Section 11.—Conceptual Understanding and Groundwater Quality of the Basin-Fill Aquifer in the Middle Rio Grande Basin, New Mexico

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in

Conceptual Understanding and Groundwater Quality of Selected Basin-Fill Aquifers in the Southwestern United States

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National Water-Quality Assessment Program

Professional Paper 1781

U.S. Department of the Interior
U.S. Geological Survey

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Basin Overview

The Middle Rio Grande Basin is a 2,900-mi^2 alluvial basin extending along the Rio Grande in central New Mexico (fig. 1) that includes both geologic sources of natural contaminants and a long history of agricultural and urban land uses, but only local areas of substantial intrinsic groundwater susceptibility to contamination. The basin lies within the Rio Grande Rift, an area of crustal extension stretching from Colorado to Texas, and is hydraulically connected to other alluvial basins to the north and south. Despite being considered part of the Rio Grande aquifer system that extends along the Rift (Robson and Banta, 1995), the Middle Rio Grande Basin lies within the Basin and Range Physiographic Province (Fenneman, 1931) and has hydrogeologic characteristics similar to those in alluvial basins in the Basin and Range aquifer system of the southwestern United States. Altitudes range from about 4,700 ft, where the Rio Grande drains the basin at its southern end, to more than 6,200 ft in the foothills of the Jemez Mountains on the north and the Sandia and Monzano Mountains on the east. The Nacimiento Uplift, Rio Puerco fault zone, and Lucero Uplift are the primary boundary features on the west (fig. 1).

Most of the Middle Rio Grande Basin is categorized as having a semiarid climate, characterized by abundant sunshine, low humidity, and a high rate of evaporation that substantially exceeds the generally low rate of precipitation. Mean annual precipitation for 1914–2005 at Albuquerque was 8.7 in. (Western Regional Climate Center, 2006a), although mean annual precipitation for 1953–1979 at higher altitudes in the Sandia Mountains that border the basin to the east was 22.9 in. (Western Regional Climate Center, 2006b). Analysis of modeled precipitation data for 1971–2000 (PRISM Group, Oregon State University, 2004) resulted in an average annual precipitation value of about 10.6 in. over the alluvial basin as a whole (McKinney and Anning, 2009). Most precipitation within the alluvial basin falls between July and October as a result of local, short duration, and high-intensity thunderstorms; winter storms of longer duration and lower intensity make a greater contribution to annual precipitation in the surrounding mountains. The mean monthly maximum temperature for 1914–2005 at Albuquerque was 47.2°F in January and 91.7°F in July (Western Regional Climate Center, 2006a).

The Middle Rio Grande Basin includes the Albuquerque metropolitan area (the most populous area in New Mexico), which grew about 20 percent between 1990 and 2000, from about 589,000 to 713,000 people (U.S. Census Bureau, 2001). Analysis of LandScan population data for 2000 (Oak Ridge National Laboratory, 2005) indicated a population of 756,000 for the alluvial basin as a whole (McKinney and Anning, 2009). Prior to substantial urbanization of the basin, land in upland areas outside of the historical Rio Grande flood plain (also referred to as the "inner valley") was almost exclusively rangeland; at 83 percent of the basin area, rangeland has remained the dominant land-use type according to the National Land Cover Database (NLCD) dataset for 2001 (U.S. Geological Survey, 2003). Irrigated agriculture is practiced throughout the Rio Grande flood plain, which is up to about 4.5 mi wide (fig. 1); irrigated cropland makes up just over 2 percent of land in the basin. Alfalfa was the most abundant crop type in 1993, followed by planted pasture (Kinkel, 1995, appendix 4). Population growth since about 1940 has led to urbanization of former agricultural land and rangeland in the Albuquerque area, resulting in urban turf grass being the second most abundant crop (in terms of planted acreage) in Bernalillo County in 1992 (Bartolino and Cole, 2002). As of 2001, the NLCD dataset classified only about 6 percent of land in the basin as urban.

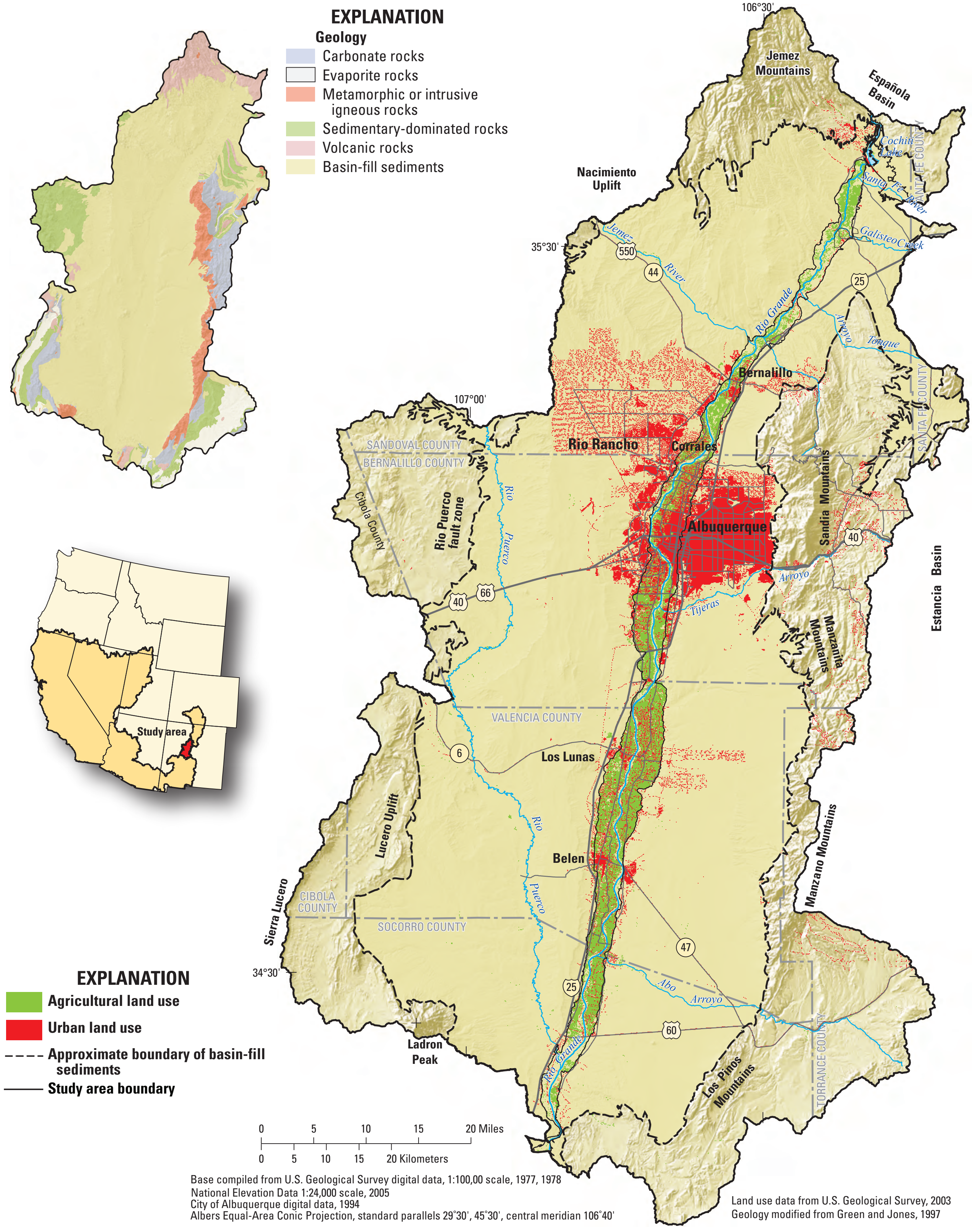


Figure 1. Physiography, land use, and generalized geology of the Middle Rio Grande Basin, New Mexico.

