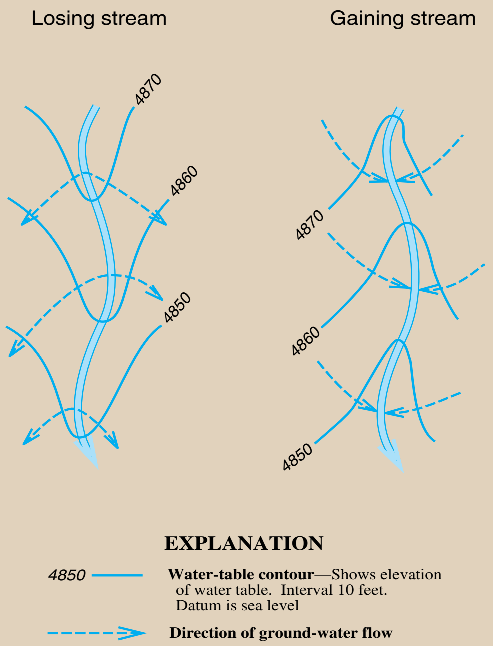


Figure F.3.*—Examples of water-table contours and directions of ground-water flow in the vicinity of losing and gaining streams. Streamflow is toward bottom of the diagram.*

A pumping well lowers the ground-water level around the well in a funnel-like shape known as a *cone of depression*. In more permeable areas of an aquifer, the size of the cone of depression is smaller. Similarly, at larger pumping rates, the cone of depression is larger. As the diameter of the cone of depression around a pumped well increases, it may intersect other wells, lowering the water level in those wells. Because a pumped well locally depresses ground-water levels, ground-water-level measurements made in a recently pumped well show a lower water level than the undisturbed *static* water level outside the cone of depression. For this reason, ground-water-level measurements are best made in nonpumped *observation* or *monitoring wells*—also called *piezometers*.

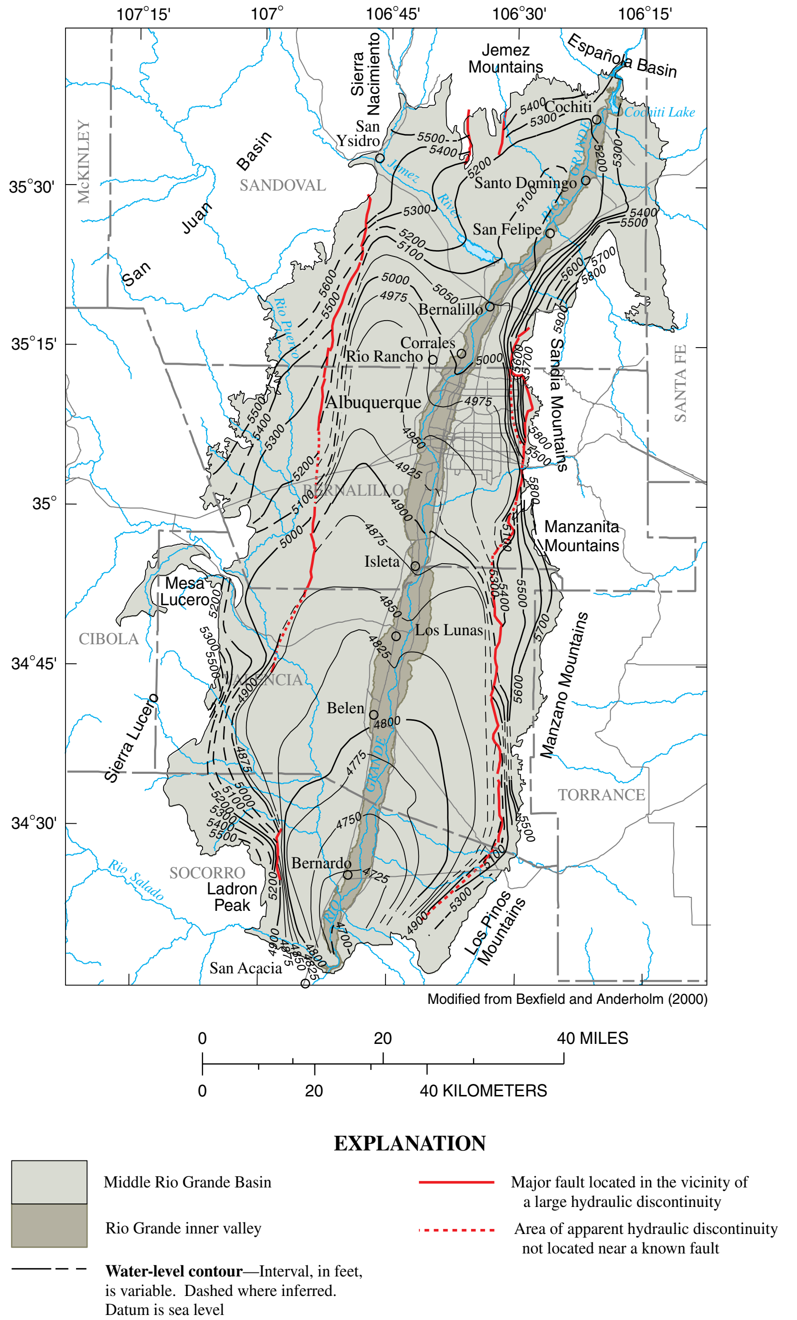
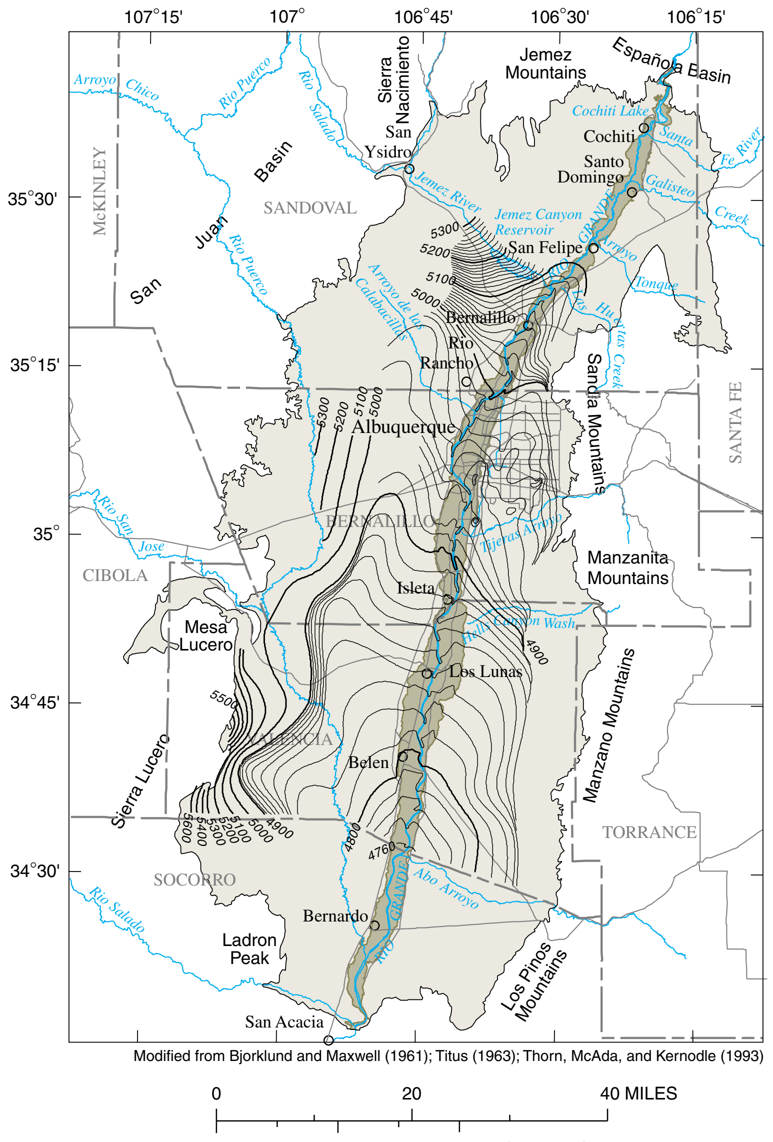


Figure 4.4.*—Ground-water levels that represent predevelopment conditions in the Santa Fe Group aquifer system in the Middle Rio Grande Basin.*

Thorn, McAda, and Kernodle (1993) combined ground-water-level maps of the Albuquerque area by Bjorklund and Maxwell (1961) and of Valencia County by Titus (1963) to construct a ground-water-level map for most of the Middle Rio Grande Basin that represented conditions in 1960–61 (fig. 4.5). The effects of ground-water production by City of Albuquerque wells are shown by the presence of circular, closed water-level contours on the south side of Albuquerque and large deflections in the water-level contours in northeast Albuquerque. For this time period in most of the mapped area, the ground-water-level contours indicate water



EXPLANATION

Middle Rio Grande Basin

Rio Grande inner valley

Water-level contour—Interval, in feet, is variable. Dashed where inferred. Datum is sea level

Figure 4.5.—*Ground-water levels that represent 1960–61 conditions in the Santa Fe Group aquifer system in the Middle Rio Grande Basin.*

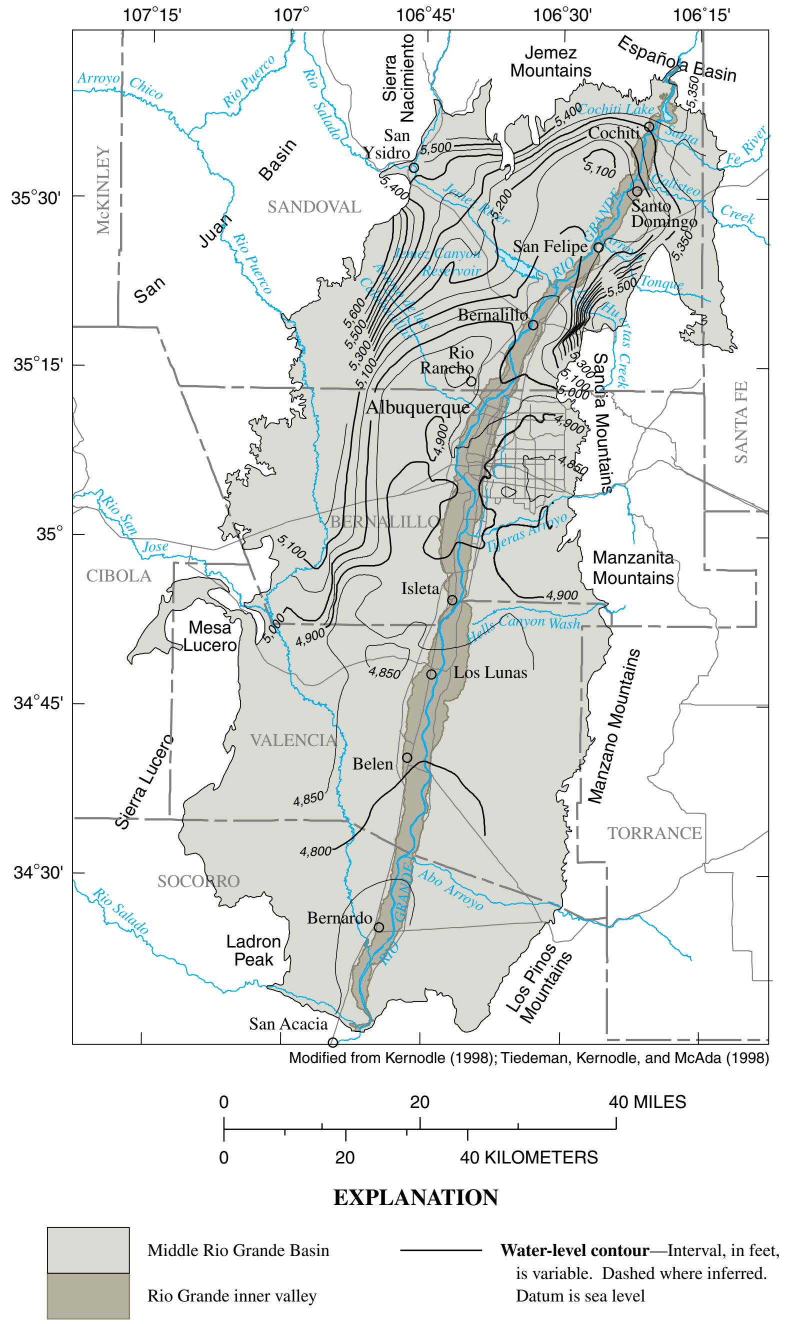


Figure 4.6.—*Ground-water levels that represent winter 1994–95 conditions in the Santa Fe Group aquifer system in the Middle Rio Grande Basin.*

A USGS hydrologist collecting ground-water levels at the Sierra Vista monitoring well. Frequent and consistent measurements of ground-water levels are crucial for understanding the aquifer system and tracking water-level declines.

movement from the river into the aquifer. Titus (1961) published a ground-water-level map of 1958–61 conditions using much of the same data but included areas outside and adjacent to the Middle Rio Grande Basin.

Several ground-water-level maps have been constructed showing conditions in the Albuquerque area in the late 1980's (Summers, 1992) and early 1990's (Thorn, McAda, and Kernodle, 1993). The ground-water-level map of the entire Middle Rio Grande Basin showing the most recent conditions was constructed by Tiedeman, Kernodle, and McAda (1998) and represents winter 1994–95 conditions (fig. 4.6). Well-defined cones of depression in the Albuquerque and Rio Rancho areas and marked distortion of water-level contours in the Albuquerque area are visible on this map.

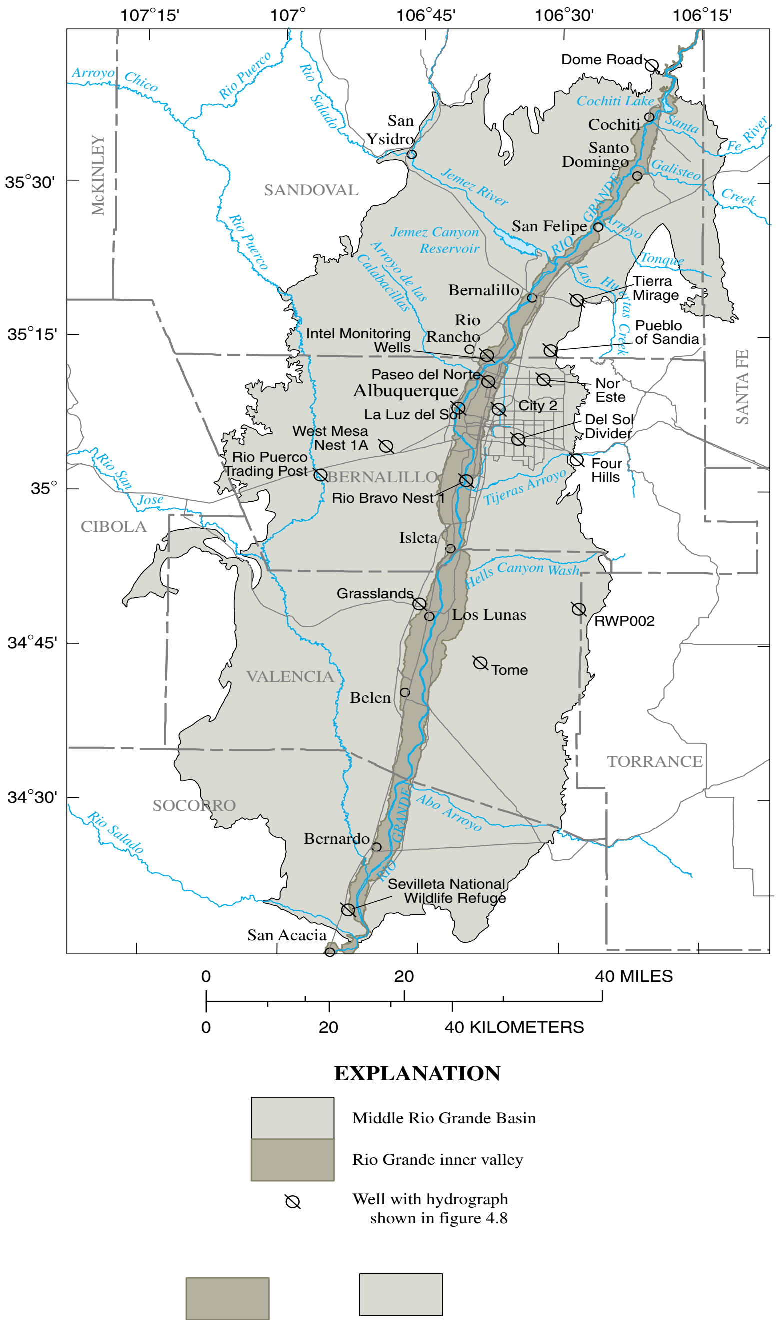
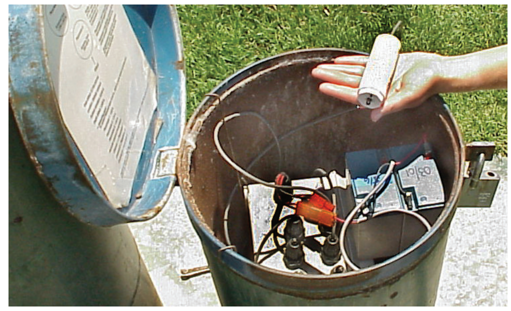


***Figure 4.7.**—Location of selected wells in the Middle Rio Grande Basin. Hydrographs for these wells are shown in figure 4.8.*



Electronic equipment used to automatically record ground-water levels. The white cylinder being held is a pressure transducer that is placed below the water surface in a well. As water levels fluctuate, the transducer detects changes in pressure and transmits the data to the electronic recorder.

Currently (2002), ground-water levels in the basin are monitored through two main programs conducted by the USGS: one in cooperation with the New Mexico Office of the State Engineer (NMOSE) and the other in cooperation with the City of Albuquerque. The NMOSE program is part of a monitoring network of selected wells in 34 areas in New Mexico and adjoining States that are measured periodically (usually every 5 years) or are equipped with continuous water-level recorders. The Middle Rio Grande monitoring area of this program extends from about Jemez Canyon Reservoir to about 35 miles south of Socorro and included 123 wells in 1995 (Wilkins and Garcia, 1995).

A graph showing water levels over time at a single site is known as a *hydrograph*. Hydrographs can be constructed for either ground- or surface-water levels, and they are a common way to visualize water-level changes over time. See figure 4.8 for examples of hydrographs.

The City of Albuquerque program encompasses the Albuquerque Basin (or Middle Rio Grande Basin as defined in this report) and includes 255 wells. Ground-water levels in these wells are measured by the USGS and other agencies, and the measurement interval for wells in the network varies from continuous (collected by water-level recorder) to multiyear (Rankin, 2000).