Despite expanding urbanization, irrigated agriculture continues to be the largest water user within the Middle Rio Grande Basin. Estimates of year-2000 water use by Wilson and others (2003) for the four counties that cover most of the basin (but also including some areas outside the basin; table 1) and by the U.S. Geological Survey (USGS) (http://water.usgs.gov/watuse/) for the area within the alluvial basin, indicate that nearly three-quarters of total combined surface-water and groundwater withdrawals were associated with irrigated agriculture; more than 90 percent of the water used for irrigated agriculture was surface water, primarily diverted from the Rio Grande and delivered to areas within the inner valley. About half of total water depletion was associated with irrigated agriculture (Wilson and others, 2003). Virtually all water demand for public supply has historically been met by groundwater withdrawals (Wilson and others, 2003; USGS water-use estimates, http://water.usgs.gov/watuse/). Combined, public supply, domestic uses, industry, and commercial uses represented about one-quarter of total withdrawals and one-third of total groundwater depletion in the major counties of the basin in 2000 (Wilson and others, 2003). Development of the water resources of the basin for agricultural and urban purposes has resulted in substantial changes to the groundwater and surface-water systems and how they interact.

Groundwater-quality issues identified in the Middle Rio Grande Basin include both naturally occurring contaminants and anthropogenic compounds. Concentrations of dissolved solids and arsenic across broad areas, particularly in the western part of the basin, exceed U.S. Environmental Protection Agency (USEPA) drinking-water standards (U.S. Environmental Protection Agency, 2009; each time a drinking-water standard or guideline is mentioned in this section, it denotes this same citation). As described later in this section, local occurrences of nitrate at concentrations greater than about 5 mg/L are believed to be natural in some areas, but to be associated with anthropogenic sources—particularly septic tanks—in others. Anthropogenic compounds that have been detected in groundwater of the basin include volatile organic compounds (VOCs) (particularly chlorinated solvents and petroleum hydrocarbons) and pesticides (particularly herbicides with urban uses). Most detections of these compounds have been in monitoring wells in or near the Rio Grande inner valley—an area that is intrinsically susceptible to groundwater contamination because of the presence of recharge and depths to groundwater generally less than about 30 ft (Anderholm, 1987)—and the detected concentrations have been below maximum concentrations specified in the USEPA's water-quality standards. In some cases, however, VOC detections near known chemical releases have resulted in the closure of private domestic wells and public-supply wells (U.S. Environmental Protection Agency, 2006).

Table 1. Water-use estimates for the Middle Rio Grande Basin, New Mexico, 2000.

[Counties included Bernalillo, Sandoval, Socorro, and Valencia. All values in acre-feet. Data from Wilson and others, 2003]

Water-use category	Surface-water withdrawal	Groundwater withdrawal	Total withdrawal	Total depletion
Public water supply	226	138,712	138,938	66,285
Domestic	0	12,576	12,576	12,576
Irrigated agriculture and livestock	429,096	47,581	476,677	146,970
Commercial, industrial, mining, and power generation	10	15,450	15,460	10,354
Reservoir evaporation	17,940	0	17,940	17,940
Total	**447,272**	**214,320**	**661,592**	**254,126**

Water Development History

By the time Spanish settlement had extended well into the Middle Rio Grande Basin in the early 1600s (Bartolino and Cole, 2002), most of the "major" pueblos of the area had already been in existence for hundreds of years (Scurlock, 1998). The pueblos had developed community irrigation ditches (or acequias) for farming in the inner valley, which the Spaniards imitated in developing their own irrigation systems (Bartolino and Cole, 2002). The intensity and extent of irrigated agriculture grew rapidly during the mid- to late-1800s with the arrival of large numbers of Anglo farmers and the introduction of improved farming practices (Scurlock, 1998). However, problems that included drought, sedimentation, salinization, and waterlogging reduced irrigated acreage after the early 1890s (Wozniak, 1996; Scurlock, 1998).

In the early- to mid-1900s, extensive efforts were undertaken throughout the Rio Grande Valley to protect and enhance the suitability of the inner valley for agriculture. A system of levees and jetty-jack works was used to confine the river to a single channel. The modern system of irrigation canals and groundwater drains also was constructed during this time (Thorn and others, 1993). The riverside and interior drains were put in place to lower the water table and allow reclamation of lands that had previously been waterlogged by canal leakage and irrigation. Reservoirs were constructed on the Rio Grande and its tributaries north of the basin as early as 1913 (Crawford and others, 1993). Cochiti Dam, at the north end of the Middle Rio Grande Basin, began operation in 1973 for flood control purposes.

Construction and operation of these man-made structures along the Rio Grande have substantially altered the configuration of the river, its seasonal discharge patterns, and its interaction with the groundwater system. The Rio Grande probably was once a perennial, braided river that migrated back and forth across the inner valley and had highly variable discharge reflecting seasonal snowmelt and storm events (Crawford and others, 1993). Currently (during 2006), the river does not deviate from its confined channel. However, surface water is diverted for irrigation through an extensive system of mostly unlined canals and applied to land throughout the inner valley between March and October of each year. The regulation of flows at dams upstream from the Middle Rio Grande Basin to sustain adequate discharge along the Rio Grande throughout the irrigation season results in a more uniform seasonal distribution of flow at Albuquerque (mean annual discharge 1,330 ft^3/s from USGS digital data for 1974–2005) than would be expected under "natural" conditions. Substantial irrigation diversions affect discharge along the river and reportedly have at times resulted in a dry stretch of channel downstream from the town of Bernalillo (Norman, 1968). The presence of the canal and drain systems within the Rio Grande inner valley has substantially increased the magnitude of fluxes between the surface-water and groundwater systems, as well as the area over which interaction between the two systems occurs. Riverside drains intercept leakage from the Rio Grande and eventually return that water to the river, along with irrigation water from the canal system and water captured by the interior drains as a result of seepage from canals and irrigated fields.

Utilization of the groundwater resources of the Middle Rio Grande Basin probably began when early settlers dug shallow wells for domestic use in unconsolidated river alluvium (Kelly, 1982). Albuquerque had about 1,307 residents in 1880, and within several years, the town had a public water-supply system that consisted of a few shallow wells located in the inner valley (Ground-Water Science, Inc., 1995). Albuquerque's population increased steadily to about 35,500 in 1940, and then climbed rapidly to about 200,000 people in 1960 (fig. 2) (Ground-Water Science, Inc., 1995). During this period of rapid growth, Albuquerque met its increasing water demand with an expanding network of public-supply wells, including several located in upland areas, which were becoming extensively urbanized. In 1989, the city had about 90 public-supply wells and pumped 127,000 acre-ft of groundwater (City of Albuquerque files) to supply a population of almost 385,000. Although the population had increased to nearly 450,000 city residents in 2000, Albuquerque's water demand declined—ranging from 100,000 to 114,000 acre-ft/yr during 1997–2004 (City of Albuquerque files). The decline in water use resulted primarily from conservation efforts initiated after studies indicated that groundwater resources of the basin were more limited than previously believed (City of Albuquerque, 2010). Groundwater withdrawals by domestic, commercial, and industrial users in the basin have continued to increase overall (Wilson, 1992; Wilson and Lucero, 1997; Wilson and others, 2003).

Sustained groundwater withdrawals from the Middle Rio Grande Basin have resulted in extensive water-level declines, which exceed 120 ft in eastern Albuquerque (Bexfield and Anderholm, 2002a). These declines have substantially altered groundwater flow directions (as discussed in more detail in a later section), reduced flows in the Rio Grande by inducing additional infiltration (McAda and Barroll, 2002), and decreased the amount of evapotranspiration within the Rio Grande inner valley (McAda and Barroll, 2002). Declines in water levels also have increased the cost of groundwater pumping and, if allowed to continue, have the potential to result in widespread land-surface subsidence and(or) degradation of groundwater quality in the future (Bexfield and others, 2004).

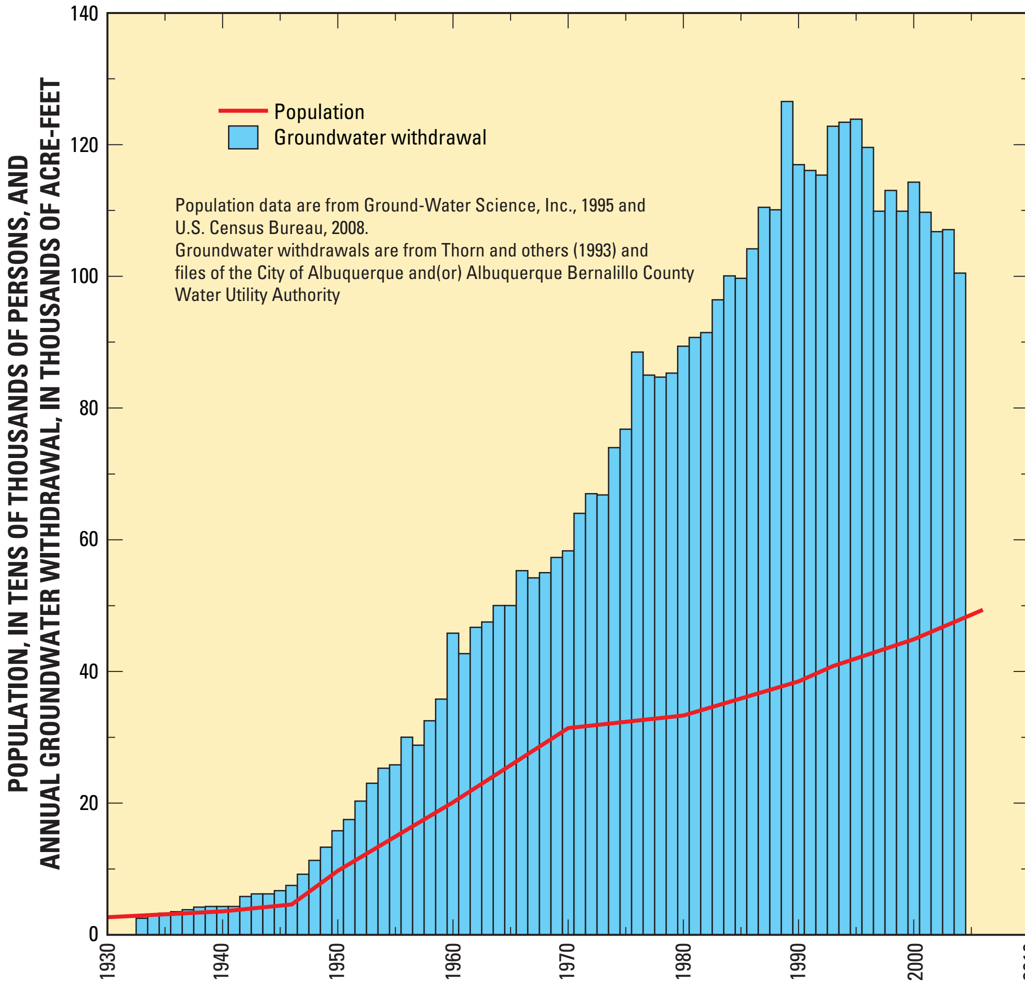


Figure 2. Albuquerque population (1930–2006) and groundwater withdrawals (1933–2005).

Recognition of existing and potential future problems resulting from continued development of groundwater resources at recent levels prompted the City of Albuquerque to adopt a new water-supply strategy in 1997 (City of Albuquerque, 2010). The City of Albuquerque owns rights to about 48,200 acre-ft/yr of surface water imported into the Rio Grande Basin from the Colorado River Basin by the San Juan Chama Transmountain Diversion Project (completed in 1971) and about 23,000 acre-ft/yr of native Rio Grande water. Under the new strategy, direct use of this surface water for public supply began in December 2008. Groundwater will still be used, but primarily to supplement supplies during periods of drought and months of high demand (typically June through September). Because the City of Albuquerque has historically been responsible for a large portion of groundwater withdrawals from the basin, as evidenced by the estimation that it was responsible for just over half of total groundwater withdrawals from the basin in 2000 (City of Albuquerque and the New Mexico Office of the State Engineer files), this change in water-supply strategy is expected to have substantial effects on the groundwater and surface-water systems, including rises in groundwater levels and decreases in the infiltration of river water (Bexfield and McAda, 2003). Additional strategies that are being implemented to reduce groundwater withdrawals include the use of treated municipal wastewater, recycled industrial wastewater, and nonpotable surface water to irrigate urban turf areas (Albuquerque Bernalillo County Water Utility Authority, 2010).

Hydrogeology

The Middle Rio Grande Basin lies along the Rio Grande Rift, which is a generally north-south trending area of Cenozoic crustal extension. Successive episodes of extension starting about 32 million years ago (Russell and Snelson, 1990) caused large blocks of crust to drop down relative to adjacent areas, forming a series of structural and physiographic basins, many of which are hydraulically connected. The Middle Rio Grande Basin includes three subbasins that are separated by bedrock structural highs and contain alluvial fill as much as about 15,000 ft thick (Grauch and others, 1999). Bedrock benches on the east and west bound the deeper parts of the basin. In addition to major faults that juxtapose alluvium and bedrock along uplifts and benches near the basin margins, numerous other primarily north-south trending faults have caused offsets within the alluvial fill (Grauch and others, 2001; Connell, 2006). The Sandia, Manzanita, Manzano, and Los Pinos Mountains on the east, the Ladron Mountains on the southwest, and the Nacimiento Uplift on the northwest are composed of Precambrian plutonic and metamorphic rocks, generally overlain by Paleozoic and(or) Mesozoic sedimentary rocks (Hawley and Haase, 1992; Hawley and others, 1995) (fig. 1). The Jemez Mountains on the north are a major Cenozoic volcanic center. Primarily Paleozoic and Mesozoic sedimentary rocks border the basin on the west.

The alluvial fill of the Middle Rio Grande Basin is composed primarily of the unconsolidated to moderately consolidated Santa Fe Group deposits of late Oligocene to middle Pleistocene age, which overlie lower and middle Tertiary rocks in the central part of the basin, and Mesozoic, Paleozoic, and Precambrian rocks near the basin margins (McAda and Barroll, 2002). Post-Santa Fe Group valley- and basin-fill deposits of Pleistocene to Holocene age typically are in hydraulic connection with the Santa Fe Group deposits; in combination, these deposits form the Santa Fe Group aquifer system (Thorn and others, 1993). The sediments in the basin consist generally of sand, gravel, silt, and clay that were deposited in fluvial, lacustrine, or piedmont-slope environments.