Because of the limitations of ground-water levels measured in or near production wells, the USGS in cooperation with the City of Albuquerque, NMOSE, and Bernalillo County began a program in 1996 to install a number of specialized monitoring wells in the Middle Rio Grande Basin. Most of these wells are groups, or nests, of several wells completed at different depths in the aquifer. The locations for these wells were chosen to be at least 1 mile away from high-capacity production wells, and the goal was to monitor changes in the static water level of the aquifer over an extended period of time. (Because of the production-well density in much of the basin, however, the placement of the monitoring wells can only minimize the short-term fluctuations caused by pumped wells.) Currently (2002), 59 such monitoring wells have been installed at 23 sites. Continuous water-level recorders have been installed on nearly all these wells, and all have been incorporated into the City of Albuquerque ground-water-level monitoring program.

Locations of selected well nests and single wells in the Middle Rio Grande Basin are shown in figure 4.7. Hydrographs associated with these wells are shown in figure 4.8. Ground-water levels in wells located away from pumping centers generally do not show a continually declining trend over time, though some variation is present. However, wells located in areas near pumping centers have had a general decline in water levels. (Because of the high variability of aquifer conditions, not all wells show the same trends.)

The USGS monitoring well at Sister Cities Park.

Seasonal water-level fluctuations can be clearly seen in the hydrographs for three sites: Nor Este, Del Sol Divider, and Rio Bravo nest 1. These water-level fluctuations reflect increased municipal pumping from nearby wells during the summer months, when demand is greatest, and water-level recovery during the winter months, when demand is least. Wells completed at different depths at the same site do not always respond in the same manner, which indicates that the aquifer is not of uniform composition and that vertical water movement may be somewhat restricted.

Hydrographs from the eight sites with multiple wells can be used to determine the vertical direction of ground-water flow because water generally flows from areas of high hydraulic head (lesser depth to water) to areas of low hydraulic head (greater depth to water). Thus, at five sites (such as Paseo del Norte nest 1) flow appears to be downward; at three sites (such as West Mesa nest 1A) flow generally appears to be upward.

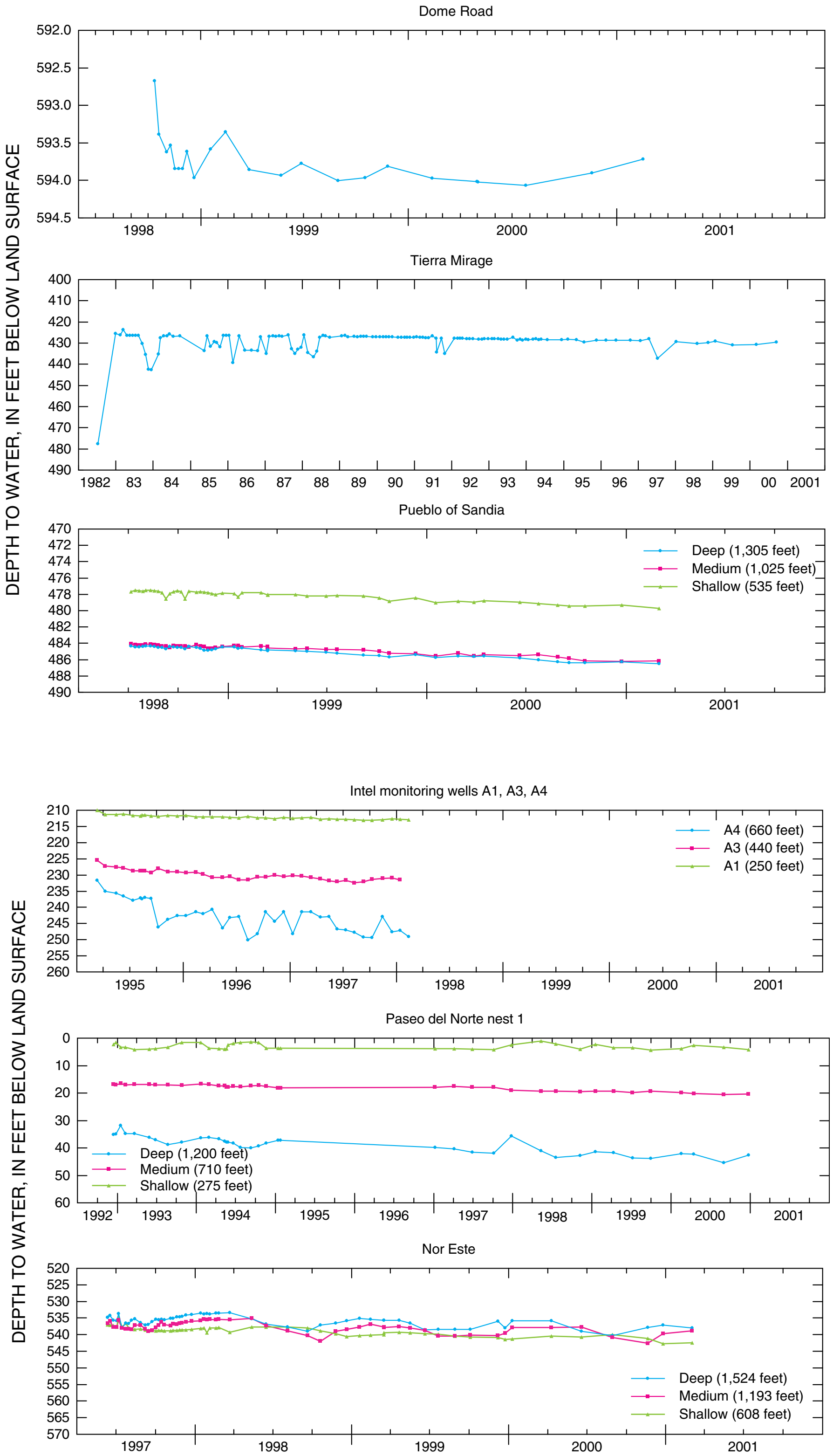


Figure 4.8.*—Water levels in selected wells in the Middle Rio Grande Basin. Water levels for separate wells in a single well nest are differentiated by total well depth.*

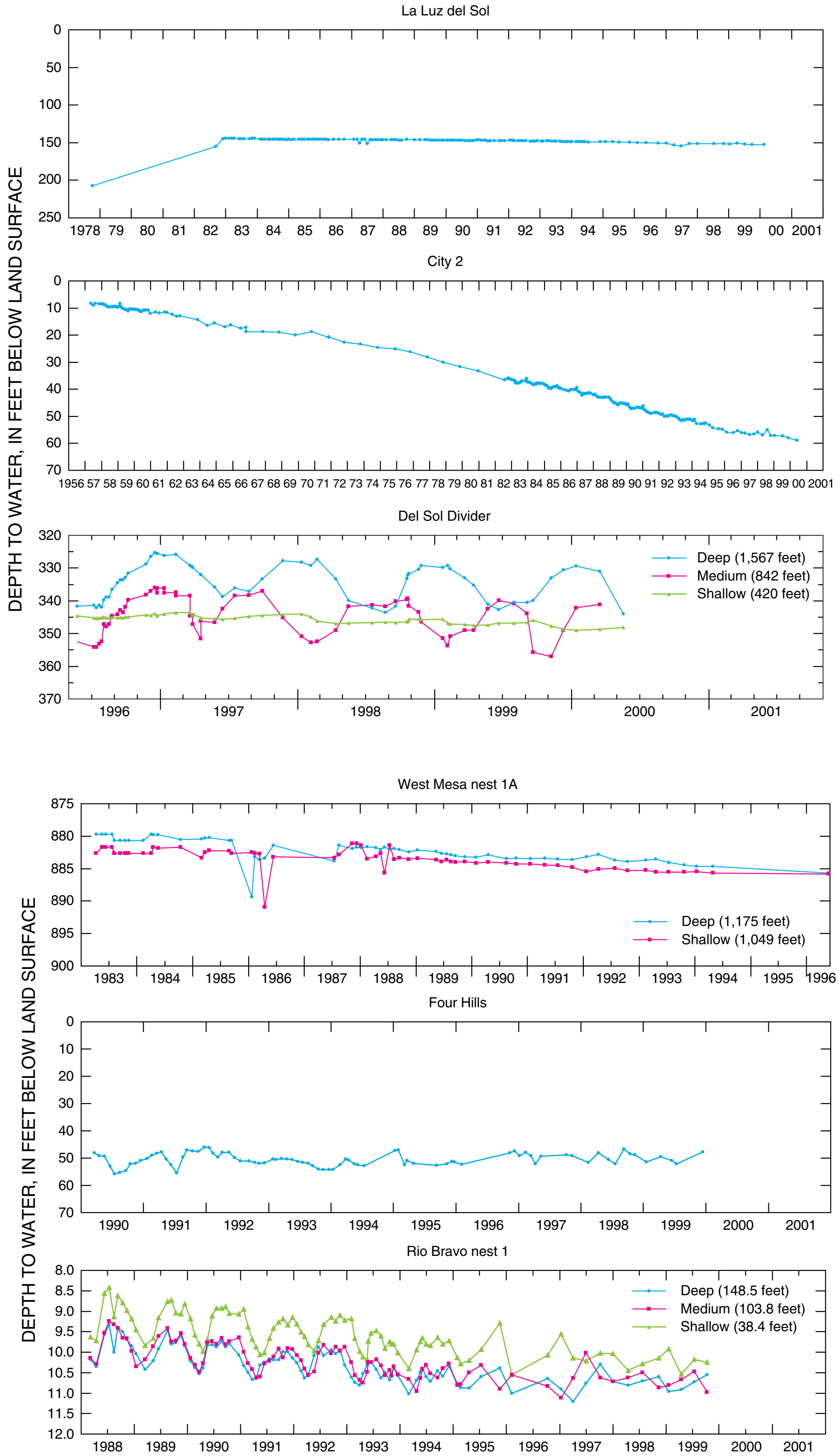


Figure 4.8.*—Water levels in selected wells in the Middle Rio Grande Basin. Water levels for separate wells in a single well nest are differentiated by total well depth—Continued.*

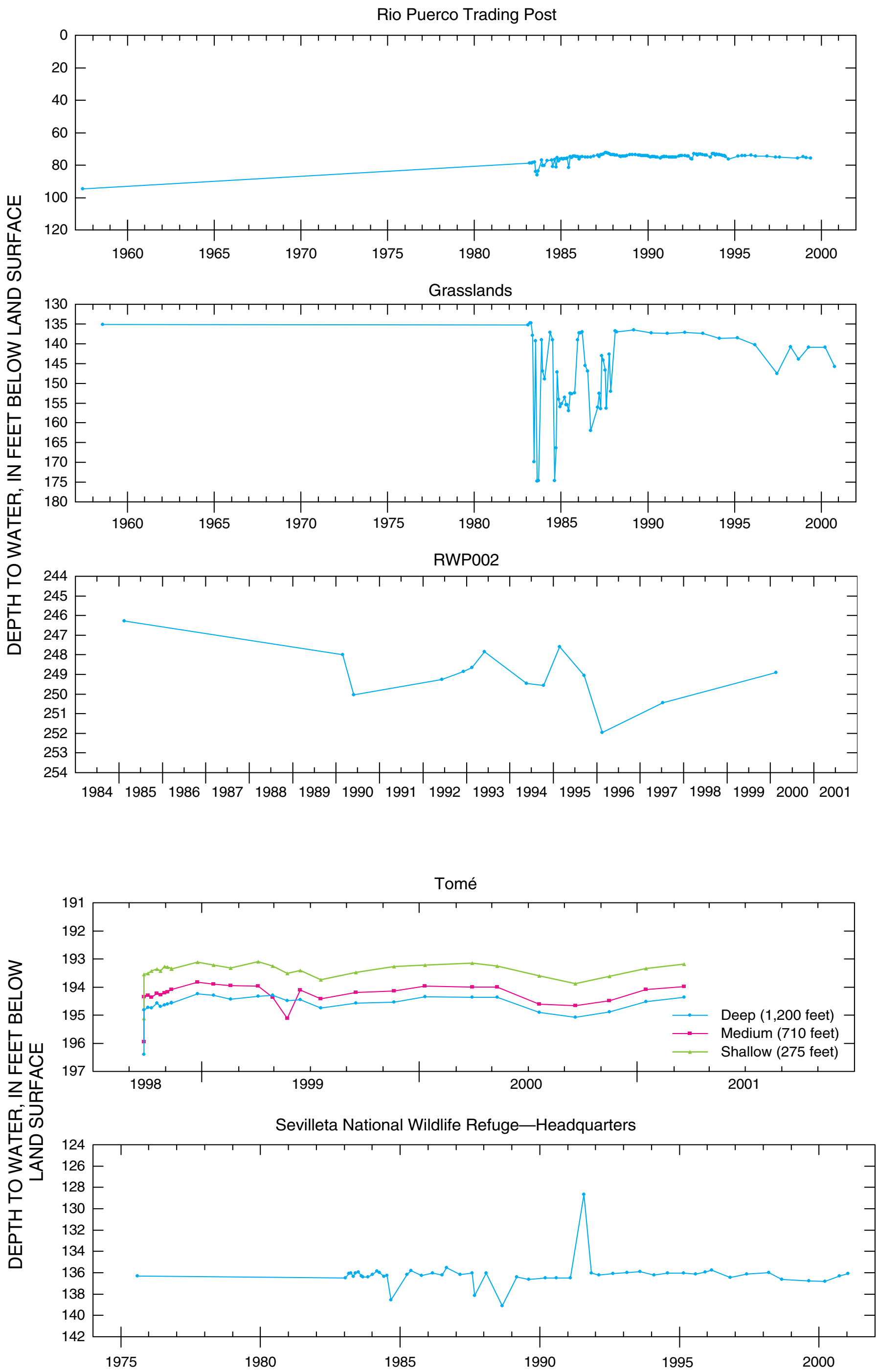


Figure 4.8.—*Water levels in selected wells in the Middle Rio Grande Basin. Water levels for separate wells in a single well nest are differentiated by total well depth—Continued.*

Aquifer productivity

Perhaps the most important parameter that ground-water scientists use to characterize an aquifer is its *hydraulic conductivity,* which is a measure of how quickly water can move through a rock unit. In English units, hydraulic conductivity is commonly defined as the volume of water (in cubic feet) that will move in a unit of time (1 day) under a unit of hydraulic gradient (1 foot per foot) through a unit of area (1 square foot), but is simplified to units of velocity (distance divided by time or feet per day). This report uses feet per day to report hydraulic conductivity. The larger the value of hydraulic conductivity, the more water an aquifer is able to yield to wells and springs. Sand and gravel typically have values in the range of 1 to 10,000 feet per day, whereas silt and clay can have values ranging from 0.0000001 to 1 foot per day. In general, the coarser and more uniform the aquifer material, the higher the hydraulic conductivity (Heath, 1983).

Measurements of hydraulic conductivity can be made in several ways, the most common methods being aquifer tests, laboratory measurements of drill cores, and air permeameter measurements of the rock units where they crop out on the surface. All these methods have their limitations, and because they are expensive, usually only a limited number of hydraulic-conductivity values are obtained for a given rock unit. Typically, the estimated values of hydraulic conductivity for a rock unit are applied to large areas of the unit in the subsurface.

The aquifer definition stated previously on page 23 is quite subjective—there is no absolute standard that defines whether a rock unit is usable as an aquifer. Other than the presence of potable water, the most important characteristics that contribute to the productivity of an aquifer are hydraulic conductivity and saturated thickness.

As mentioned in the previous chapter, sediments in each of the three parts of the Santa Fe Group were deposited in a range of different depositional environments that influence the hydraulic conductivity of the aquifer. For convenience, the Santa Fe Group is subdivided into units with similar characteristics and depositional history—these units are known as lithofacies. Because of their similarities, rock units within a lithofacies tend to have similar values of hydraulic conductivity. Thus, maps of lithofacies can be converted to maps showing the distribution of hydraulic conductivity in an aquifer or hydrostratigraphic units, as discussed in Chapter 3. Such maps are a necessary step in the creation of a ground-water-flow model.

Because actual measurements of hydraulic conductivity are scarce, any map of the hydraulic conductivity of an aquifer is an approximation at best. Zones of estimated values of horizontal hydraulic conductivity (in the east-west direction) in the upper part of the saturated zone of the aquifer (as used in the ground-water-flow model of McAda and Barroll [2002]), are shown in figure 4.9. This map shows that the aquifer beneath eastern Albuquerque has some of the highest hydraulic conductivity in the basin. Because Albuquerque's post-Second World War growth was largely in this area, most of the new municipal-supply wells drilled to support the growth were completed in an area of high hydraulic conductivity, which led to the popular belief that the entire Middle Rio Grande Basin was underlain by a very productive aquifer and that the aquifer contained a volume of water equivalent to one of the Great Lakes (*Albuquerque Living*, 1984; Thorn, McAda, and Kernodle, 1993; Niemi and McGuckin, 1997).

Because of the large values of hydraulic conductivity, the City of Albuquerque has been able to complete wells that yielded large quantities of water. This is in stark contrast to other areas of New Mexico that have less productive aquifers. For instance, some wells in the Buckman well field in Santa Fe are completed in a portion of the Santa Fe Group aquifer system with hydraulic conductivity values approximately 100 times less than those in Albuquerque (Black and Veatch, 1978; Thorn, McAda, and Kernodle, 1993).