Hawley and Haase (1992) defined broad lower, middle, and upper parts of the Santa Fe Group on the basis of both the timing and the environment of deposition. Sediments of the lower Santa Fe Group, which may be as much as 3,500-ft thick in places, include extensive basin-floor playa deposits with low hydraulic conductivity. The middle Santa Fe Group ranges from about 250 to 9,000-ft thick and consists largely of basin-floor fluvial deposits in the north and fine-grained playa deposits in the south. The upper unit generally is less than about 1,000-ft thick, except in some areas near Albuquerque, and was deposited during development of the ancestral Rio Grande system (about 1 to 5 million years ago). The axial-channel deposits of this high-energy, fluvial system include thick zones of well-sorted sand and gravel that constitute the most productive aquifer materials in the basin. Most public-supply wells in the study area are completed in the upper and(or) middle units east of the Rio Grande and in the middle and(or) lower units west of the river. Post-Santa Fe Group valley-fill sediments generally are less than about 130-ft thick. These sediments, in which the estimates for hydraulic conductivity vary widely, provide a connection between the surface-water system and the underlying Santa Fe Group deposits.

Conceptual Understanding of the Groundwater System

Groundwater within the Santa Fe Group aquifer system of the Middle Rio Grande Basin generally is unconfined, but is semiconfined at depth. Depths to water range from a few feet near the Rio Grande to more than 700 ft beneath upland areas both east and west of the river (and at least 900 ft beneath parts of Rio Rancho). Transmissivity estimates for the aquifer system have ranged widely because of variations in both aquifer thickness and hydraulic conductivity across the basin, but estimates from aquifer tests (mostly in Albuquerque public-supply wells) generally fall between about 3,000 and 70,000 ft^2/d (Thorn and others, 1993). These values were used by Thorn and others (1993) to estimate horizontal hydraulic conductivities as ranging from about 4 to 150 ft/d; in their groundwater-flow model of the basin, McAda and Barroll (2002) used hydraulic conductivity values of 0.05 to 60 ft/d. The basin-wide occurrence of interbedded fine- and coarse-grained sediments suggests a relatively high degree of anisotropy, that is, a large ratio of horizontal to vertical hydraulic conductivity. Through calibration, McAda and Barroll (2002) selected a ratio of 150:1 for their model (compared with ratios of 80:1 to 1,000:1 used in previous models).

Water Budget

Water budgets have been developed for the Middle Rio Grande Basin in association with groundwater-flow models. The McAda and Barroll (2002) model incorporated estimates of various budget components resulting from the most recent multiagency study of hydrogeology in the basin, during 1995–2001; the water budget from this model (table 2) provides the basis for most of the discussion in this section. Individual components of recharge and discharge are illustrated in the conceptual diagrams of regional groundwater flow in figures 3*A* and 3*B*.

Table 2. Water-budget components for the Middle Rio Grande Basin, New Mexico, under predevelopment and modern conditions, as simulated by the McAda and Barroll (2002) groundwater-flow model.

[All values are in acre-feet per year and are rounded to the nearest thousand. Small differences in total recharge and total discharge that are not accounted for by change in aquifer storage are the result of rounding and(or) model error. Percentages of water-budget components are illustrated on figure 3]

	Predevelopment conditions (steady state)	Modern conditions (year ending October 1999)	Change from predevelopment to modern conditions
Budget component		**Net recharge**	
Mountain-front recharge[1]	12,000	12,000	0
Tributary recharge	9,000	9,000	0
Subsurface recharge[2]	31,000	31,000	0
Canal seepage	0	90,000	90,000
Crop-irrigation seepage	0	35,000	35,000
Rio Grande and Cochiti Lake	63,000	316,000	253,000
Jemez River and Jemez Canyon Reservoir	15,000	17,000	2,000
Septic-field seepage	0	4,000	4,000
Total recharge	**130,000**	**514,000**	**384,000**
Budget component		**Net discharge**	
Riverside drains	0	208,000	208,000
Interior drains	0	133,000	133,000
Groundwater withdrawal	0	150,000	150,000
Riparian evapotranspiration	129,000	84,000	-45,000
Total discharge	**129,000**	**575,000**	**446,000**
Change in aquifer storage	0	-60,000	-60,000

[1]As defined for the McAda and Barroll (2002) model, the mountain-front recharge budget component does not include mountain-front recharge along the Jemez Mountains on the north because mountain-front recharge could not be distinguished from subsurface recharge through the mountain block in this area.

[2]As defined for the McAda and Barroll (2002) model, the subsurface recharge budget component includes groundwater inflow from adjacent basins on the west and north, groundwater inflow from mountain blocks on the east, and combined subsurface and mountain-front recharge along the Jemez Mountains on the north.

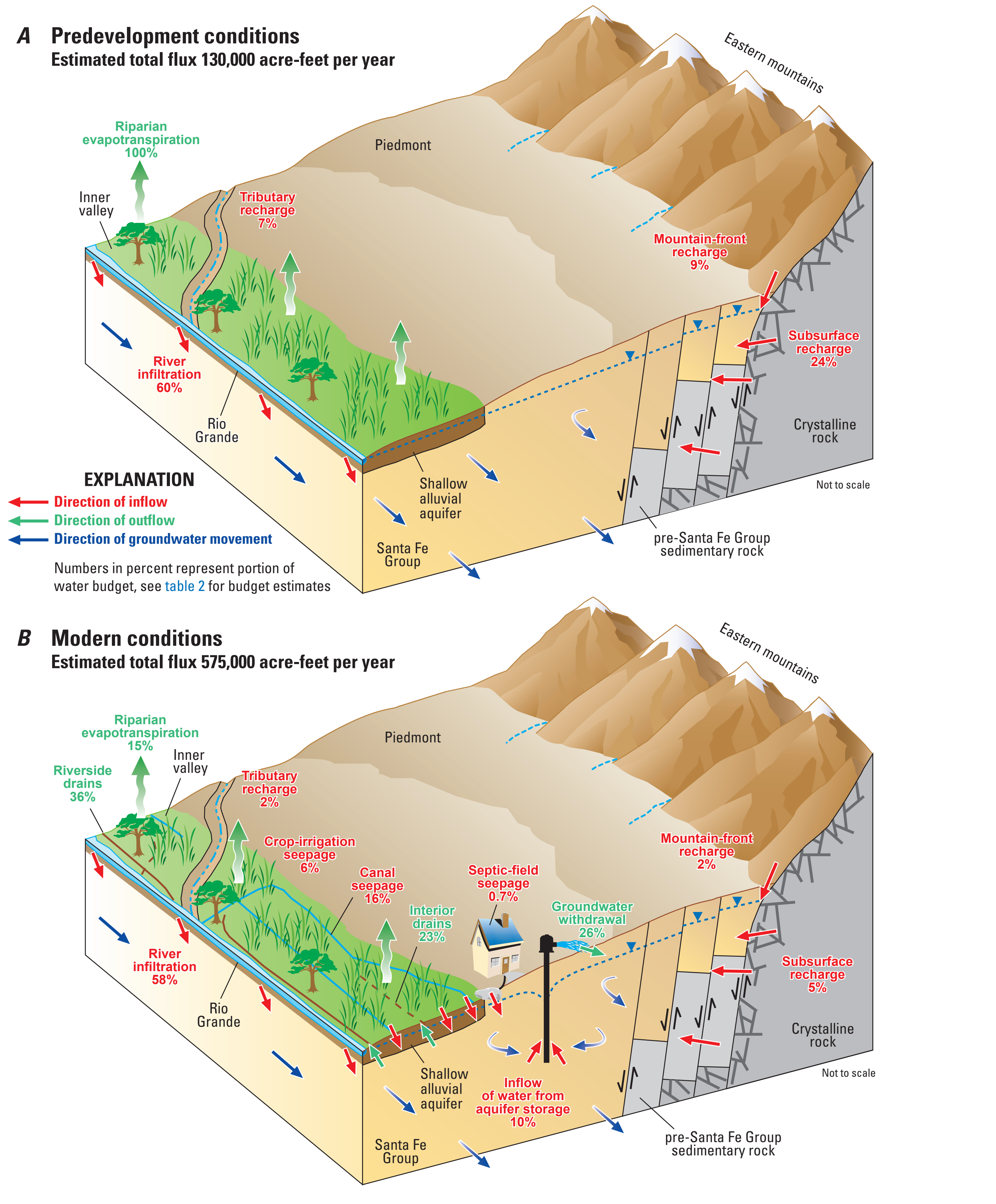


Figure 3. Generalized diagrams for the Middle Rio Grande Basin, New Mexico, showing the basin-fill deposits and components of the groundwater system under (*A*) predevelopment and (*B*) modern conditions.

As a result of low precipitation rates combined with high evaporation rates and generally large depths to groundwater, areal recharge to the Santa Fe Group aquifer system of the Middle Rio Grande Basin from precipitation is believed to be minor (Anderholm, 1987; 1988). Instead, groundwater recharge occurs primarily along surface-water features and at the basin boundaries (fig. 3). Using the chloride-balance method, Anderholm (2001) calculated mountain-front recharge along the entire eastern margin of the basin to total about 11,000 acre-ft/yr. The McAda and Barroll (2002) model uses a value of about 12,000 acre-ft/yr for the basin (table 2), excluding areas along the Jemez Mountains to the north; this value is about 9 percent of the total simulated recharge of 130,000 acre-ft/yr under steady-state (that is, predevelopment) conditions. Subsurface recharge occurring as groundwater inflow from adjacent basins to the west and north (through sedimentary rocks and alluvial fill), subsurface recharge occurring as groundwater inflow from mountain blocks to the east, and combined subsurface and mountain-front recharge occurring along the Jemez Mountains to the north (fig. 3) has been estimated through groundwater-flow modeling, using supporting evidence from studies of hydrogeology (Smith and Kuhle, 1998; Grant, 1999) and groundwater ages (Sanford and others, 2004a, 2004b). McAda and Barroll (2002) use a total of about 31,000 acre-ft/yr of subsurface recharge for the basin (including combined subsurface and mountain-front recharge along the Jemez Mountains), or about 24 percent of total simulated recharge under steady-state conditions.

Within the Middle Rio Grande Basin, most recharge to the aquifer system results from infiltration of surface water (shown by the red arrows in fig. 3; table 2), which occurs along the Rio Grande and its main tributary, the Jemez River. By comparison, tributary recharge along the Rio Puerco in the west, the Rio Salado in the south, and streams and arroyos entering the basin from the east (which generally do not contain persistent flow more than a few hundred feet from the mountain front) is small. Tributary recharge assigned in the McAda and Barroll (2002) model totals about 9,000 acre-ft/yr, or about 7 percent of total simulated recharge under steady-state conditions. The Rio Grande, which is in hydraulic connection with the Santa Fe Group aquifer system, is believed to lose water along most of its length within the basin. The McAda and Barroll (2002) model simulated infiltration of Rio Grande streamflow to the aquifer system under steady-state conditions to be about 63,000 acre-ft/yr, or about 48 percent of total steady-state recharge. Along the Jemez River (which is in hydraulic connection with the aquifer system through most of its length within the basin), these losses are simulated to be about 15,000 acre-ft/yr under steady-state conditions, or about 12 percent of total steady-state recharge.

Since urbanization and the development of large-scale irrigation systems in the Middle Rio Grande Basin, fluxes of water through the aquifer system have increased substantially, as illustrated by the simulated water budget of McAda and Barroll (2002) for the year ending in October 1999 (table 2). Infiltration of water to the aquifer system in the Rio Grande inner valley is about seven times larger than it was under predevelopment conditions and is spread over a much larger area of the inner valley. The model simulates seepage from irrigation canals (including some along the Jemez River) as contributing about 90,000 acre-ft/yr of water to the aquifer system. By applying an estimated average recharge rate of about 0.5 acre-ft/acre to all irrigated cropland in the model, recharge through crop-irrigation seepage is estimated to total about 35,000 acre-ft/yr. Given the declines in groundwater levels as a result of withdrawals for public supply, along with filling of the Cochiti Reservoir starting in 1973, infiltration along the Rio Grande is simulated to be 316,000 acre-ft/yr, or about five times the infiltration simulated under steady-state conditions. An additional source of recharge resulting from urbanization is septic-field seepage, which occurs both within and outside the Rio Grande inner valley and is estimated by McAda and Barroll (2002) to total about 4,000 acre-ft/yr for the year ending in October 1999, based on census data and an estimated seepage rate of 60 gallons per day per person. Additional sources of recharge outside the inner valley that have likely resulted from urbanization, but that would be expected to occur only locally and are not represented in the McAda and Barroll (2002) model include seepage from sewer and water-distribution lines and from turf irrigation.

Under predevelopment conditions, water was discharged from the aquifer system primarily through evapotranspiration from riparian vegetation and wetlands in the Rio Grande inner valley (Kernodle and others, 1995). Groundwater withdrawals for public supply and construction of an extensive groundwater drainage system in the inner valley have lowered the water table and resulted in reduced evapotranspiration from native riparian vegetation and wetlands (about 84,000 acre-ft for the year ending in October 1999 in comparison with about 129,000 acre-ft/yr under steady-state conditions, as simulated by McAda and Barroll [2002]). The largest component of outflow from the aquifer system currently is discharge to the groundwater drain system ("Riverside drains" and "Interior drains" in table 2), which McAda and Barroll (2002) simulated to total about 341,000 acre-ft/yr (table 2). Slightly more than 60 percent of this discharge was to the riverside drains, and the remainder discharged to interior drains located farther from the Rio Grande. Most of the groundwater discharging to the drain system is water that has moved through the shallow system after infiltrating from the Rio Grande or seeping from irrigation canals and irrigated fields (McAda and Barroll, 2002), although groundwater from the deep regional system also discharges to the drains.

Some groundwater discharges from the aquifer system by means of subsurface flow through alluvial fill to the Socorro Basin on the south, but this discharge is considered negligible relative to other budget components (Sanford and others, 2004a). Some groundwater also may discharge directly to the Rio Grande in individual reaches, particularly in the northern part of the basin (Trainer and others, 2000). Groundwater withdrawals currently are a major component of the water budget, discharging an estimated 150,000 acre-ft from the aquifer system during the year ending in October 1999 (table 2) and resulting in the removal of water from aquifer storage.