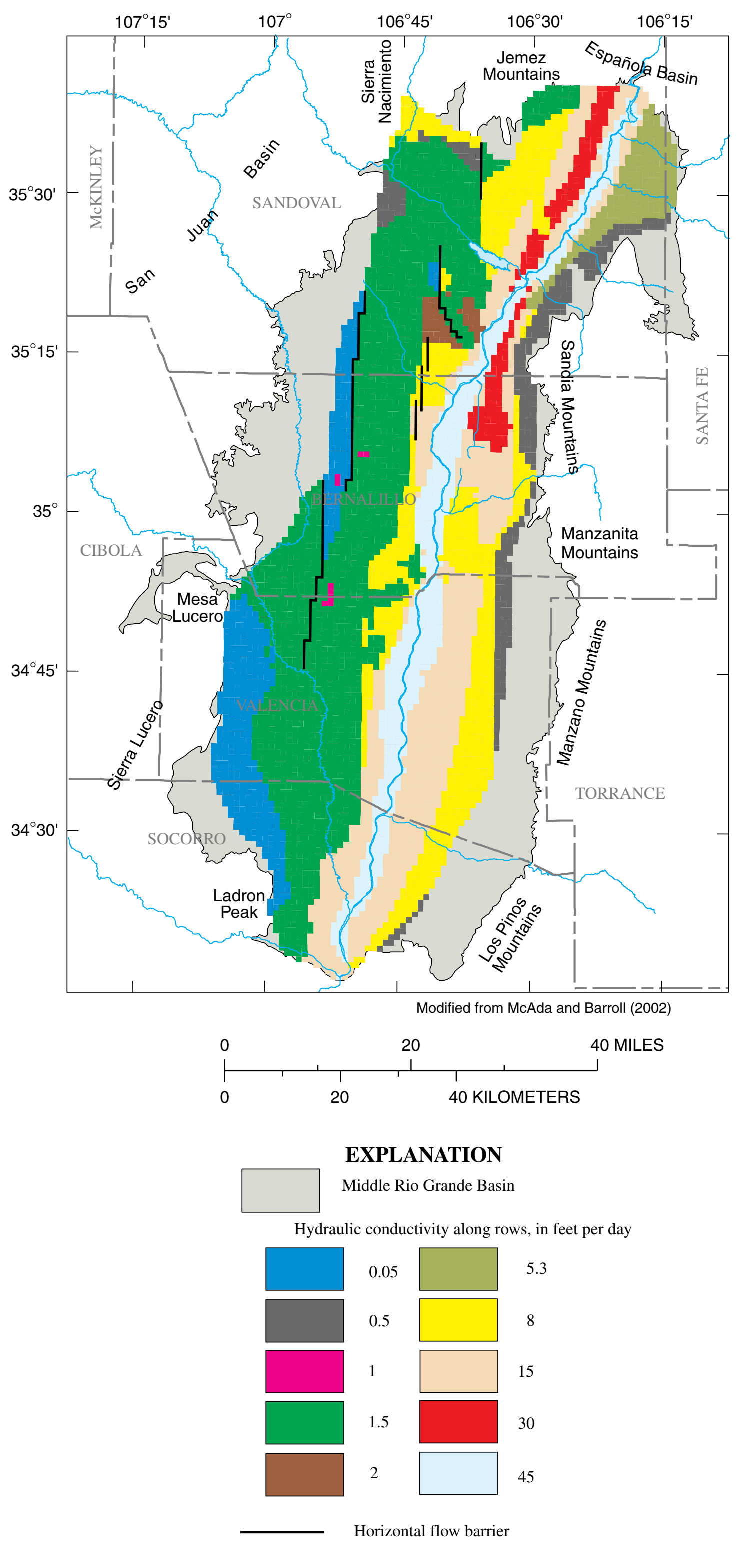


Figure 4.9.—*Distribution of east-west horizontal hydraulic conductivity in the upper part of the Santa Fe Group aquifer system in the ground-water-flow model of McAda and Barroll (2002). View is of layer 1 (30 to 50 feet below the predevelopment water table).*

Hydraulic conductivity in a rock unit usually differs in the horizontal and vertical directions, a property referred to as *anisotropy.* Sedimentary deposits, such as in the Middle Rio Grande Basin, are usually deposited in a series of beds with varying grain sizes. This bedding is responsible for lower hydraulic-conductivity values (by as much as several orders of magnitude) in the vertical direction. Generally, rock units with smaller values of hydraulic conductivity control vertical hydraulic conductivity; rock units with larger values of hydraulic conductivity control horizontal hydraulic conductivity (Ingebritsen and Sanford, 1998). The difference between vertical and horizontal hydraulic conductivity also varies with the scale on which it is examined: the greater the thickness or areal extent of the rock unit, the greater the difference tends to be (Freeze and Cherry, 1979).

Ground-water quantity

Porosity is the ratio of openings (or voids) to the total volume of a rock, such as between sedimentary grains or within fractures, and is usually expressed as a percentage. Such openings may not be connected; thus, a rock with significant porosity may have a low value of hydraulic conductivity. In general, the more uniform the rock material, the greater the porosity. Additionally, fine-grained materials tend to be better sorted than coarser materials. Thus, sands typically have porosity values in the range of 25 to 50 percent, whereas clays typically vary between 40 and 70 percent. As shown on page 58, this relation between fine- and coarse-grained materials is opposite of that seen in typical values of hydraulic conductivity (Freeze and Cherry, 1979; Heath, 1983).

One of the most common questions about the Santa Fe Group aquifer system in the Middle Rio Grande Basin is "How much water is left?" This question is difficult to answer or, perhaps, the answer is of little use. It is comparatively easy to make assumptions about the porosity and saturated thickness of the Santa Fe Group aquifer system and thus estimate a volume of water. However, the composition of the aquifer remains an educated guess in much of the basin, and little is known about the water quality in much of the aquifer. In addition, silty units with large amounts of clay and low values of hydraulic conductivity will not conduct usable quantities of water to wells, so the water contained in these deposits is virtually unobtainable. Thus, any estimate of the volume of water remaining in the aquifer would include large volumes that are unusable or unobtainable, and a large uncertainty would be associated with the estimate.

Water use in the basin

At the current time (2002), the main direct consumptive use of surface water in the Middle Rio Grande Basin is irrigation in the inner valley of the Rio Grande. Water is also consumed by reservoir evaporation, recharge to ground water, and evapotranspiration by riparian vegetation. Other nonconsumptive uses include recreation, esthetics, and ceremonial use by Native Americans.

Ground water from the Santa Fe Group aquifer system is currently (2002) the sole source of water for municipal supply and domestic, commercial, and industrial use in the Middle Rio Grande Basin. The municipalities of Bernalillo, Rio Rancho, Albuquerque, Bosque Farms, Los Lunas, and Belen have water-supply wells and distribution systems. A number of smaller communities such as Algodones and Cochiti Lake have formed Mutual Domestic Water Consumers Associations (MDWCA) to provide a public supply of water. Several private utilities such as Sandia Peak Utility Company or New Mexico Utilities Incorporated serve single or multiple subdivisions or parts of municipalities. Most of the pueblos in the Middle Rio Grande Basin have public-supply wells that serve at least part of the pueblo. Kirtland Air Force Base in southeast Albuquerque uses its own supply wells. A large number of domestic-supply wells in the basin furnish water for single households. In addition, small production wells scattered throughout the basin supply water for livestock. Finally, a number of commercial firms have their own wells to provide ground water for industrial use, the largest being Intel Corporation in Rio Rancho.

Saturated thickness is the thickness of the aquifer saturated with water. In an unconfined aquifer, the saturated thickness varies with the position of the water table.

Every 5 years the NMOSE compiles and publishes water-use estimates for New Mexico, aggregated by counties and river basins. A summary of water use from 1995 estimates in the seven counties that make up the Middle Rio Grande Basin is listed in table 4.2 (Wilson and Lucero, 1997). Neither county boundaries nor river-basin boundaries correspond to the boundaries of the Middle Rio Grande Basin, so estimates based on entire counties overestimate water use. However, the estimates are useful for a rough comparison of the source and use of water in each county. The relative ground- and surface-water use by category for the counties in the Middle Rio Grande Basin is shown in graph form in figure 4.10.

Table 4.2.—Water withdrawal estimates during 1995 for counties in the Middle Rio Grande Basin

[Wilson and Lucero, 1997]

County	Category	Surface-water withdrawal (acre-feet)	Ground-water withdrawal (acre-feet)	Total withdrawal (acre-feet)
Bernalillo	Public water supply	0.00	135,467.80	135,467.80
	Domestic	0.00	2,162.33	2,162.33
	Irrigated agriculture and livestock	65,261.43	4,661.87	69,923.30
	Commercial, industrial, mining, and power generation	0.00	5,107.96	5,107.96
	Reservoir evaporation	0.00	0.00	0.00
	County totals:	**65,261.43**	**147,399.96**	**212,661.39**
Cibola	Public water supply	0.00	2,840.01	2,840.01
	Domestic	0.00	968.76	968.76
	Irrigated agriculture and livestock	3,131.31	2,534.07	5,665.38
	Commercial, industrial, mining, and power generation	0.00	407.42	407.42
	Reservoir evaporation	1,080.00	0.00	1,080.00
	County totals:	**4,211.31**	**6,750.26**	**11,961.57**
Sandoval	Public water supply	125.95	15,201.07	15,327.02
	Domestic	0.00	2,529.00	2,529.00
	Irrigated agriculture and livestock	54,629.41	1,166.95	55,796.36
	Commercial, industrial, mining, and power generation	10.00	1,987.60	1,997.60
	Reservoir evaporation	15,033.00	0.00	15,033.00
	County totals:	**69,798.36**	**20,884.62**	**90,682.98**
Santa Fe	Public water supply	5,365.55	10,039.81	15,405.36
	Domestic	0.00	2,341.46	2,341.46
	Irrigated agriculture and livestock	18,971.28	13,766.43	32,737.71
	Commercial, industrial, mining, and power generation	19.54	544.09	563.63
	Reservoir evaporation	143.00	0.00	143.00
	County totals:	**24,499.37**	**26,691.79**	**51,191.16**
Socorro	Public water supply	0.00	2,183.55	2,183.55
	Domestic	0.00	323.23	323.23
	Irrigated agriculture and livestock	122,610.61	38,596.13	161,206.74
	Commercial, industrial, mining, and power generation	0.00	1,079.76	1,079.76
	Reservoir evaporation	7,570.00	0.00	7,570.00
	County totals:	**130,180.61**	**42,182.67**	**172,363.28**
Torrance	Public water supply	0.00	982.72	982.72
	Domestic	0.00	745.39	745.39
	Irrigated agriculture and livestock	29.82	45,449.74	45,479.56
	Commercial, industrial, mining, and power generation	0.00	104.66	104.66
	Reservoir evaporation	0.00	0.00	0.00
	County totals:	**29.82**	**47,282.51**	**47,312.33**
Valencia	Public water supply	0.00	4,917.37	4,917.37
	Domestic	0.00	3,302.98	3,302.98
	Irrigated agriculture and livestock	182,737.03	9,361.22	192,098.25
	Commercial, industrial, mining, and power generation	0.00	1,116.73	1,116.73
	Reservoir evaporation	0.00	0.00	0.00
	County totals:	**182,737.03**	**18,698.30**	**201,435.33**
Totals	Public water supply	5,491.50	171,632.33	177,123.83
	Domestic	0.00	12,373.15	12,373.15
	Irrigated agriculture and livestock	447,370.89	115,536.41	562,907.30
	Commercial, industrial, mining, and power generation	29.54	10,348.22	10,377.76
	Reservoir evaporation	23,826.00	0.00	23,826.00
	Total for all counties:	**476,717.93**	**309,890.11**	**786,608.04**

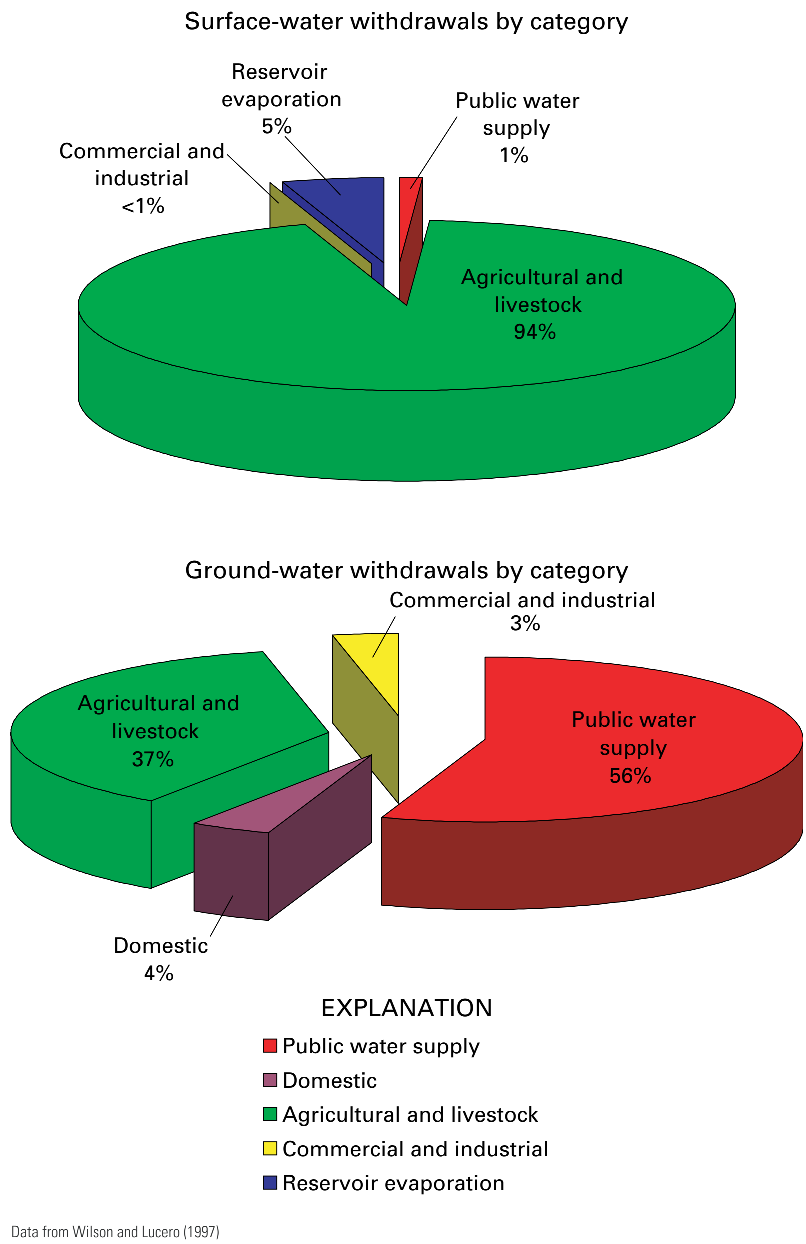


Figure 4.10.*—Water withdrawal estimates by category for surface and ground water during 1995 for counties in the Middle Rio Grande Basin. See table 4.2 for the data by county.*

One of the most important data gaps in our understanding of the water resources in the Middle Rio Grande Basin is an exact accounting of ground-water withdrawals. The NMOSE requires a permit for the construction of all water wells and, in many cases, each well must be metered and the volume of water produced must be reported. However, production data that are reported are often incomplete or production totals are combined for a number of wells. Consequently, the locations and amounts of much of the ground-water withdrawal in the basin are poorly constrained estimates.

The NMOSE permits as much as 3 acre-feet per year to be withdrawn from single household domestic or stock wells, though pumpage does not have to be reported for either these wells or wells on pueblo lands. Consequently, no production information is available for a large number of wells in the basin. In addition, only about 60 to 70 percent of permits issued for these types of wells result in a completed well (Larry Webb, City of Rio Rancho, oral commun., 2000). Thus, the number of domestic-supply and stock wells and the amount of ground water pumped from them in the Middle Rio Grande Basin are unknown.

Wilson and Lucero (1997) estimated the volume of water pumped from domestic-supply wells by county (table 4.2) by multiplying the population not served by municipal or private water systems in an area by an average per capita use of 85 gallons per day (0.095 acre-foot per day). In addition, communities such as Bosque Farms encourage the construction of domestic-supply wells by stipulating that municipally supplied water cannot be used for outside watering. The large number of unmetered domestic-supply wells in communities served by municipal water probably leads to underestimation of per capita water use in those communities. Wilson and Lucero (1997) used a similar process for estimating ground-water pumping for livestock uses, though in table 4.2, it is grouped with irrigated agriculture.

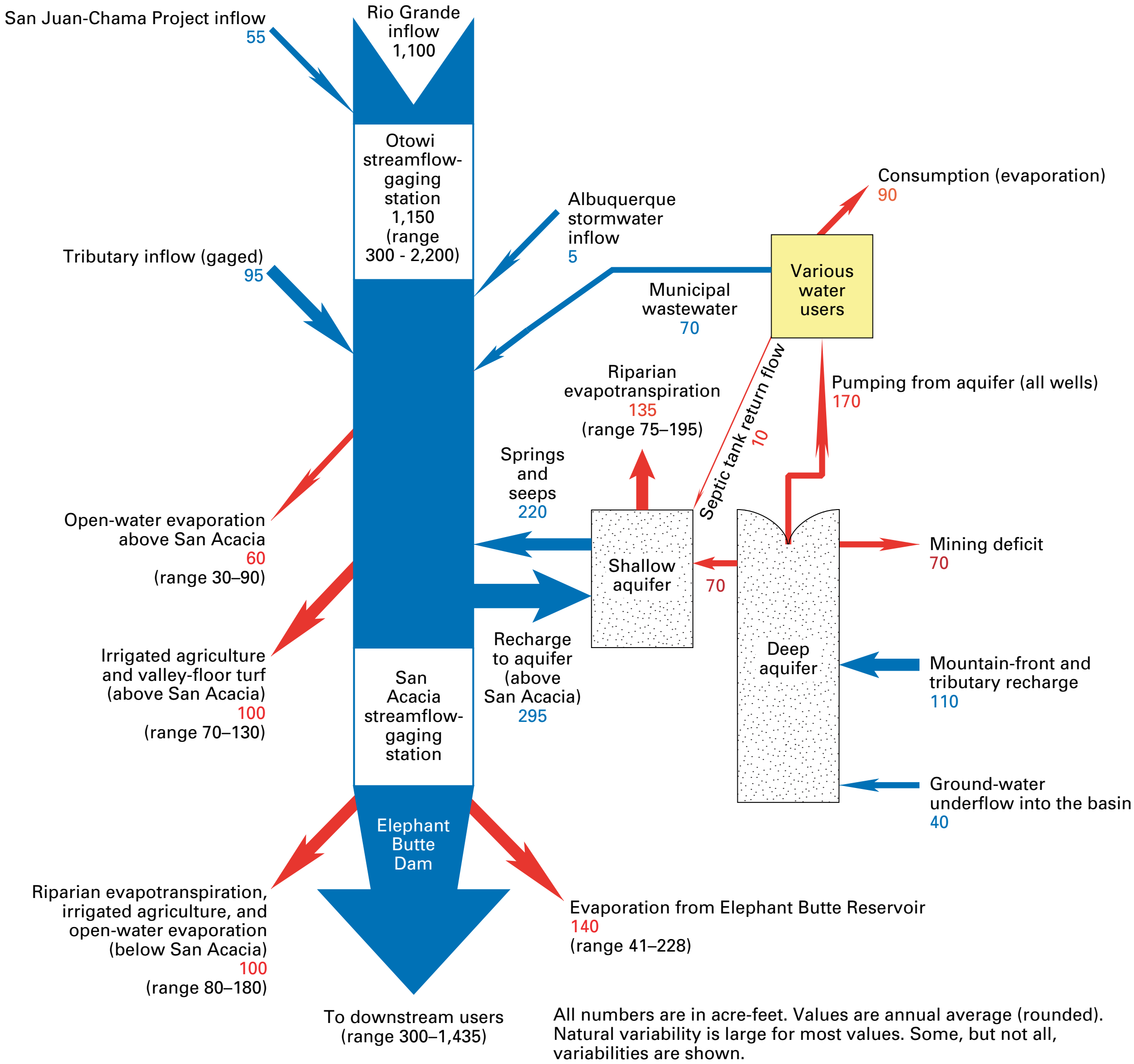
Water budgets

A water budget is essentially an accounting of water and its movement in a hydrologic system. It can be as simple as a few numbers representing water added to and subtracted from the system or as complex as a numerical simulation of the hydrologic system. This system can range in scale from global to site specific and may include only ground water, only surface water, or both. A water budget is a useful tool for helping water-resource scientists and managers conceptualize the hydrologic system. Because some of the inflows and outflows from the system cannot be measured directly, however, they must be estimated. Thus, the resulting water budget is only an approximation of the physical system, and the measured inflow and outflow totals may not balance exactly.

Several water budgets have been developed for the Middle Rio Grande Basin with varying ranges of complexity and with different areas of emphasis. Water budgets by Thorn, McAda, and Kernodle (1993), Gould (1995), and the Action Committee of the Middle Rio Grande Water Assembly (1999) are quite comprehensive because they address the surface- and ground-water components of the hydrologic system. The essential values for inflows, outflows, and indirect parameters of the hydrologic system are the same for these three budgets, though the latter

The USGS streamflow-gaging station on the Rio Grande at San Felipe. Such gaging stations provide critical streamflow data for water budgets and water management.

two reports used a slightly different areal extent of the Middle Rio Grande Basin. A report by S.S. Papadopulos and Associates, Inc. (2000) attributes differences among the budgets to differing timeframes and to whether the ground- or surface-water system was emphasized. A new comprehensive water budget was not done as part of the USGS Middle Rio Grande Basin Study because of the relative agreement among these water budgets. The water budget for the Rio Grande between the Otowi streamflow-gaging station and Elephant Butte Dam (fig 3.1), as developed by the Action Committee of the Middle Rio Grande Water Assembly (1999), is shown in figure 4.11.



Water delivery calculated from this water-budget analysis: 850
Average water deliveries from Rio Grande Compact records (1972–97): 729
Average water deliveries mandated by the Rio Grande Compact: 786
Average Elephant Butte effective supply (delivery plus change in storage): 799

Modified from the Action Committee of the Middle Rio Grande Water Assembly (1999)

Figure 4.11.—*Middle Rio Grande water budget for the reach from the Otowi stream-gaging station to Elephant Butte Dam as prepared by the Action Committee of the Middle Rio Grande Water Assembly (1999). Annual values are averages for 1972–97.*

The ground-water-flow model of McAda and Barroll (2002) produced the latest ground-water-specific water budget of the Middle Rio Grande Basin. Previous versions of ground-water-specific water budgets were presented by Kernodle and Scott (1986); Kernodle, Miller, and Scott (1987); and Kernodle, McAda, and Thorn (1995).

Major legal and institutional controls on water in the basin

New Mexico water law forms the basis for water-resource management in the Middle Rio Grande Basin. Based on Spanish water law (as developed in the generally arid climate of Spain), its main feature is the ownership of unappropriated surface and ground water by the public (to be administered by the State). Also called the doctrine of prior appropriation, the first person to put the water to beneficial use has the appropriation right to that water before the users of subsequent claims, sometimes summarized as "first in time, first in right." Water rights are permitted by the State on the basis of "beneficial use," including irrigation, livestock, municipal, domestic, and industrial uses. Rights are issued for "consumptive" use, though they sometimes take into account water returned to the stream for use by others. Rights are also issued by date of their permit application, with older (or senior) rights receiving priority. For rights claimed prior to enactment of the New Mexico Water Code in 1907 (or the declaration of a ground-water basin), the priority date is when the water was first put to beneficial use; these rights are called "vested." Water users with pre-1907 rights are not required to have a water-use permit unless changes are made in use or withdrawal. Water-use permits issued later cannot impair older rights; thus, during times of low flow, there may be no water remaining for the more junior users after holders of the oldest rights receive their water. Water rights cannot be detrimental to the public welfare and cannot be wasteful of water. If a water right is not put to beneficial use for 4 years (with some exceptions), after notice and an additional year, it expires and reverts to the public, though water rights may be transferred as long as other claims are not affected. Nearly all uses are considered beneficial, regardless of the economic value produced by the use (with the exception of willful waste). Currently (2002), New Mexico law does not recognize water remaining in a stream for the preservation of plants and animals as a beneficial use (Harris, 1984; Niemi and McGuckin, 1997).

In 1927 and 1931, the New Mexico Legislature included ground water in certain State Engineer-demarcated "declared basins" to be under prior appropriation regulations as well, thus subjecting it to similar laws as surface water. In 1956, the NMOSE declared the Rio Grande Underground Water Basin, thus formally bringing the development of ground water in the basin under the jurisdiction of the State. An important change in the laws affecting ground water was made in the 1999 New Mexico legislative session when the Ground Water Storage and Recovery Act was passed to allow local governments to store surface water underground by artificial recharge and to later withdraw that water for beneficial use.

The sovereignty of the pueblos in New Mexico differs from that of other Indian tribes in the United States, largely because the Spanish and Mexican governments recognized their sovereignty prior to New Mexico's

The Middle Rio Grande Conservancy District diversion dam on the Rio Grande at Isleta Pueblo. This structure diverts water from the Rio Grande for irrigation between Isleta and San Acacia.

incorporation into the United States. Pueblo water rights are not subject to New Mexico water law, and some obviously predate 1907. Because of these and other issues, the extent of pueblo water rights is currently (2002) unknown, though the collective recognized rights of the pueblos are 18,579 acre-feet of consumptive use (Niemi and McGuckin, 1997). (For the purpose of comparison, tables 4.1 and 4.2, in addition to figure 4.11, may be used to gain an idea of the significance of the water volumes discussed in this section.)

Kellner jetties in the bosque near Paseo del Norte. More than 100,000 Kellner jetties have been installed upstream from Elephant Butte Reservoir for bank stabilization (Bullard and Wells, 1992).

In 1925, after lobbying by the local community, the Middle Rio Grande Conservancy District (MRGCD) was formed as a political subdivision of the State in response to the reduction of productive farmland (mainly due to waterlogging) and an increase in flooding in the Middle Rio Grande Basin. The MRGCD, in cooperation with the Bureau of Reclamation and U.S. Army Corps of Engineers, has constructed flood and irrigation structures along the river and is responsible for delivering Rio Grande water to irrigators in the area between Cochiti Dam and San Marcial, about 43 miles downstream from San Acacia. The MRGCD delivers most of the surface water for consumptive use in the Middle Rio Grande Basin by delivering irrigation water to Cochiti, Santo Domingo, San Felipe, Santa Ana, Sandia, and Isleta Pueblos as well as many other irrigators with vested or senior water rights. The MRGCD claims water rights to irrigate 123,267 acres with 2.1 acre-feet of water per year, for a total consumptive use of 258,861 acre-feet per year (Bullard and Wells, 1992; Niemi and McGuckin, 1997).

Though many communities, subdivisions, and individuals withdraw water from the Santa Fe Group aquifer system, the largest user of ground water in the Middle Rio Grande Basin is the City of Albuquerque. Consequently, its water-management strategy is of the most importance. Since the 1960's, Albuquerque's water plan has consisted of meeting water demand solely by pumping ground water. The scientific understanding of the hydrogeology of the Middle Rio Grande Basin in the 1960's suggested that seepage from the Rio Grande replenished the water in the aquifer withdrawn by pumping. To this end, Albuquerque began acquiring and retiring surface-water rights to offset the perceived depletion of the river caused by ground-water withdrawals. A substantial portion of this water was obtained with the purchase of 42,700 acre-feet annually of San Juan-Chama Project water. The revised understanding of the hydrogeology of the basin, including the connection between the Rio Grande and Santa Fe Group aquifer system, spurred Albuquerque to revise its water-use strategy: in addition to the direct use of the San Juan-Chama Project water, this revised plan calls for significant conservation and water reuse/recycling (City of Albuquerque Public Works Department, 1997b).

Rio Grande Compact

Perhaps the most important single document governing flow in the Rio Grande is the Rio Grande Compact—an agreement between Colorado, New Mexico, Texas, and Mexico that attempts to allocate the water in the Rio Grande upstream from Fort Quitman, Texas, in a fair and impartial manner. Though Congress gave permission to negotiate the Compact in 1923, the three States and Congress did not approve it until 1939. The

Compact is overseen by a board of commissioners with representatives from the three States and is chaired by a nonvoting Federal representative appointed by the President. The main feature of the Compact is explicit water-delivery requirements by the upstream State to the downstream State and Mexico. Since the Compact went into effect in 1939, there have been a number of years in which Colorado and New Mexico have been unable to meet their downstream obligations and have consequently been in debt (Bullard and Wells, 1992).

San Juan-Chama Transmountain Diversion Project

Though the San Juan-Chama Transmountain Diversion Project is outside the Middle Rio Grande Basin, it contributes to the amount of water that flows through the basin (fig. 4.12). In 1971, the San Juan-Chama Project was completed to move water from the Colorado River Basin over the Continental Divide into the Rio Grande Basin. On the Rio Blanco in Colorado, the Blanco Diversion Dam and the Blanco Tunnel convey water to the Oso Tunnel. On the Little Navajo River, the Little Oso Diversion Dam diverts water into the Oso Tunnel. On the Navajo River, the Oso Diversion Dam diverts water into the Azotea Tunnel, where it is joined with water from the Oso Tunnel. The Azotea Tunnel then moves the water into the Rio Chama Basin in New Mexico. Once in the Rio Chama Basin, San Juan-Chama Project water is stored in Heron and El Vado Reservoirs (Bureau of Reclamation, 2001d). The San Juan-Chama Project is authorized to divert a maximum of 270,000 acre-feet in any year, limited to a total of 1.35 million acre-feet in any 10-year period. The governmental agencies that have contracted with the U.S. Department of the Interior for San Juan-Chama Project water include the U.S. Department of Energy, Albuquerque, MRGCD, Santa Fe Metropolitan Water Board, Española, Taos, Twining, Pojoaque Valley Irrigation District, Los Lunas, and Bernalillo. The Bureau of Reclamation controls the remainder of the water, some of which is used to offset evaporation losses from the permanent pool at Cochiti Lake. Though San Juan-Chama Project water is generally not subject to regulation under the Rio Grande Compact, its release is controlled by the Compact under certain conditions (Bullard and Wells, 1992).

Endangered species

The declaration by the U.S. Fish and Wildlife Service of the Rio Grande silvery minnow (*Hybognathus amarus*) as an endangered species in 1994 and the southwestern willow flycatcher (*Empidonax traillii extemus*) as endangered in 1995 have introduced new constraints on the management of water resources in the Middle Rio Grande Basin. For the Rio Grande silvery minnow, critical habitat has been proposed for the river reach immediately downstream from Cochiti Dam to near San Marcial, about 43 miles downstream from San Acacia, though 95 percent of the

Rio Grande silvery minnow. (Courtesy of U.S. Fish and Wildlife Service.)

Southwestern willow flycatcher. (Courtesy of Suzanne Langridge, USGS.)

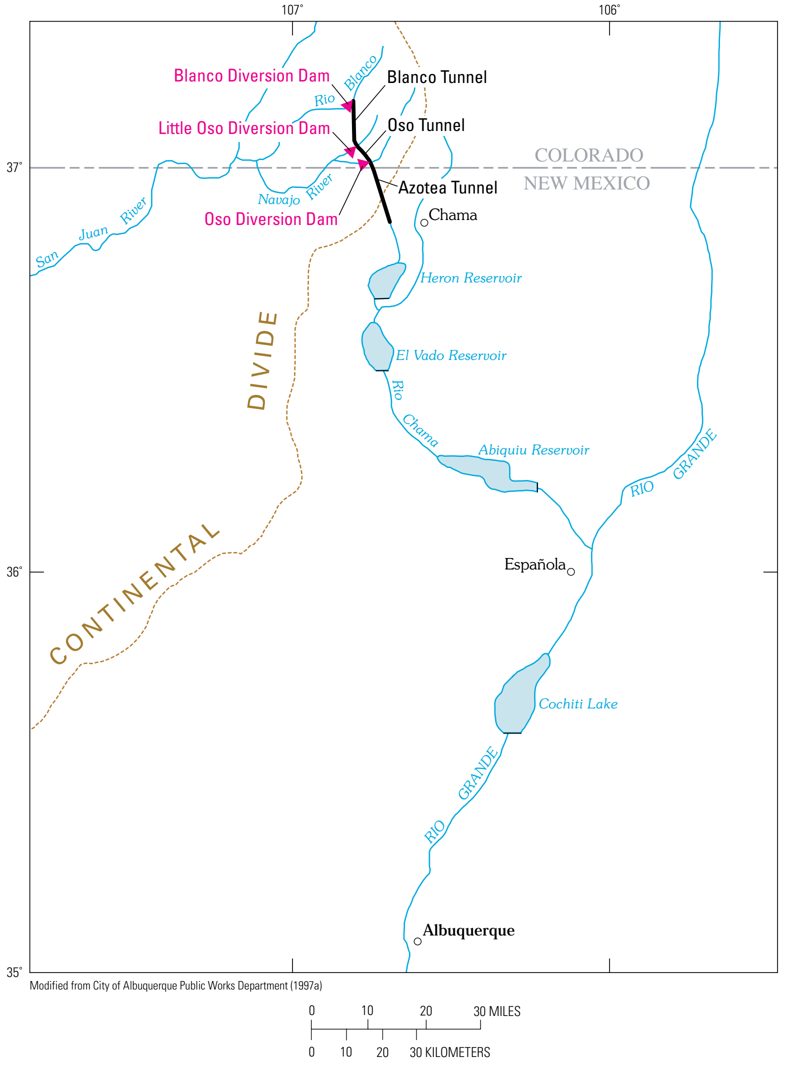


Figure 4.12.—*Diversion dams and tunnels of the San Juan-Chama Transmountain Diversion Project.*

extant population is concentrated downstream from the San Acacia diversion dam (Soussan, 2000). Among the actions proposed for its preservation and recovery are maintenance of minimum streamflows through certain reaches of the river and operation of reservoirs on the Rio Grande to more closely mimic natural streamflow conditions (U.S. Fish and Wildlife Service, 1999).

The population of the southwestern willow flycatcher has declined primarily because of the loss of native riparian vegetation, though in Southwestern States other than New Mexico, the flycatchers have been found to nest in areas composed primarily of tamarisk. Parasitism by the brown-headed cowbird (*Molothrus ater*) and predation have also contributed to the population decline (U.S. Fish and Wildlife Service, 2001a). The U.S. Fish and Wildlife Service released a draft recovery plan in June 2001 (U.S. Fish and Wildlife Service, 2001b). The recovery plan prioritizes 38 implementation tasks including water acquisition, research, water-use efficiency gains, and additional regulations.

Water-rights adjudication is the process that "determines the extent and ownership of each water right in a specific geographical area, usually a river-drainage or ground-water basin" (New Mexico Office of the State Engineer, 2001b). There are two phases to the adjudication process in New Mexico: a technical phase in which a hydrographic survey maps and reports water rights in the adjudication area, and a legal phase in which the court system determines the amount, priority, and use of water to which each right holder is entitled. Because adjudication is complicated, the process can take many years; for example, the Upper Pecos stream system adjudication was begun in 1956 and has yet to be completed (New Mexico Office of the State Engineer, 2001a). Currently (2002), only 3 of the 33 declared ground-water basins in New Mexico have been adjudicated (New Mexico Office of the State Engineer, 2001a).

Water appropriation

Even though water rights in the Middle Rio Grande Basin are divided into senior and junior classes, they have not been adjudicated. Surface flows of the Rio Grande are considered fully appropriated by the NMOSE, and an equivalent surface-water right must be obtained to offset any ground-water withdrawals that deplete the river. Because the Rio Grande is fully appropriated and additional supply cannot be created for new uses, competing water demands in the Middle Rio Grande Basin exceed the available supply.

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.

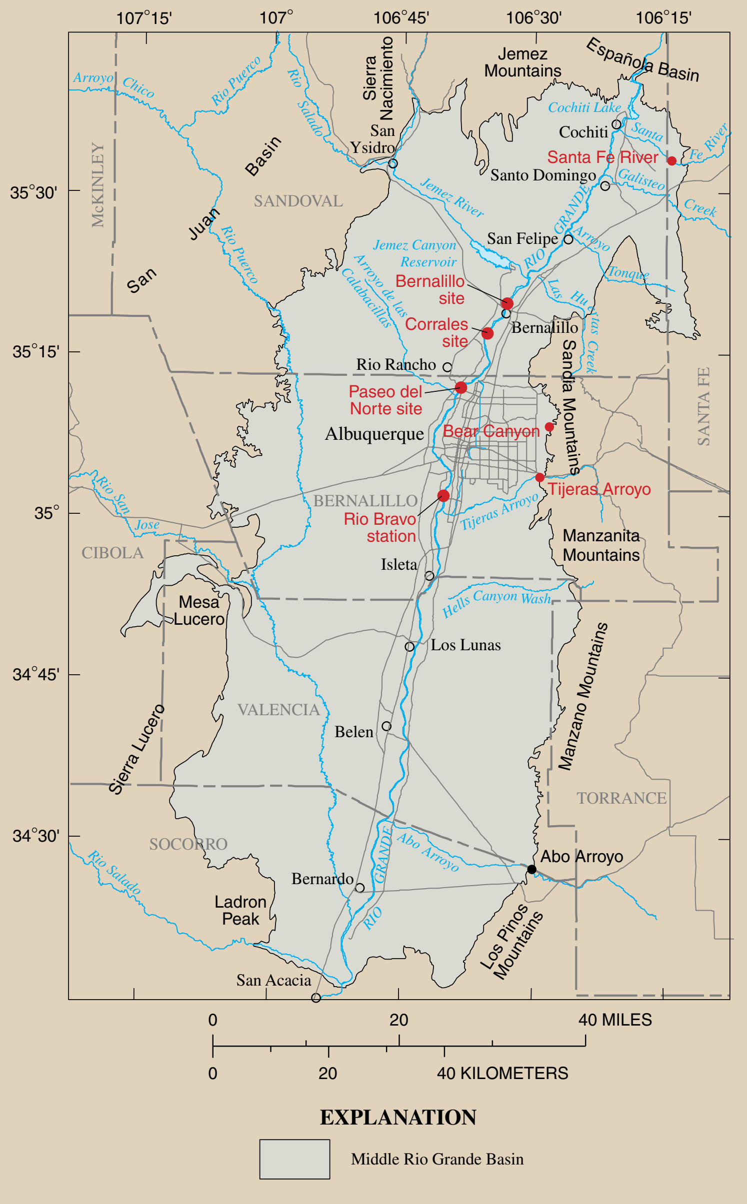


Figure G.1.*—Locations of study sites for mountain-front recharge and water temperature in the Middle Rio Grande Basin.*

[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.