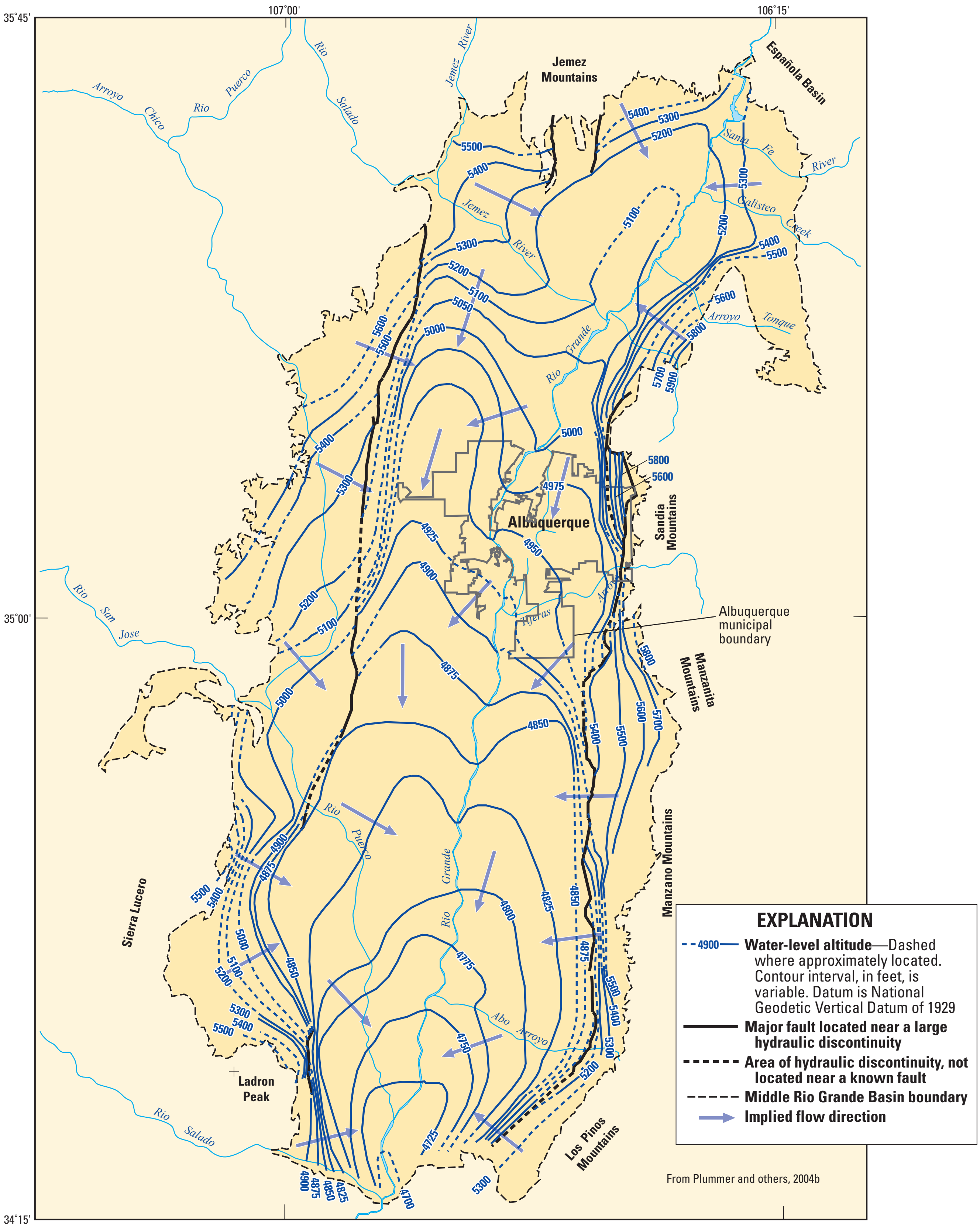
Groundwater Flow

Maps of predevelopment (generally, pre-1960) groundwater levels in the study area (Meeks, 1949; Bjorklund and Maxwell, 1961; Titus, 1960; Bexfield and Anderholm, 2000) indicate that the principal direction of groundwater flow was from north to south through the center of basin, with greater components of east-to-west flow near the basin margins (fig. 4). This general flow pattern reflects the areal distribution of groundwater recharge and discharge (fig. 3). Predevelopment water-level maps indicate the presence of depressions—or "troughs"—in the water-level surface both east and west of the Rio Grande. The origin of these troughs has not been conclusively determined, but McAda and Barroll (2002) suggest the presence of high-permeability pathways, horizontal anisotropy, and(or) faults acting as flow barriers as possible explanations for their presence. Plummer and others (2004a, 2004b, 2004c) and Sanford and others (2004a, 2004b) hypothesized that the trough west of the Rio Grande may be a transient feature that reflects changes in the quantity and spatial distribution of recharge through time.

Large and extensive water-level declines caused by sustained groundwater withdrawals for public supply have substantially altered the direction of groundwater flow in the Albuquerque metropolitan area (Bexfield and Anderholm, 2002a) (fig. 5). Water-level declines since predevelopment in the production zone (the range of aquifer depths from which most withdrawals by public-supply wells occur—typically from about 200 to 900 ft or more below the water table) have exceeded 100 ft across more than 15 mi^2 east of the Rio Grande and 80 ft across smaller areas west of the Rio Grande. Consequently, groundwater currently flows toward the major pumping centers from all directions (fig. 5), and the magnitudes of horizontal hydraulic gradients in the Albuquerque area have increased (figs. 4 and 5). Water-level declines in the aquifer also have induced additional inflow from the surface-water system compared to that under predevelopment conditions. In most areas where water-level declines have occurred, the saturated thickness of the aquifer has not been substantially affected because of the large thickness of Santa Fe Group sediments.

Water-level data from deep piezometer nests across the Albuquerque area indicate that vertical hydraulic gradients generally are downward in the Rio Grande inner valley and areas to the west, and upward in areas east of the inner valley, except in proximity to the mountain front (Bexfield and Anderholm, 2002b). These deep nests typically include three piezometers that are screened across relatively short depth intervals near the water table (shallow), near the middle of the production zone (middle), and near the bottom of the production zone (deep). Using data from continuous water-level monitors for 1997–99, Bexfield and Anderholm (2002b) illustrated that water levels in the middle and deep zones tended to show fairly substantial changes (exceeding 20 ft in places) in response to seasonal variations in groundwater withdrawals, whereas water levels at the water table (where the storage coefficient is largest) generally showed much smaller seasonal changes. Similar patterns can be seen in water-level data for 2001–04 (fig. 6). Groundwater withdrawals, therefore, tend to increase the magnitude of—and, in some cases, change the direction of—vertical hydraulic gradients. The magnitudes of typical vertical gradients also vary among locations, probably reflecting local variations in the degree of vertical hydraulic connection and in the intensity of groundwater withdrawals. In one piezometer nest (at Garfield Park in the Rio Grande inner valley; fig. 6), water-level changes at the water table appear to be affected by land use—in particular, seasonal operation of the irrigation system (Bexfield and Anderholm, 2002b).

The age of most groundwater in the Santa Fe Group aquifer system of the Middle Rio Grande Basin is on the order of thousands of years (fig. 7), as estimated using carbon-14 dating methods (Plummer and others, 2004a, 2004b, 2004c) for water from wells generally screened within about the upper 1,000 ft of the aquifer. (See Section 1 of this report for a discussion of groundwater age and environmental tracers.) Groundwater less than 2,000 years in age typically is found only near known areas of recharge—primarily, basin margins and surface-water features. Chlorofluorocarbons and tritium—indicators of the presence of at least a small fraction of young (post-1950s) recharge—were relatively common at shallow depths within the Rio Grande inner valley, along mountain fronts, and near arroyos (Plummer and others, 2004a). Chlorofluorocarbons and tritium were detected in some samples collected from near the water table beneath upland areas, indicating the potential presence of recharge sources in these areas that have not been well characterized. Overall spatial patterns in groundwater ages indicate that the residence time of most of the groundwater in the basin exceeds 10,000 years (fig. 7), thereby illustrating that the flux of water through the basin is relatively small given the volume of aquifer.



Base compiled from U.S. Geological Survey digital data, 1:100,00 scale, 1977, 1978
National Elevation Data 1:24,000 scale, 2005
City of Albuquerque digital data, 1994
Albers Equal-Area Conic Projection, standard parallels 29°30', 45°30', central meridian 106°40'

0 10 20 30 Miles
0 10 20 30 Kilometers

Figure 4. Groundwater levels representing predevelopment conditions in the Middle Rio Grande Basin, New Mexico.