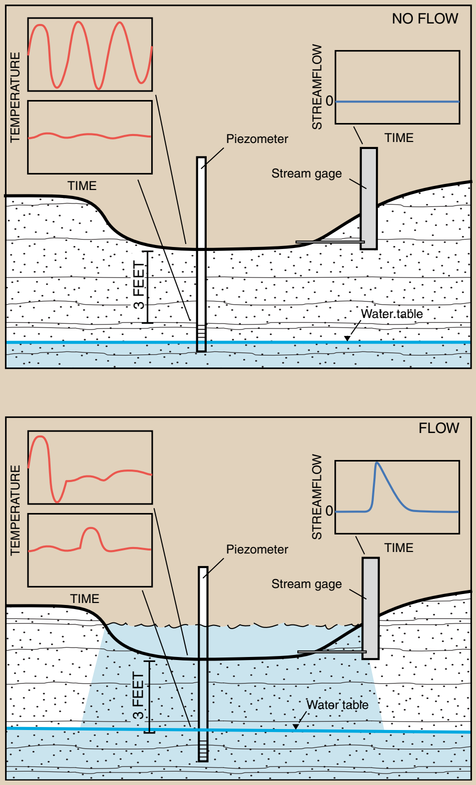
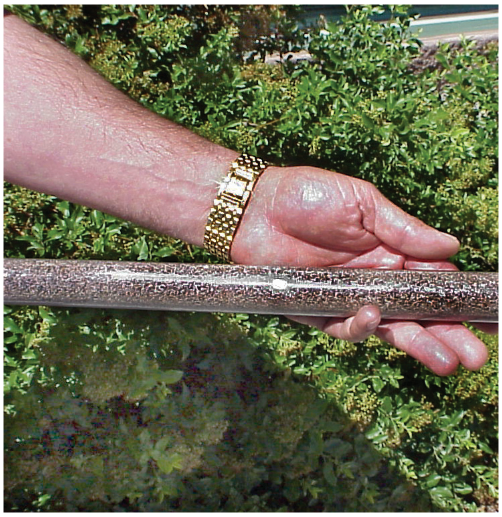


Figure G.2.*—Temperature compared to time at two depths in an ephemeral streambed during periods of no flow and flow. The top diagram shows a dry streambed with a streamflow-gaging station (right) recording no flow over approximately 3 days. On the left, the temperature over the same period of time is 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.

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.



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

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).

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.

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

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

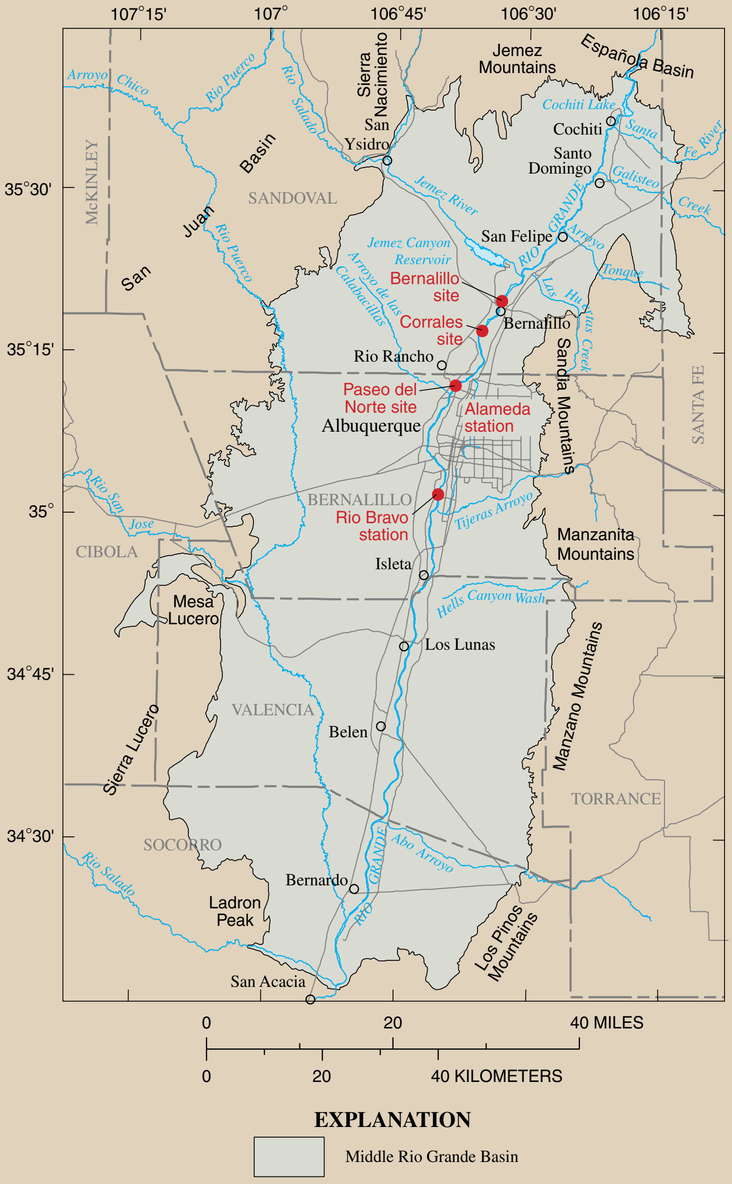


***Figure H.1.**—Locations of study sites on the Rio Grande for water temperature and flood pulses.*

[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.

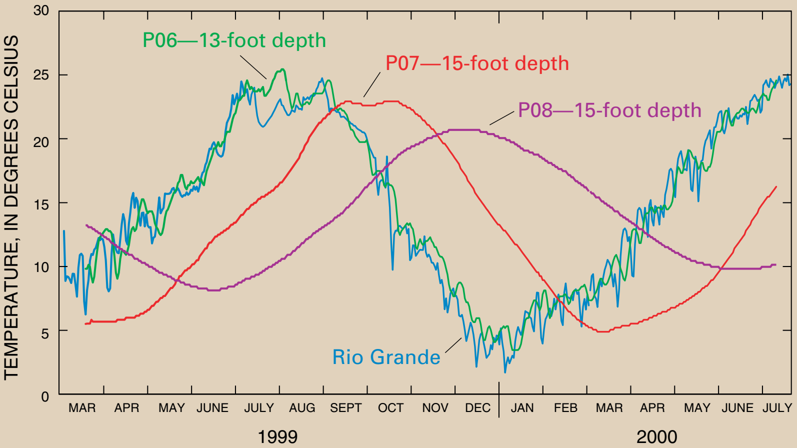


Figure H.2.*—Thermographs from Paseo del Norte section showing Rio Grande temperature and ground-water temperatures measured in wells P06, P07, and P08. P06 is on the east bank of the Rio Grande, P07 is 900 feet east, and P08 is 1,845 feet from the river and adjacent to the Albuquerque Riverside Drain. 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 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.

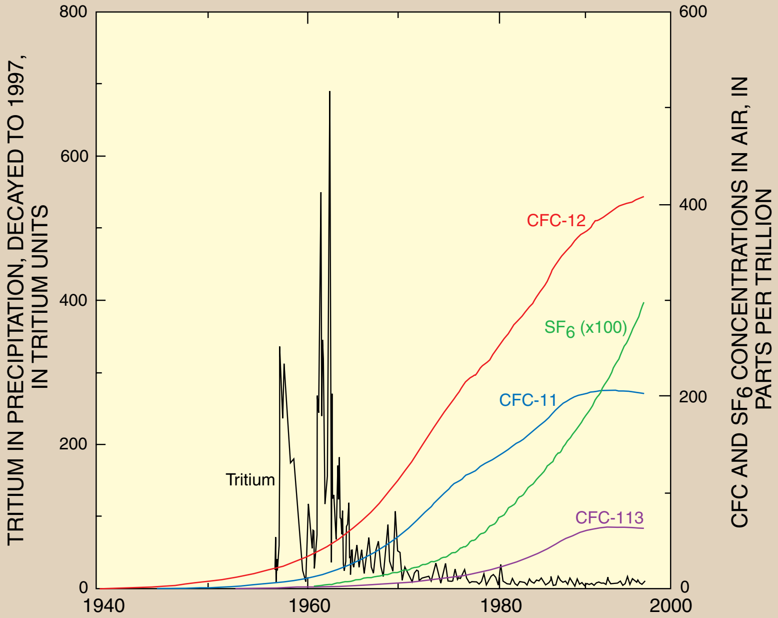


Figure I.1.—*Concentrations of tritium (^3H) in precipitation, chlorofluorocarbons (CFC-11, CFC-12, and CFC-113) in air, and sulfur hexafluoride (SF_6) in air over North America, 1940–97. The tritium concentrations in precipitation were decayed to 1997 for comparison with tritium concentrations (expressed 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.*

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

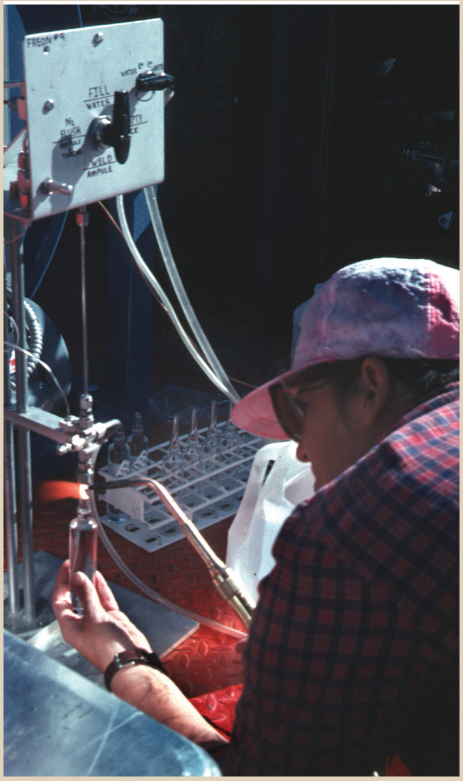
[1]U.S. Geological Survey, Reston, Virginia.

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.

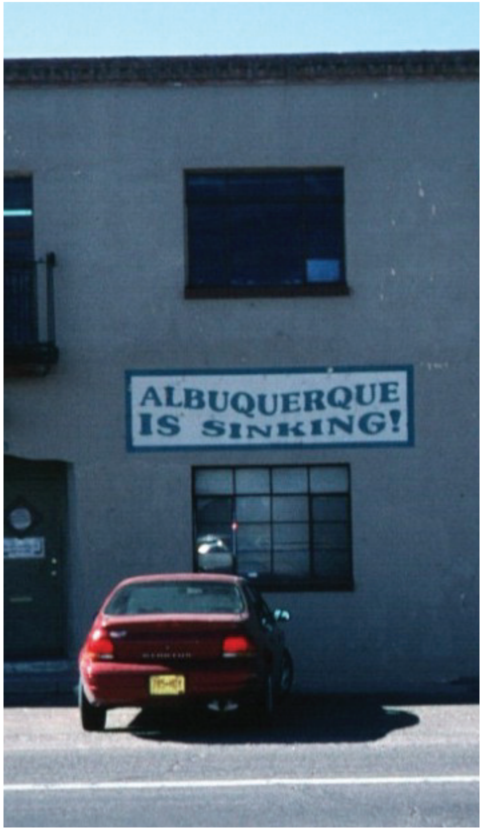
Deterioration of water quality

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).

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

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.

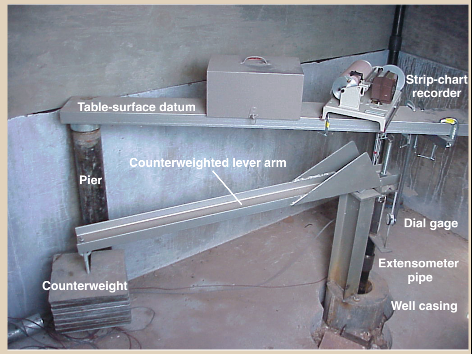


Figure J.1.*—Surface instrumentation of the Montaño extensometer. The top of the well casing is on the right; a counter-weighted lever arm balances 80 percent of the weight of the extensometer pipe. A table suspended between piers anchored 15–20 feet below land surface provides the surface datum; a strip-chart 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.*

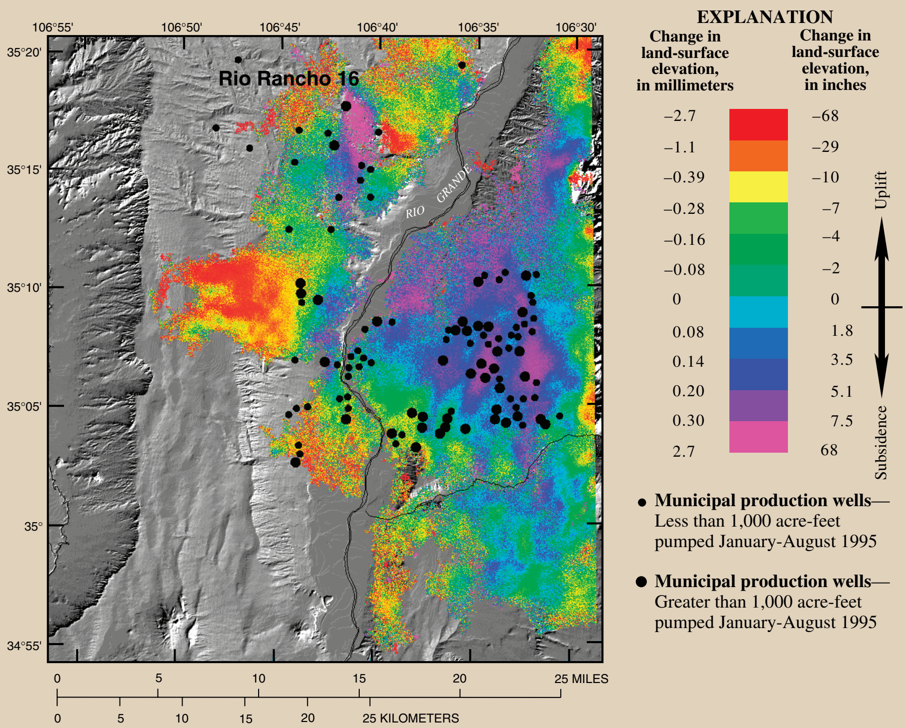


Figure J.2.*—Interferometric Synthetic Aperture Radar (InSAR) image of the Albuquerque area, July 2, 1993–September 3, 1995. Maximum subsidence of 2 inches is shown in the Rio Rancho area by purple and blue. The linear boundaries of subsidence features are parallel to and in the approximate locations 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.*

Chapter 6: Chemical characteristics of water in the aquifer system

Water quality affects the daily lives of everyone and thus is one of the most important topics addressed in water-supply studies. Concerns about the quality and safety of the Nation's water have led to the growth of a large industry devoted to filtering, treating, or bottling water for domestic use and human consumption. Not only is everyone aware of the effects of water quality on taste and plumbing fixtures, water-quality and water-contamination stories are now commonplace in the news media.

Because the Middle Rio Grande Basin Study was primarily concerned with understanding the physical aspects of the ground-water system, water-quality data for the study were collected for this purpose. However, ground- and surface-water sampling for the study has allowed the most complete and areally extensive view of water quality in the Middle Rio Grande Basin to date. The use of water quality for ground-water age dating and the definition of flow paths and traveltimes has made a large contribution to the understanding of the ground-water-flow system (see Boxes *I* and *K*). In addition, water-quality data for the Middle Rio Grande Basin Study adds to our knowledge of whether water in a particular area of the aquifer is suitable for a particular use (including human consumption) and whether human activities may be adversely affecting ground-water quality.

General quality of ground water and what it reveals about the ground-water system

In the same way that the geology of the Santa Fe Group aquifer system varies areally and with depth, so do the chemical properties of ground water in the aquifer. This variation is due to many factors including where water enters the aquifer, the distance it travels and the rock types it contacts within the aquifer, and human activity. Ground-water samples collected from 275 wells and analyzed by Plummer and others (2001) showed significant variation in many water-quality constituents and properties. Concentrations of some chemical constituents or properties in water varied over several factors of 10. This wide variation makes it difficult to generalize water quality in the basin as a whole.

A useful approach to characterizing ground-water quality in the Middle Rio Grande Basin is to divide the basin into zones of different water-quality (or hydrochemical) characteristics (Anderholm, 1988; Logan, 1990; Plummer and others, 2001). Plummer and others (2001) defined 13 hydrochemical zones by using analyses of ground-water samples from 275 different wells and springs (fig. 6.1), resulting in the most areally comprehensive water-quality study to date in the Middle Rio

A small truck-mounted soil-probing machine used in the Middle Rio Grande Basin to sample shallow ground water. The size and portability of this unit allow for the collection of more data with less disturbance.

K

How ground-water chemistry helps us understand the aquifer

L. Niel Plummer,[1] Laura M. Bexfield,[2] and Scott K. Anderholm[2]

Although water is commonly thought of as simply H_2O, literally thousands of other substances are dissolved in water in the environment. Most of these substances occur naturally, and many are present in water in only small quantities. The term "water chemistry" (or water quality) refers to the quantities of these various substances (commonly called solutes) that are present in a particular water sample, making up its chemical composition. In the Santa Fe Group aquifer system of the Middle Rio Grande Basin, patterns in the water chemistry of ground water have helped refine important concepts about the ground-water-flow system, including sources of water, directions of flow, and traveltimes. The water chemistry of a ground-water sample can be thought of as a chemical signature that reflects the sum total of all physical processes and chemical reactions that affected the water from the time it began as dilute rainfall, infiltrated the soil above the water table, passed into the aquifer (ground-water recharge), and traveled, sometimes over great distances and depth, to the point of sample collection or discharge from the aquifer.

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

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

Water acquires very small quantities of some solutes from dust and gases when it falls through the atmosphere as precipitation, but water typically acquires the majority of its solutes once it reaches the land surface. Solutes that were already present in the water increase in concentration because of the processes of evaporation and transpiration—processes that, for the most part, remove water while leaving the solutes behind. In some arid environments like New Mexico, plants can withdraw more than 90 percent of the precipitation that has infiltrated into the soil zone. As water infiltrates through the soil zone, it also tends to dissolve carbon dioxide (CO_2) gas that exists in the soil in large quantities (relative to the atmosphere) because of biological activity. When CO_2 dissolves in water in the soil zone, a weak acid is formed. This acid promotes the dissolution of minerals that are present in the soil and rocks, which releases solutes to the water and causes their concentrations to increase. Because of these processes, water in the soil zone can acquire the bulk of its chemistry before it reaches the water table.

In ground water, only seven solutes make up nearly 95 percent of all water solutes (Runnells, 1993; Herczeg and Edmunds, 1999). These solutes are calcium (Ca), magnesium (Mg), sodium (Na), potassium (K), chloride (Cl), sulfate (SO_4), and bicarbonate (HCO_3). Although many sources and reactions influence the concentrations of these solutes, the predominant sources of these solutes to ground water in the Middle Rio Grande Basin (Anderholm, 1988) include (1) the dissolution of limestone (calcite, $CaCO_3$) and dolomite ($CaMg(CO_3)_2$) for Ca, Mg, and HCO_3; (2) the dissolution of gypsum ($CaSO_4 \cdot 2H_2O$) and anhydrite ($CaSO_4$) for Ca and SO_4; (3) the dissolution of halite (NaCl) for Na and Cl; and (4) ion exchange reactions on the surfaces of some clay minerals whereby sodium is released to the water in exchange for calcium or magnesium. Sodium also is derived from the dissolution of silicate minerals, such as plagioclase feldspars, which make up some of the sand and gravel that fill the Middle Rio Grande Basin. Potassium is derived from the dissolution of some silicate minerals in granitic rocks and from reactions with some clay minerals. Few reactions remove these seven solutes from ground water. However, some minerals, such as calcite $CaCO_3$, can precipitate from solution to form a solid phase.

In addition to the seven predominant solutes in water, some other solutes known as trace elements typically exist in very small quantities, as do particular isotopes of dissolved constituents (see Box *I*). Processes that affect the concentrations of trace elements and isotopes are not always well understood. However, combined with data on the predominant water-chemistry, trace-element and isotopic data for ground water can provide a powerful tool for tracking ground-water flow.

In a very broad sense, the mineralogy of aquifers can be divided into two groups—those aquifers that contain relatively reactive minerals and those with mostly unreactive minerals. In aquifers composed of reactive rocks and minerals like limestone, dolomite, gypsum, halite, and organic matter, solute concentrations (and isotopic compositions) can change significantly with distance along a ground-water flow path, reflecting extensive chemical reaction. In aquifers composed of mostly unreactive material, like sand and gravel from the chemical and mechanical breakdown of silicate rocks and minerals, solute concentrations change only slightly with distance down a flow path. In these relatively unreactive aquifers, such as the Santa Fe Group aquifer system, water tends to acquire its predominant chemical composition during the process of recharge and retains that composition as it flows through the aquifer.

Much of the ground water in the Middle Rio Grande Basin has acquired its chemical (and isotopic) composition during recharge, either as infiltration of precipitation on the basin margin, as seepage from rivers and arroyos, or as ground-water underflow from adjacent aquifer systems that border the basin. Water chemistry differs depending on the source of water, the degree to which it has been evaporated, the types of rock and mineral it has encountered, and the time it has been in contact with reactive minerals. Therefore, water in the Middle Rio Grande Basin commonly differs in the concentration of any particular solute and the concentration of that solute relative to other solutes. These distinct differences allow for the delineation of areas of the aquifer that have similar chemical "signatures." The spatial extents and configurations of these areas can provide important information about the ground-water-flow system. For example, the chemistry of an area with a particular signature can be compared with the chemistry that might be expected from water moving through a source area with a known rock type or seeping through a river with known surface-water chemistry. The likely source of the ground water can be determined from such comparisons. Boundaries between areas of dissimilar chemical signatures can represent general boundaries between waters from the different sources. The shapes of the areas can also broadly define the directions of ground-water flow. Also, the vertical extent of ground water in the aquifer having a particular chemical signature can indicate how well water is mixing vertically through the aquifer. If this vertical extent is known, the approximate volumes of ground water with different signatures can be calculated and used to estimate the relative amounts of recharge from different sources.

Ground-water sampling at the 98th Street well. Because monitoring wells typically do not contain pumps, a portable sampling pump must be lowered into the well.

Interpretations of water-chemistry data are most reliably made within a conceptual framework of the ground-water system that has been derived from several additional types of hydrologic and geologic data, such as water levels, that indicate general directions of ground-water flow (see Box *F*). In combination with the multitude of hydrologic and geologic data obtained as part of the USGS Middle Rio Grande Basin Study, water-chemistry data have improved the understanding of the aquifer through recognition of ground-water sources, delineation of flow paths, and determination of ground-water traveltimes calculated using isotopic data (see Box *I*).

Specific conductance is an indicator of how mineralized a sample of water is. It is measured in microsiemens per centimeter (µS/cm) at a specified temperature, usually 25 degrees Celsius. Pure water is a poor conductor of electricity, but minerals dissolve in water, and the resulting ions conduct electricity. In general, the larger the value of specific conductance the greater the concentration of dissolved solids in the water sample and the poorer the water quality. The specific conductance of seawater is about 50,000 µS/cm, whereas the specific conductance of distilled water is approximately 1 µS/cm (Heath, 1983; Hem, 1985).

The concentration of *dissolved oxygen* is a general indicator of how recently ground water entered the aquifer. In general, recently recharged water has a dissolved-oxygen concentration similar to surface water (which has relatively large values in comparison to most ground water), and concentration tends to decrease as ground water moves away from the point of recharge. The presence of organic material in the aquifer can cause more rapid oxygen depletion. However, in the Santa Fe Group aquifer system, some recently recharged river water has small values of dissolved oxygen because of organic material within inner-valley sediments, and some very old (greater than 10,000 years) ground water has relatively large values of dissolved oxygen. (See Hem [1985] for a general discussion of dissolved oxygen in ground water.)

Grande Basin. Because their sampling relied primarily on existing production wells, results are not applicable to deeper areas of the aquifer beneath the production zone. Boundaries between the water-quality zones may not be vertical as implied by a two-dimensional map (fig. 6.1). The reader is referred to Plummer and others (2001) for a complete description, but general characteristics of the regions shown in figure 6.1 are summarized in table 6.1.

Not only can hydrochemical zones be used to characterize ground-water quality in different parts of the Middle Rio Grande Basin, they can also be used to delineate probable sources of recharge and their relative contributions, determine ground-water flow paths within the aquifer system, and provide an estimate of the sustainability of current ground-water pumping. Probable recharge sources for each of the hydrochemical zones defined by Plummer and others (2001) are listed in table 6.1. (Zone 13 is thought to represent a convergence of flow from multiple zones in the basin and does not represent a single recharge source.) For example, zone 4 contains the oldest ground water in the basin (based on carbon-14 age; see Box *N*), and the strongly negative values of deuterium (see Box *I*) suggest that this water originated as precipitation at a higher elevation. These data, in combination with other water-quality information, led to the interpretation that zone 3 represents “recharge from the Jemez Mountains north of the basin, primarily during the last glacial period” (Plummer and others, 2001).

Because these hydrochemical zones were defined on the basis of a limited number of samples, the characteristics listed in table 6.1 are only generalizations. A well within one of the zones may contain water with substantially different chemical characteristics from those represented by the median, or typical, values for the zone.

Naturally occurring substances that limit the use of ground water

Current (2002) U.S. Environmental Protection Agency (USEPA) and State of New Mexico drinking-water standards and the significance of selected constituents are shown in table 6.2, along with the significance of each constituent for human health and (or) the esthetic properties of water. This listing is limited to constituents or properties listed in the preceding discussion of the ground-water-quality regions defined by Plummer and others (2001).

USEPA drinking-water standards are of two types: primary and secondary. *Primary standards* are the “maximum permissible level of a contaminant in water which is delivered to any user of a public water system” (U.S. Environmental Protection Agency, 2002). The standards are enforceble, in contrast to *secondary standards*, which are nonenforceble. Constituents covered by secondary standards may cause cosmetic or esthetic effects. The presence in drinking water of chemical constituents regulated by drinking-water standards does not necessarily pose a health risk. Many constituents that are essential for good health at low concentrations may pose a health risk at higher concentrations.

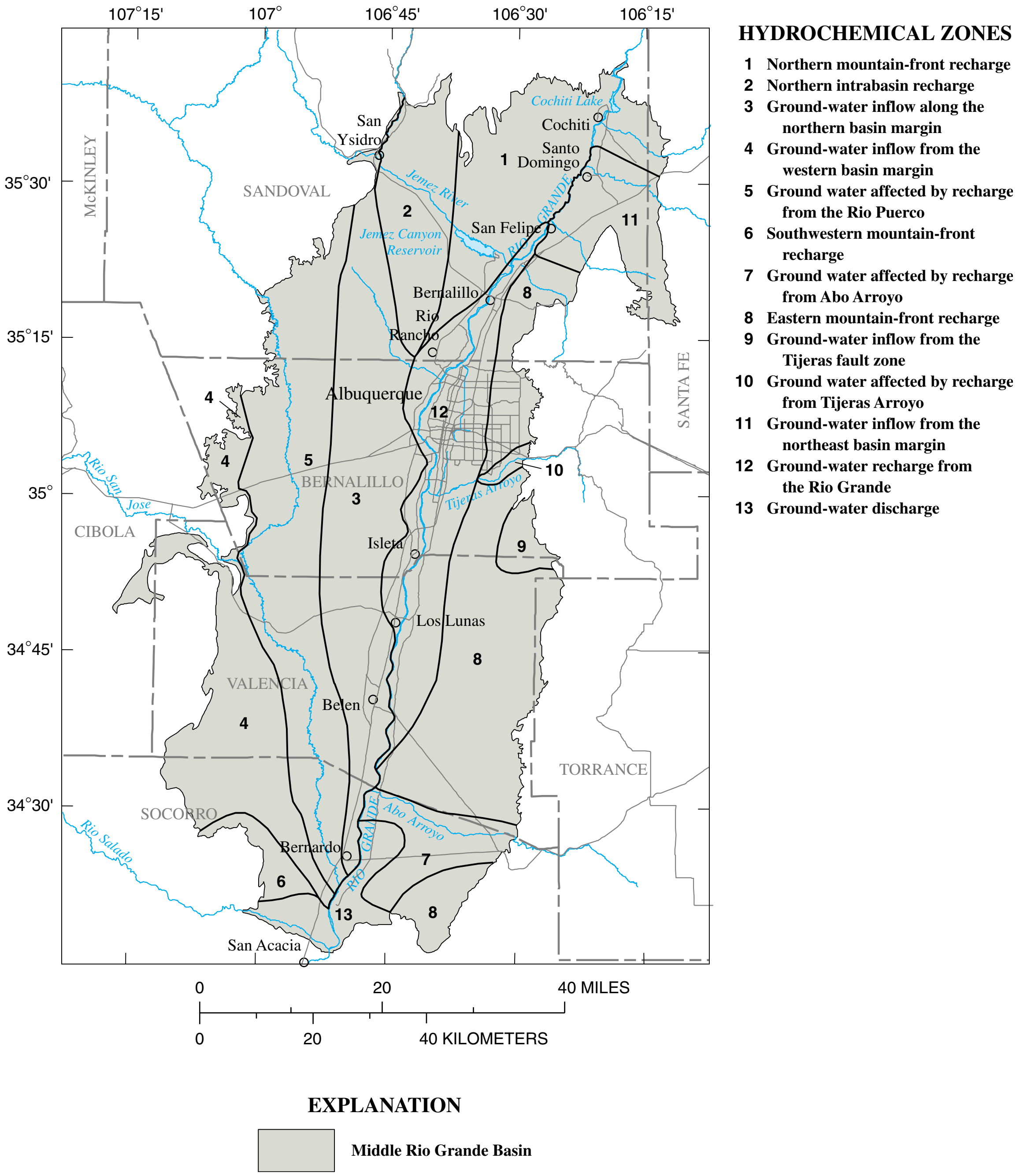


Figure 6.1.—*Hydrochemical regions of the Middle Rio Grande Basin as defined by Plummer and others (2001).*

Table 6.1.—Median values of selected parameters of the 13 hydrochemical zones delineated for the Santa Fe Group aquifer system of the Middle Rio Grande Basin

[Plummer and others (2001); years BP, years before present; µS/cm, microsiemens per centimeter at 25 degrees Celsius; mg/L, milligrams per liter]

	Hydrochemical zone and recharge source						
	1	2	3	4	5	6	7
	Northern mountain-front recharge	Northern intrabasin recharge	Ground-water inflow along the northern basin margin	Ground-water inflow from the western basin margin	Ground water affected by recharge from the Rio Puerco	Southwestern mountain-front recharge	Ground water affected by recharge from Abo Arroyo
Number of samples	16	10	44	10	12	2	5
Deuterium (parts per thousand) [1]	–79	–63	–97	–64	–63	–64	–64
Carbon-14 age (years BP)	8,800	8,800	19,500	20,400	8,100	7,700	9,400
Specific conductance (µS/cm)	380	390	590	3,300	2,400	590	920
pH (standard units)	7.5	7.8	8.3	7.6	7.5	8.0	7.4
Dissolved oxygen (mg/L)	5.1	6.8	3.1	4.9	3.0	3.7	5.6
Chloride (mg/L)	9.5	6.2	12	[2] 530	180	26	24
Sulfate (mg/L)	25	35	95	[2] 670	[2] 980	80	[2] 310
Bicarbonate (mg/L)	150	140	170	250	180	230	170
Nitrate (mg/L)	0.6	5.2	1.3	1.1	1.5	0.6	1.4
Calcium (mg/L)	39	29	10	130	170	39	91
Sodium (mg/L)	26	47	100	450	280	44	49
Potassium (mg/L)	5.4	6.2	4.1	14	12	3.2	3.4
Silica (mg/L)	47	28	28	21	26	14	22
Arsenic (mg/L)	0.0051	0.0096	[3] 0.021	0.0018	0.0011	0.0011	0.0026

	Hydrochemical zone and recharge source						
	8	9	10	11	12	13	
	Eastern mountain-front recharge	Ground-water inflow from the Tijeras fault zone	Ground water affected by recharge from Tijeras Arroyo	Ground-water inflow from the northeast basin margin	Ground-water recharge from the Rio Grande	Ground-water discharge	Average for all zones
Number of samples	47	8	6	7	105	3	275
Deuterium (parts per thousand) [1]	–81	–74	–75	–69	–95	–91	–90
Carbon-14 age (BP)	5,200	16,200	3,200	10,000	4,600	17,900	8,100
Specific conductance (µS/cm)	380	1,300	620	1,300	430	2,500	470
pH (standard units)	7.5	7.1	7.4	7.6	7.7	7.7	7.7
Dissolved oxygen (mg/L)	5.5	4.1	6.7	6.6	0.1	0.1	1.9
Chloride (mg/L)	7.7	87	29	22	16	[2] 680	16
Sulfate (mg/L)	34	150	110	[2] 400	63	[2] 290	67
Bicarbonate (mg/L)	170	290	220	170	160	160	160
Nitrate (mg/L)	0.4	1.0	3.3	1.9	0.1	0.4	0.5
Calcium (mg/L)	48	130	80	100	42	93	41
Sodium (mg/L)	22	87	29	87	29	210	44
Potassium (mg/L)	2.0	4.6	3.5	4.4	6.7	11	5.3
Silica (mg/L)	26	23	23	31	53	29	33
Arsenic (mg/L)	0.0017	0.002	0.001	0.0022	0.0055	0.008	0.005

[1]Deuterium values can be negative because they are expressed as parts per thousand differences relative to an ocean-water standard.
[2]These values exceed the U.S. Environmental Protection Agency secondary water-quality standards in table 6.2.
[3]This value exceeds the U.S. Environmental Protection Agency primary water-quality standard for arsenic in table 6.2.

Table 6.2.—Current drinking-water standards and significance of constituents commonly found in ground water in the Middle Rio Grande Basin

[USEPA, U.S. Environmental Protection Agency; mg/L, milligrams per liter; --, no standard exists or no effects known]

Constituent	USEPA drinking-water standard maximum contaminant level (mg/L)[1]		State of New Mexico drinking-water standard maximum contaminant level (mg/L)[2]	Significance
	Primary standard	Secondary standard		
Arsenic	0.01	--	0.05	Skin damage; circulatory system problems; increased cancer risk.[1]
Boron	--	--	--	--
Calcium	--	--	--	In large amounts, increases corrosiveness of water. In combination with sodium, gives water a salty taste.[3]
Chloride	--	250	--	In large amounts, increases corrosiveness of water. In combination with sodium, gives water a salty taste.[3]
Fluoride	4	2	4	Bone disease (pain and tenderness of the bones); children may get mottled teeth.[1]
Manganese	--	0.05	--	Dark brown-black stains; bitter, metallic taste.[3,4]
Nitrate (measured as nitrogen)	10	10	10	Methemoglobinemia ("Blue baby syndrome").[1]
pH (in standard units)	--	6.5–8.5	--	Values less than 4 indicate corrosive water that tends to dissolve metals and other substances that it contacts. Values greater than 8.5 indicate alkaline water that, on heating, tends to form scale in pipes and boilers.[3]
Potassium	--	--	--	In combination with sodium can cause foaming, corrosion, and scale formation in boilers.[5]
Silica	--	--	--	In combination with calcium and magnesium forms scale in pipes and boilers.[5]
Sodium	--	--	--	See chloride, potassium; in large concentrations, may affect people with cardiac difficulties, hypertension, and certain other medical conditions. In combination with calcium and magnesium may be detrimental to certain irrigated crops.[3]
Sulfate	--	250	--	Medicinal taste; laxative effect. In combination with calcium forms scale in pipes and boilers.[3,4]

[1] U.S. Environmental Protection Agency (2002).
[2] New Mexico Environment Department (1996).
[3] Heath (1983).
[4] National Water Quality Association (2002a, b).
[5] Todd (1980).

Concentrations of chemical constituents in water are typically reported as *milligrams per liter* (mg/L) or *micrograms per liter* (µg/L), which are essentially equal to parts per million and parts per billion, respectively. An example of 1 part per million is 1 ounce of a substance dissolved in 7,500 gallons of water (Heath, 1983). "Four drops of ink in a 55-gallon barrel of water would produce an "ink concentration" of 1 part per million" (Kimball, 2002). Similarly, 1 part per billion is 1 ounce of a substance dissolved in 7.5 million gallons of water, or one drop of ink in one of the largest tanker trucks used to haul gasoline (Kimball, 2002).