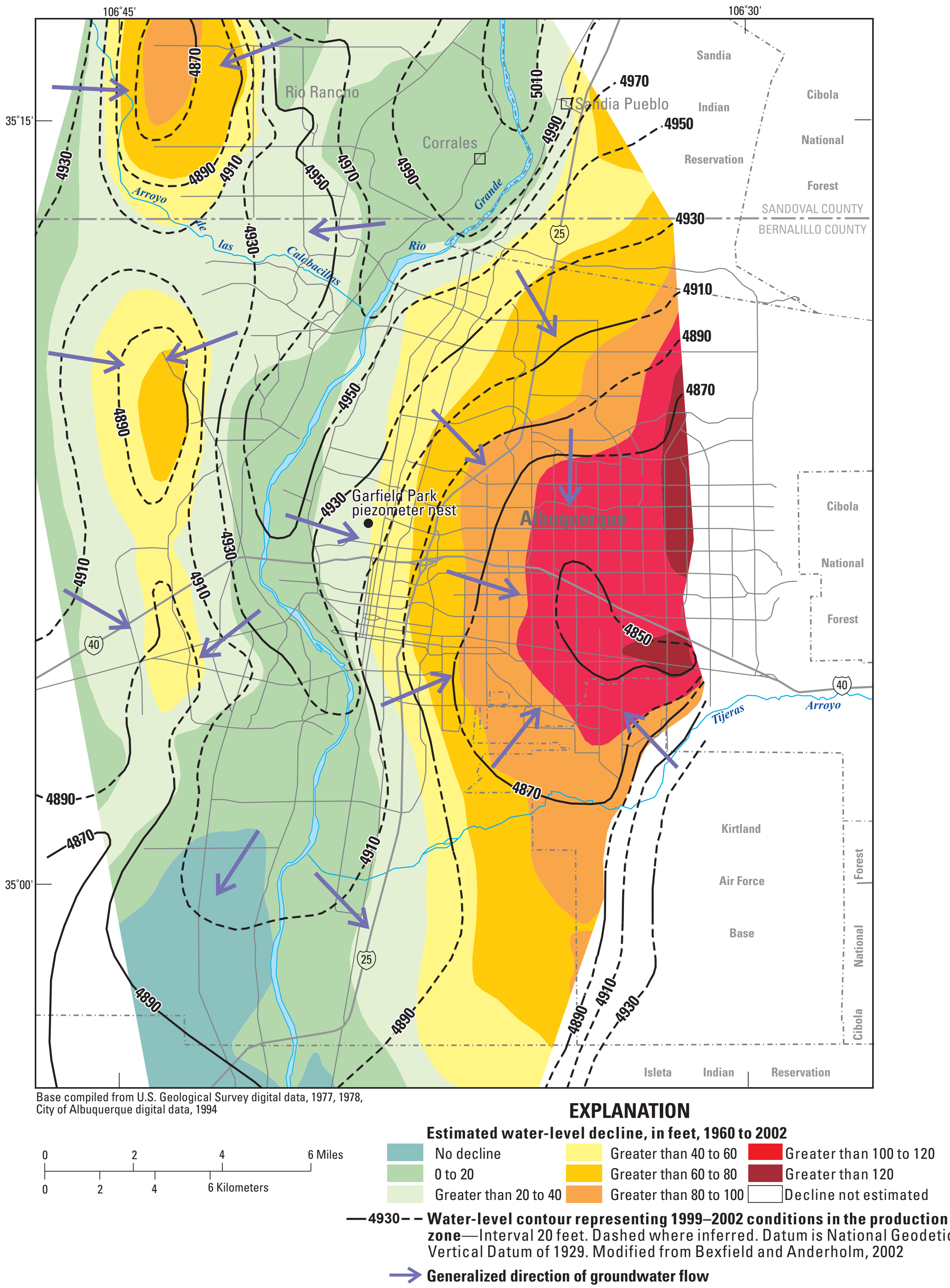


Figure 5. Water levels representing 1999–2002 conditions in the production zone, and estimated water-level declines, 1960 to 2002 , in the Albuquerque area, New Mexico.

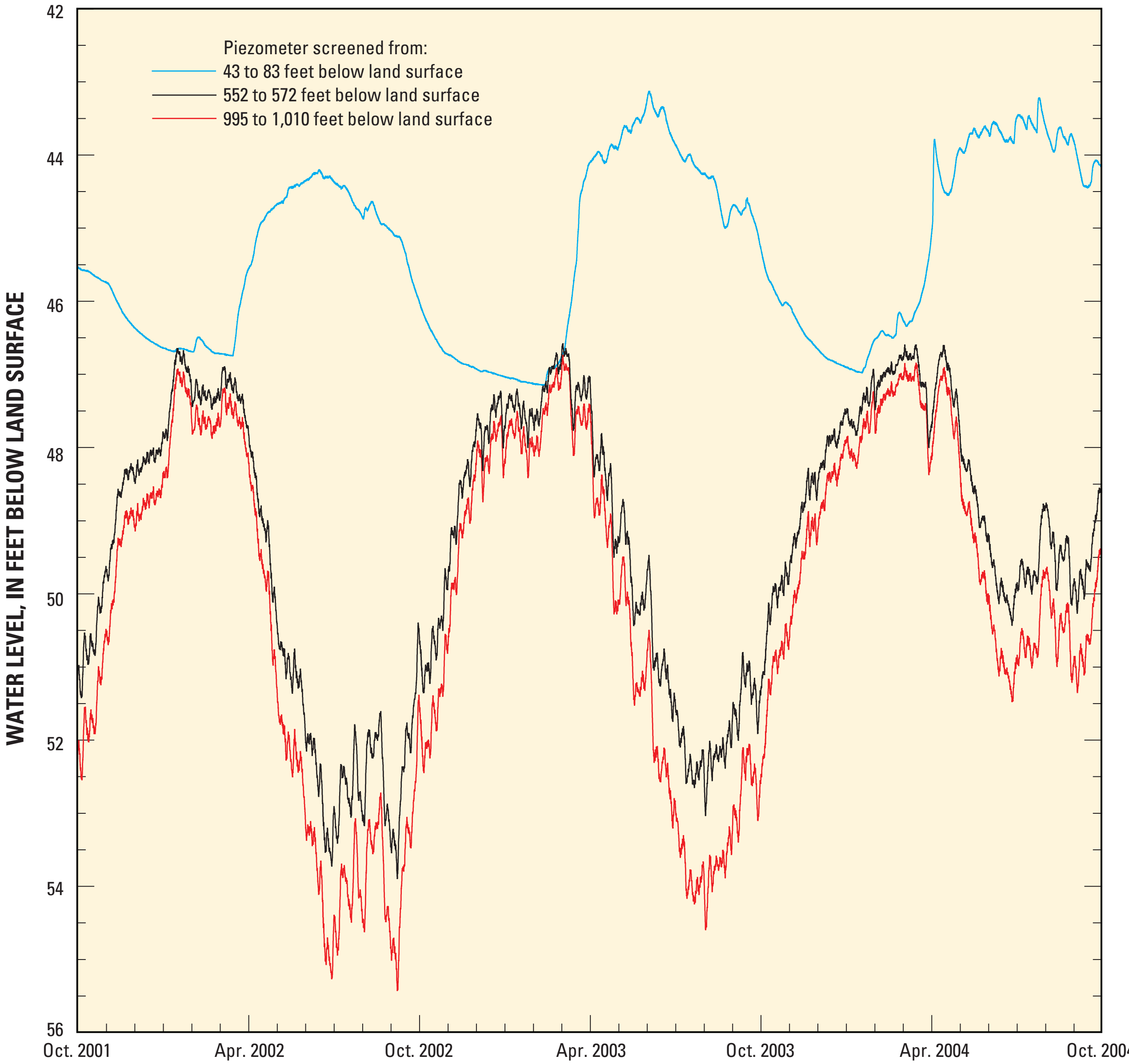


Figure 6. Water levels in the Garfield Park piezometer nest in the Rio Grande inner valley, Albuquerque, New Mexico. Location is shown on figure 5.