An examination of the median values of selected water-quality parameters by the hydrochemical zones in table 6.1 shows that three constituents exceeded at least one of the three standards listed in table 6.2 (USEPA primary or secondary standard or New Mexico standard). The median arsenic concentration of 0.021 mg/L in zone 3 exceeded the USEPA primary standard of 0.010 mg/L. The median concentrations of chloride in zones 4 and 13, 530 and 680 mg/L, respectively, exceeded the USEPA secondary standard of 250 mg/L. Concentrations of sulfate in zone 4 (670 mg/L), zone 5 (980 mg/L), zone 7 (310 mg/L), zone 11 (400 mg/L), and zone 13 (290 mg/L) exceeded the USEPA secondary standard of 250 mg/L.

The results reported in Plummer and others (2001) were a summary of a comprehensive suite of chemical analyses, not all of which were reported in the paper. In addition, the median concentration of manganese was 0.05 mg/L in zone 4, which is equivalent to the USEPA secondary standard (L.M. Bexfield, U.S. Geological Survey, written commun., 2001).

An additional two points should be made about the chemical analyses of ground water and the applicability of Federal and State standards. First, water samples analyzed by Plummer and others (2001) were untreated samples obtained directly from wells. Because such water is not being delivered directly to the consumers of a municipal supply, the standards do not strictly apply. However, the comparison is provided to give an indication of untreated source water. Second, even though the median values presented in table 6.1 may not exceed a water-quality standard, individual samples from the zone may. Conversely, even though the median values in table 6.1 may exceed a water-quality standard, individual samples from the zone may not.

The naturally occurring water-quality constituent of most concern in ground water of the Middle Rio Grande Basin has been arsenic. In 1991, seven City of Albuquerque well fields had at least one well producing water with more than 0.030 mg/L of arsenic (CH2M Hill, 1991). Generally, by blending water from different wells in each well field, water of an acceptable concentration was delivered and the water supply was not affected; however, arsenic concentrations in the Don well field (fig. *B.1A*) were too large for such dilution, causing the entire field to be taken out of production (CH2M Hill, 1991). Concerns also have been raised about arsenic concentrations in the discharge of treated wastewater to the Rio Grande. Because essentially all of this wastewater originates as ground water and because the wastewater-treatment process does not remove arsenic, water with arsenic concentrations larger than the naturally occurring concentrations in the river could be conveyed to the Rio Grande. A study by Wilcox (1997) found that mean dissolved-arsenic concentrations in Rio Grande water generally increased downstream from 0.002 mg/L at San Felipe Pueblo to 0.004 mg/L at Los Lunas. Mean dissolved-arsenic concentrations in treated wastewater from the Bernalillo, Rio Rancho, and Albuquerque wastewater-treatment plants ranged from 0.008 mg/L to 0.016 mg/L. Mean dissolved-arsenic concentration in the Jemez River below Jemez Reservoir was 0.018 mg/L.

In October 2001, the USEPA issued a final arsenic primary standard of 0.010 mg/L for drinking water and extended compliance beyond community water systems to all systems that serve at least 25 of the same people more than 6 months per year (U.S. Environmental Protection Agency, 2001a). Annual compliance costs for New Mexico are estimated at \$49–\$60 million to meet the primary standard of 0.010 mg/L of arsenic (Bitner, Thomson, and Chwirka, 2001).

Contaminants of human origin and ground water

Human contamination of ground water in the Middle Rio Grande Basin, though severe in some localities, is not widespread and does not affect a large quantity of water in the aquifer. Most of the ground water in the basin has a "low susceptibility to contamination because the depth to water is greater than 100 feet and there is virtually no natural mechanism for [direct] recharge to the ground-water system" (Anderholm, 1987). An exception is the basin- and valley-fill deposits of the inner valley of the Rio Grande, which have a "relatively high susceptibility to contamination because the depth to water is generally less than 30 feet and there are many types of recharge to the ground-water system" (Anderholm, 1987). Among the facilities or activities that are potential sources of ground-water contamination in the Middle Rio Grande Basin are military and industrial operations, leaking underground-storage tanks, landfills, agricultural activities, and domestic septic systems.

The USEPA currently (2002) lists five Superfund sites in the Middle Rio Grande Basin (U.S. Environmental Protection Agency, 2001b). One of these sites was removed from the priority list after contaminated soil was removed from the site, and another was removed from the priority list after site investigation. The remaining three sites have ground water contaminated with organic chemicals and are currently undergoing remediation.

The New Mexico Environment Department (NMED) currently (2002) lists about 700 former and present leaking underground-storage-tank sites in the Middle Rio Grande Basin (New Mexico Environment Department, 2001), though not all these leaks resulted in ground-water contamination. Most of these tanks stored some form of fuel.

Currently (2002), three RCRA (**R**esource **C**onservation and **R**ecovery **A**ct of 1976) sites are in the Middle Rio Grande Basin (U.S. Environmental Protection Agency, 1999). Two of these sites, Kirtland Air Force Base and Sandia National Laboratories, are composed of a number of individual sites on large installations. These individual sites represent activities such as landfilling, fire training, and explosives testing. Potential ground-water contaminants are organic chemicals, radioactive elements, and metals. The third RCRA site has ground water contaminated with organic chemicals from electronics manufacturing. All three sites are undergoing remediation.

A study by Anderholm (1997), intended to examine the effects of land use on water quality at the water table, sampled and analyzed ground water from 24 monitoring wells having total depths within 20 feet of the water table in the basin- and valley-fill deposits in the Albuquerque area. This study found that "human activities have affected shallow ground-water quality." Organic chemicals (pesticides, solvents, metal degreasers, and a gasoline additive) were detected in water from 11 of the 24 wells sampled, though no concentrations were equal to or greater than applicable drinking-water standards (not all chemicals had standards) (Levings and others, 1998). Other water-quality constituents indicated that "infiltration from septic-system effluent . . . has affected the shallow ground-water composition" in parts of the inner valley in the Albuquerque area (Anderholm, 1997). A later study by Bexfield and Anderholm (1997)

Basalt flows exposed in Boca Negra Canyon. Arsenic in ground water is commonly associated with volcanic rocks in the subsurface.

One of the typical steps in producing a ground-water-flow model is model *calibration*. Inevitably, some of the values used in creating the model are estimated. Calibration is the process of changing these model-input values to reduce model error by varying the estimated values over a range of probable values until there is an acceptable match between simulated and observed data (Leake, 1997; Spitz and Moreno, 1996).

examined the chemical quality of ground water being used for domestic supply in an area susceptible to contamination. Water from 14 domestic supply wells was sampled and analyzed. These wells had total depths ranging from 45 to 350 feet below the water table, which included wells completed in basin- and valley-fill as well as Santa Fe Group deposits. Bexfield and Anderholm (1997) concluded, "no strong evidence was found of effects on ground-water chemistry from human activities."

Kues and Garcia (1995) sampled 81 water-supply wells in four unincorporated areas of Bernalillo County during 1990–93. Three of these areas were in the Middle Rio Grande Basin and included 61 wells of varying depth: the inner valley of the Rio Grande both north and south of Albuquerque and an area northeast of Albuquerque. Pesticide concentrations were greater than detection limits in three wells in the inner valley. Concentrations of detergent additives (indicating the presence of domestic sewage) were greater than detection limits in four wells: three in the inner valley and one in the northeast area.

All municipal and community water systems are required to periodically test their water to ensure that it meets applicable drinking-water standards and to report the results to water users. In Albuquerque, ground-water samples from each well in the distribution system are analyzed on a regular basis to ensure compliance with drinking-water standards (City of Albuquerque, 2000). The results from this compliance monitoring are periodically mailed to water-utility customers. The City of Albuquerque has voluntarily collected and analyzed additional ground-water samples from its production wells to better characterize the ground-water resource. These data, which were not collected for compliance purposes, are summarized by Bexfield, Lindberg, and Anderholm (1999).

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

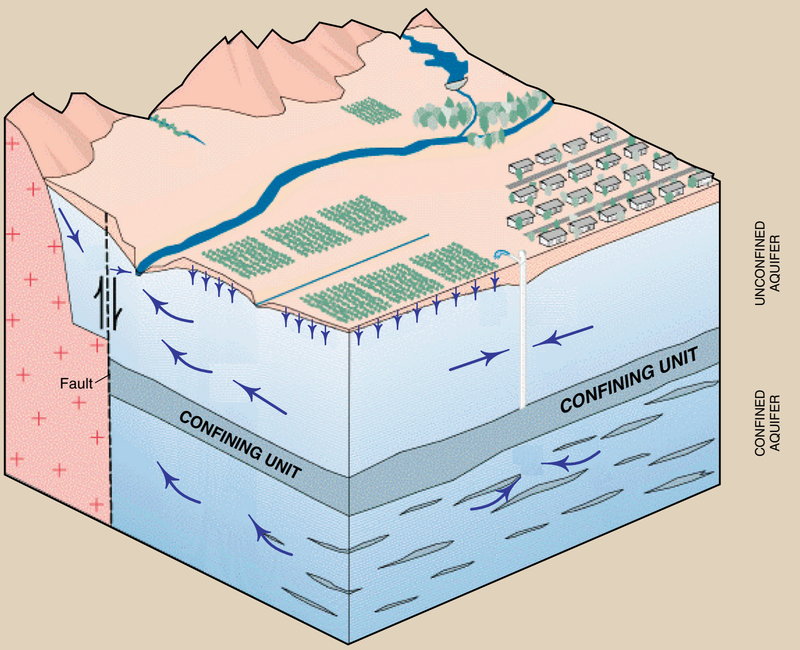


Figure L.1.—*Block diagram of a part of a hypothetical basin-fill ground-water system. The blue arrows show the direction of ground-water flow. Among the features shown are an unconfined aquifer overlying a confining unit and confined aquifer, a gaining stream, infiltration from irrigated agriculture,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

[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.

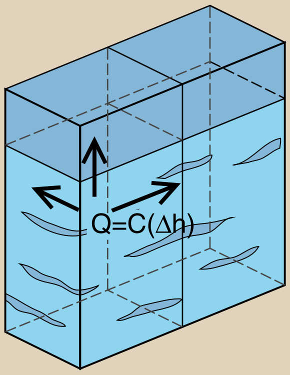


Figure L.3.*—Subset of the model cells that represent an aquifer, indicating that flow is calculated between adjacent cells. A form of the Darcy equation, which is used to calculate flow between each cell, is shown. In the equation, Δh is the head difference between the cell and adjacent cells, Q is 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.*

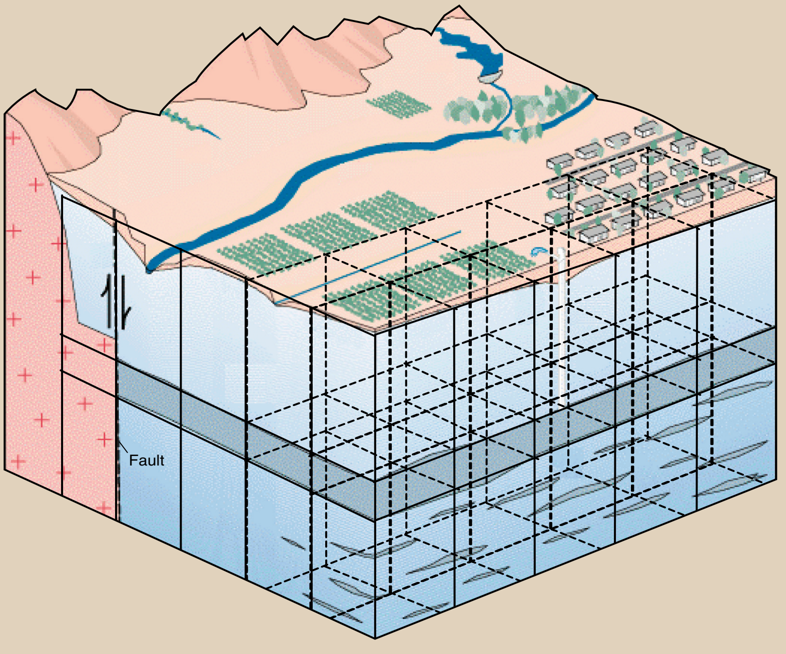


Figure L.2.*—Block diagram of part of a hypothetical basin-fill ground-water system with some model cells shown superimposed. The model cells cover the entire ground-water system being simulated.*

> 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.

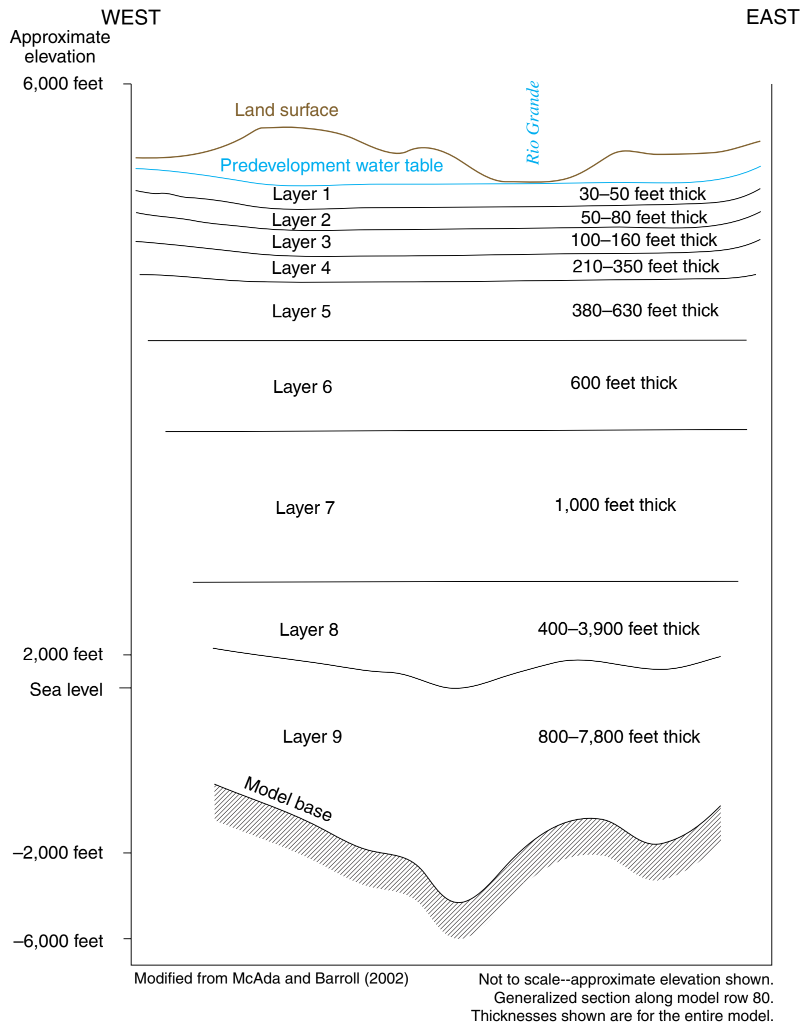


Figure 7.1.*—Generalized configuration of ground-water-flow model layers used by McAda and Barroll (2002) along model row 80.*

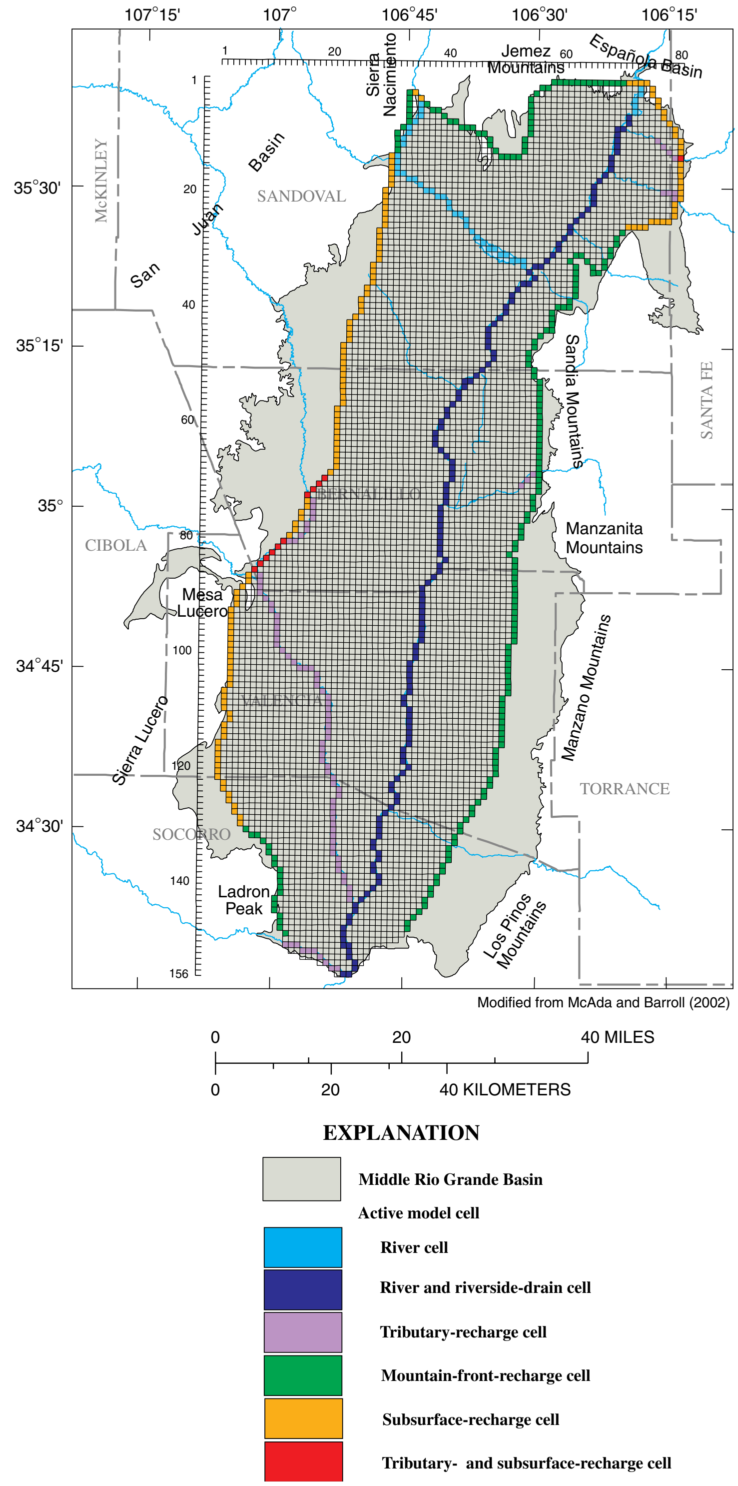


Figure 7.2.*—Active cells in the ground-water-flow model grid (layer 1) of McAda and Barroll (2002). Different types of recharge and drain cells are shown.*

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).

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.

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.

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]

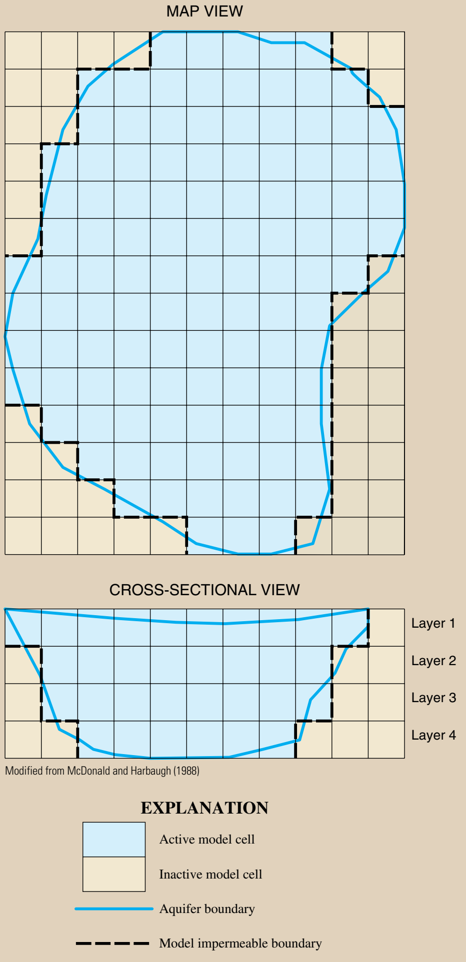


***Figure M.1.**—Schematic representation of an aquifer in a finite-difference ground-water-flow model.*

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

[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.

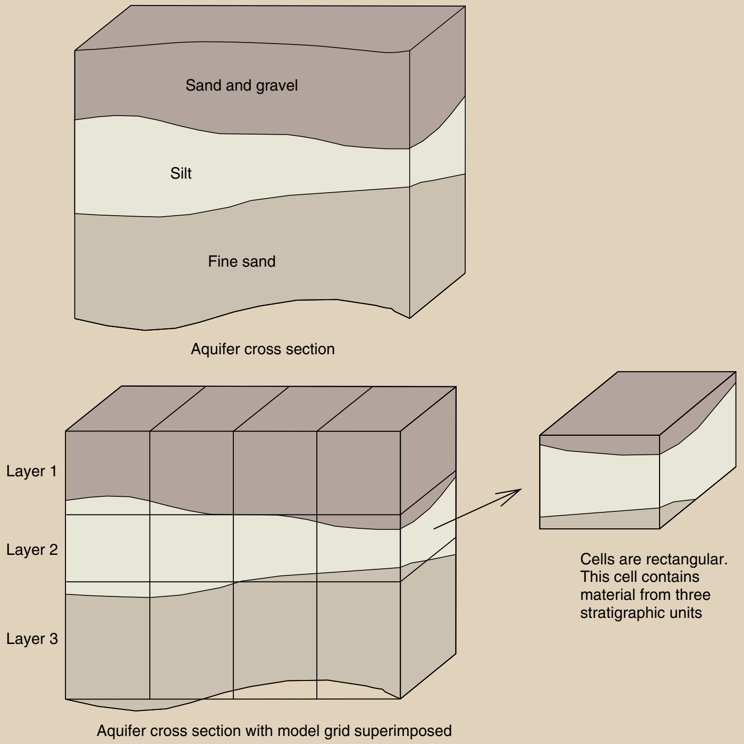


Figure M.2.*—Schematic representation of ground-water flow-model cells related to sedimentary deposits.*

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.

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

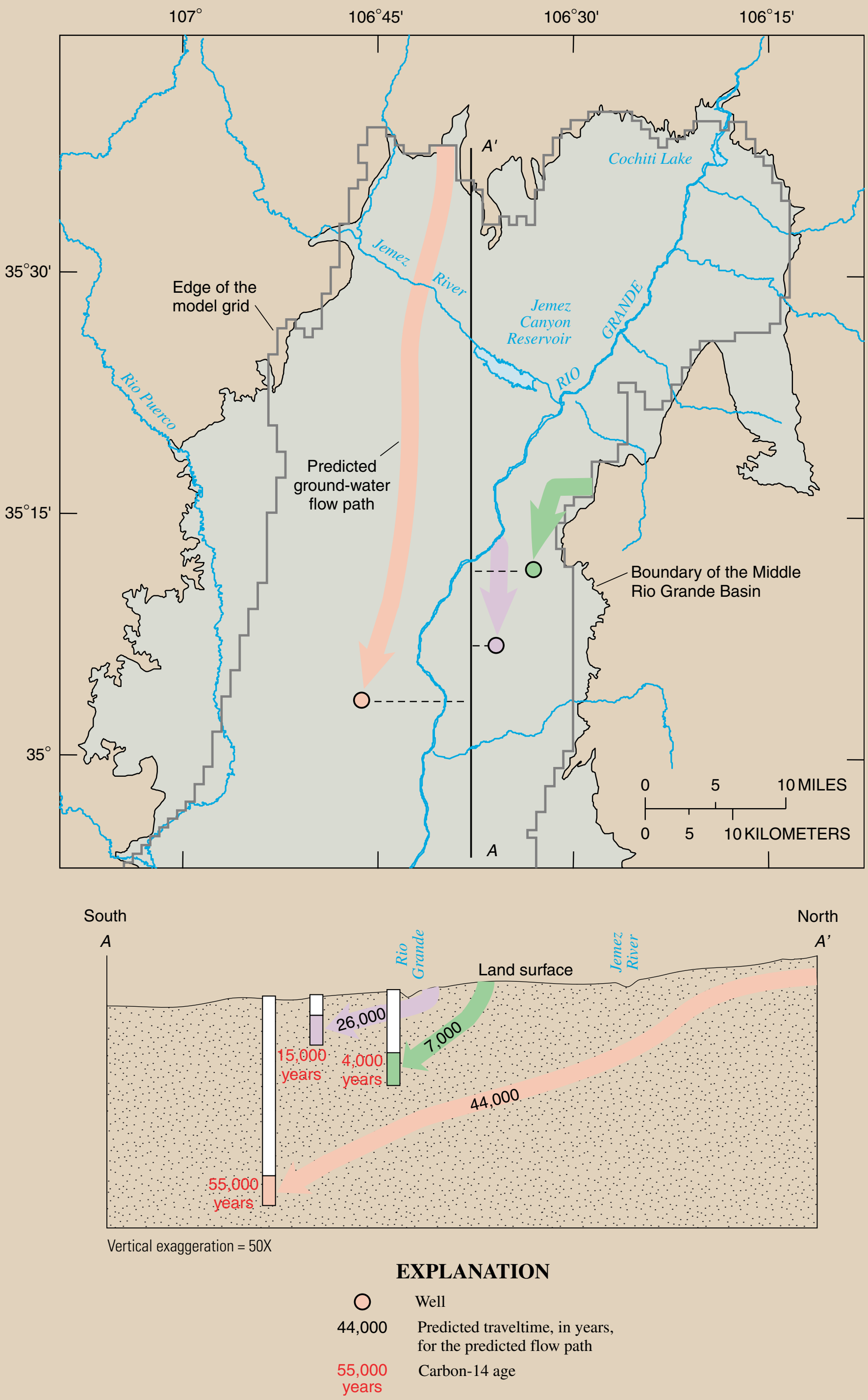


Figure N.1.—*Traveltimes and ground-water flow paths predicted by a preliminary version of the current revision of the ground-water-flow model of the Middle Rio Grande Basin (Sanford, 1999). Three flow paths are shown that extend from recharge areas to observation wells from which samples were analyzed 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.

Chapter 8: Important questions that remain about water resources of the Middle Rio Grande Basin

Instead of providing final, definitive answers, the study of the water resources of an area tends to lead to more questions about the system. This may be because new data conflict with the current understanding of the system or because changes in the management and use of water raise new questions. Though many of the elements listed in the plan of study by McAda (1996) have been addressed by the Middle Rio Grande Basin Study, we still do not have all the information that lawmakers and managers will ultimately need to best manage the water resources in the basin. Therefore, it is important to continue studying the Middle Rio Grande Basin to deal with the issues of today and be prepared for those of tomorrow. Among the questions that could be better defined:

How much water is pumped where and by whom?

Until the locations and pumping characteristics of the major supply wells in the Middle Rio Grande Basin are known with more certainty, estimates of these important parameters will introduce error into simulations and estimations of ground-water behavior. However, it may be impossible to know exactly the locations of all domestic-supply wells in the basin and the volumes of water pumped from each.

What are the availability and quality of water in deeper parts of the aquifer?

On the basis of limited data and similar conditions in other aquifers, ground water in the deeper parts of the aquifer is assumed to be of limited quantity and poor quality. Until more is known, however, the suitability of this water for a given use remains speculative. Few deep wells have been drilled in the basin because deep wells are expensive and because shallower wells have provided adequate supply. The expense to drill deeper may be justified in the future if deeper supplies are needed.

Upper Santa Fe Group (Ceja Member of the Arroyo Ojito Formation) sediments exposed on the northern side of the Los Lunas volcano. Much of the Santa Fe Group aquifer system in the Middle Rio Grande Basin is composed of such deposits. (Courtesy of J.C. Cole.)

How much water does vegetation in the bosque use?

As discussed in Chapter 5, estimates of evapotranspiration in the Middle Rio Grande Basin vary because it is a difficult parameter to measure directly. Because maintenance of the bosque has become a priority for esthetic and wildlife purposes, the measurement of actual evapotranspiration is of critical importance. With the availability of new techniques for quantifying evapotranspiration, several groups including Dahm and others (2000) and the Bureau of Reclamation (2001a, b, c) have begun to work to refine previous estimates of evapotranspiration.

How is the aquifer responding to pumping over the long term?

Tamarisk (in the foreground) and cottonwood (in the background) along the Albuquerque Drain near Paseo del Norte. Such plants in the bosque account for much of the water consumption in the Middle Rio Grande Basin.

To characterize the long-term response of the aquifer to ground-water pumping, ground-water levels in the monitoring network must continue to be measured. Such long-term monitoring is perhaps the most important information that can be collected for long-term aquifer-system and water-resource management.

Another aspect of aquifer response to ground-water pumping is subsidence. By using new and traditional tools, such as interferometric synthetic aperture radar (InSAR) and repeat surveys, respectively, the onset of subsidence can be detected early.

Is septic-system effluent contaminating ground water?

The possibility of effects from septic-system effluent on the quality of water from domestic-supply wells in rapidly developing rural areas will continue to raise questions. The continuing development of new methods may improve the unambiguous detection of septic-system effluent in ground water.

How will the more stringent arsenic standard affect water supplies?

The reduction in the drinking-water standard for arsenic presents new challenges for water-resource managers. To reduce treatment costs, wells pumping water with large concentrations of arsenic may need to be taken out of production or the water blended with water of an acceptable concentration. As more is learned about naturally occurring arsenic in ground water, the completion of production wells might be possible in areas or at specific depths of the aquifer with acceptable concentrations of arsenic.

Are pharmaceuticals present in ground or surface water?

Recently, pharmaceutically active compounds have been detected at very small (parts per billion) concentrations in treated wastewater either discharged to surface water or recharged to ground water. Though the effects of these very small concentrations on humans are unknown, concentrations as small as parts per trillion have been found to adversely affect fish (Sedlak, Gray, and Pinkston, 2000). In 1999 and 2000, USGS researchers sampled 139 streams in 30 States for 95 pharmaceuticals, hormones, and other organic wastewater contaminants (Kolpin and others, 2002). These compounds were detected in 80 percent of the streams sampled, and of the 95 compounds, 82 were detected in surface water. In 2000, the New Mexico Environment Department and Department of Health began analyzing ground- and surface-water samples for 28 drug residues from 24 sites throughout the State and found five different compounds at eight sites (McQuillan and others, 2000). Given concern about the silvery minnow and other fish species in the Rio Grande, as well as the planned direct use of surface water for municipal supplies, this topic will likely be investigated in more detail in the Middle Rio Grande Basin in the near future.

USGS personnel sampling shallow ground water for chemical analysis on the Rio Grande upstream from Corrales. (Courtesy of F.E. Gebhardt, USGS.)

Chapter 9: Key points regarding water resources of the Middle Rio Grande Basin

The most prominent hydrologic feature in the largely semiarid Middle Rio Grande Basin is the Rio Grande, whereas the sole source of water for municipal, domestic, and commercial supply is currently (2002) the Santa Fe Group aquifer system. The water resources of the Middle Rio Grande Basin are a combination of these surface- and ground-water systems, which are intimately linked through a series of complex interactions. These interactions often make recognizing the boundary between the two systems difficult, and changes in one system often affect the other. The most important points in our present understanding of the water resources of the Middle Rio Grande Basin are:

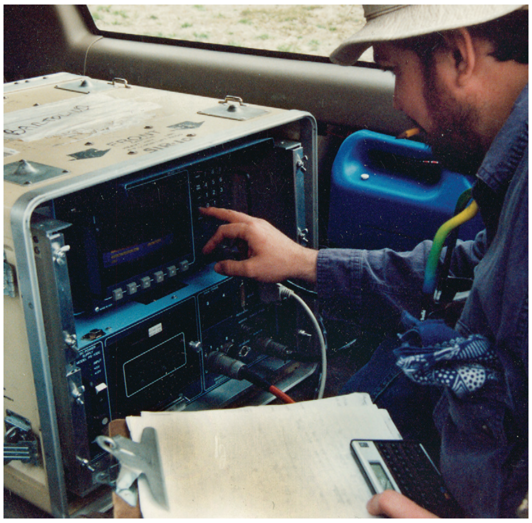
- When ground water is pumped from an aquifer system faster than it is recharged, ground-water levels decline, a condition known as ground-water mining. Ground-water levels have declined with the economic development of the Middle Rio Grande Basin. The effects of ground-water pumping are evident when comparing historical (1960–61) and the most recent (1994–95) ground-water-level maps; water-level declines are more than 160 feet in an area beneath east Albuquerque.

- Previous studies found the Rio Grande to be very well connected hydraulically to the Santa Fe Group aquifer system, and years of water-management policy were based on this understanding. Recent studies of the interaction between the river and aquifer (including ground-water-flow models) indicate that the hydraulic connection is less than previously thought.

- As Albuquerque grew, most of the new municipal-supply wells were completed in high-quality parts of the Santa Fe Group aquifer system. The quantity and quality of the water led to the popular belief that the entire Middle Rio Grande Basin was underlain by a high-quality aquifer; it is now known that such areas of high-quality aquifer are relatively limited and that much less water is available for pumping than previously thought.

- Geophysical studies of the Middle Rio Grande Basin in conjunction with computer modeling of the Santa Fe Group aquifer system indicate that faults are more numerous than previously thought and that they can affect ground-water movement, particularly when they juxtapose aquifer materials of substantially different hydraulic properties.

- Previous estimates of mountain-front recharge were based on indirect calculations from water budgets and computer modeling of the Santa Fe Group aquifer system. New studies using direct measurements and ground-water age dating have shown that mountain-front recharge is substantially less than previously believed.



A USGS hydrologist collecting geophysical data. Geophysical studies such as this one have contributed to understanding the Santa Fe Group aquifer system.

- The bosque assumed its present character in about the past 60 to 70 years, developing in an area that was formerly semibarren flood plain with scattered stands predominantly of cottonwood and willow. The present character was caused by the spread of exotic plant species and the construction of bank-stabilization and flood-control structures, including dams and levees. Though estimates vary, a substantial amount of ground and surface water is consumed by evapotranspiration from the bosque.

By increasing the understanding of the water resources of the Middle Rio Grande Basin, water-resource managers and planners will have additional tools to make sound, scientifically based decisions on the future of water in the basin.

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Abbreviations and Chemical Notation

AMAFCA: Albuquerque Metropolitan Arroyo Flood Control Authority
API: American Petroleum Institute
As: arsenic
AWARDS: Agricultural Water Resources Decision Support System
BP: before present
°C: degree Celsius
Ca: calcium
$CaCO_3$: calcite
$CaMg(CO_3)_2$: dolomite
$CaSO_4$: anhydrite
$CaSO_4 \cdot 2H_2O$: gypsum
CERCLA: Comprehensive Environmental Response Compensation and Liability Act of 1980 ("Superfund")
CFC: chlorofluorocarbon (Freon compounds)
Cl: chloride
cm: centimeter
CO_2: carbon dioxide
ET: evapotranspiration
°F: degree Fahrenheit
GPS: Global Positioning System
^1H: hydrogen
^2H: deuterium
^3H: tritium
HCO_3: bicarbonate
H_2O: water
InSAR: Interferometric Synthetic Aperture Radar
K: potassium
LiDAR: Light Detection and Ranging
Ma: mega-annum (million years before present)
MCL: maximum contaminant level
MDWCA: Mutual Domestic Water Consumers Association
Mg: magnesium
mg/L: milligrams per liter, approximately equal to parts per million
mGal: milligal
mmho: millimho, equivalent to millisiemen
MRGCD: Middle Rio Grande Conservancy District
MRGCOG: Middle Rio Grande Council of Governments
mS: millisiemens, equivalent to millimhos
µg/L: micrograms per liter, approximately equal to parts per billion
µS/cm: microsiemens per centimeter
N: nitrogen
Na: sodium
NaCl: halite (sodium chloride or table salt)
NMBGMR: New Mexico Bureau of Geology and Mineral Resources, formerly NMBMMR
NMBMMR: New Mexico Bureau of Mines and Mineral Resources, now NMBGMR
NMED: New Mexico Environment Department
NMOSE: New Mexico Office of the State Engineer

NO_3: nitrate
nT: nanoTesla
ohm-m: ohm-meter
ppt: parts per thousand
pptv: parts per trillion volume
RCRA: Resource Conservation and Recovery Act of 1976
S: siemen
S: sulfur
SAR: synthetic aperture radar
SF_6: sulfur hexafluoride
SI: International System of Units (metric system)
SiO_2: silica (silicon dioxide or quartz)
SLEUTH: Slope, Land Use, Exclusions, Urban, Transportation, and Hillshade
SO_4: sulfate
SSC: steady-state centrifuge
SSCAFCA: Southern Sandoval County Arroyo Flood Control Authority
TDEM: time-domain electromagnetic
TU: tritium units
URGWOM: Upper Rio Grande Water Operations Model
USACE: U.S. Army Corps of Engineers
USEPA: U.S. Environmental Protection Agency
USFWS: U.S. Fish and Wildlife Service
USGS: U.S. Geological Survey
VOC: volatile organic compound
WSFO: Weather Service Field Office

Prefixes for Abbreviations for Multiples and Submultiples

T: tera (10^{12})
M: mega (10^6)
k: kilo (10^4)
c: centi (10^{-2})
m: milli (10^{-3})
µ: micro (10^{-6})
n: nano (10^{-9})
p: pico (10^{-12})