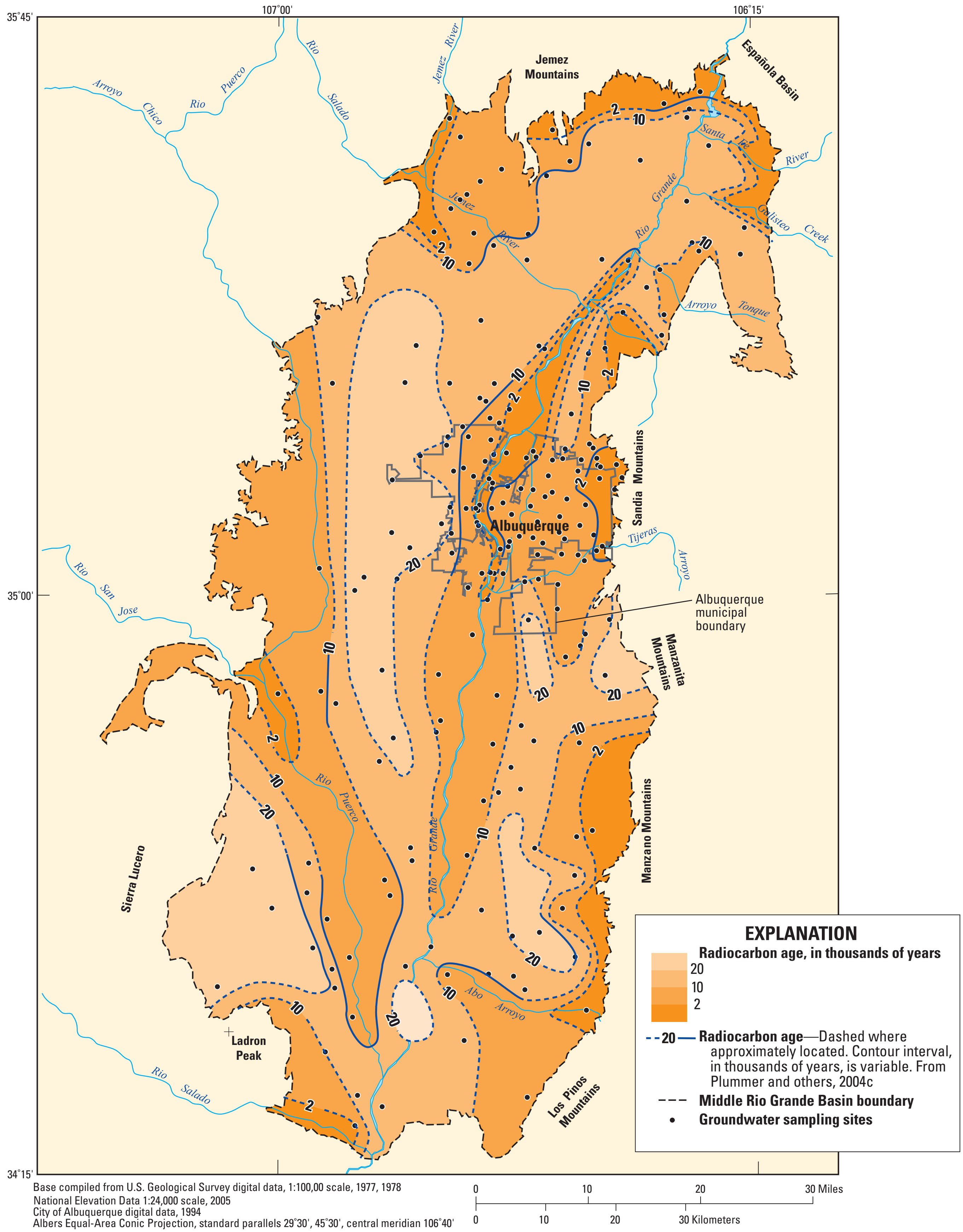


Figure 7. Estimated ages of groundwater in the Santa Fe Group aquifer system of the Middle Rio Grande Basin, New Mexico.

Effects of Natural and Human Factors on Groundwater Quality

Because sediments of the Santa Fe Group aquifer system are relatively unreactive, groundwater quality in the Middle Rio Grande Basin is determined primarily by the source and composition of recharge rather than by geochemical reactions and other processes occurring within the aquifer (Plummer and others, 2004a). Studies by Anderholm (1988), Logan (1990), Bexfield and Anderholm (2002b), and Plummer and others (2004a, 2004b) have illustrated spatial patterns in water chemistry across the Albuquerque area and(or) the basin. Based on primarily patterns in the hydrochemical data from hundreds of wells of various types (public-supply, monitoring, domestic, and other) that were generally screened within about the upper 1,000 ft of the aquifer, Plummer and others (2004a, 2004b) delineated 13 individual hydrochemical zones throughout the basin (fig. 8 and table 3), each with relatively homogeneous groundwater chemistry that is distinct from that in the other zones. Twelve zones represent individual sources of recharge to the basin and are used to facilitate this discussion of water chemistry within the basin. The other zone represents the area in which groundwater from upgradient zones and from depth within the aquifer system converges before discharging to the inner valley or the Socorro Basin to the south.

General Water-Quality Characteristics and Natural Factors

The Northern Mountain Front and Eastern Mountain Front zones of Plummer and others (2004a, 2004b) delineate areas of the basin where groundwater recharges primarily through relatively high-elevation mountain-front recharge processes (shallow subsurface inflow and infiltration through mountain stream channels). Groundwater in these zones has among the smallest dissolved-solids concentrations found in the basin, as indicated by specific-conductance values that typically are less than 400 µS/cm (fig. 9 and table 3). The groundwater chemistry is generally reflective of the chemistry of local precipitation that has undergone some evapotranspiration during recharge (Plummer and others, 2004a). Dissolved-oxygen concentrations indicate that the groundwater is well oxidized; nitrate also is present in most wells, but generally at concentrations less than 1 mg/L. In most areas of the Middle Rio Grande Basin, groundwater continues to be well oxidized even far from sources of recharge and at depths of several hundred feet (figs. 10*A* and 10*B*), probably because of a general paucity of organic carbon in aquifer materials (Plummer and others, 2004a). Arsenic concentrations in the Northern and Eastern Mountain Front zones generally are 3 µg/L or less (fig. 11 and table 3), but locally approach or exceed the drinking-water standard of 10 µg/L. In the Northern Mountain Front zone, most elevated concentrations of arsenic probably are associated with volcanic sources in the Jemez Mountains. In the Eastern Mountain Front zone (and some other areas of the basin), elevated concentrations of arsenic typically are associated with old, deep, mineralized water that upwells along major structural features (Bexfield and Plummer, 2003; Plummer and others, 2004a).

In the Northwestern zone, which delineates groundwater believed to have recharged at relatively low elevations along the Jemez Mountain Front (Plummer and others, 2004a), concentrations of dissolved solids are slightly larger than those found in the Northern Mountain Front zone (table 3). Concentrations of nitrate also are larger, and commonly approach or exceed 5 mg/L. Because there is relatively little human activity in the area, and the age of the groundwater is generally greater than 7,000 years, these concentrations of nitrate likely result from natural sources in precipitation and(or) soils (Plummer and others, 2004a). Concentrations of arsenic commonly approach or exceed 10 µg/L (fig. 11) and probably are primarily associated with volcanism in the Jemez Mountains. Groundwater chemistry in the small Southwestern Mountain Front zone also represents recharge by relatively low-elevation mountain-front processes.

The West Central zone extends southward from the area of the Jemez Mountains through much of the western half of the Middle Rio Grande Basin (fig. 8) and extends at depth beneath adjacent hydrochemical zones to the east. The West Central zone represents relatively old groundwater inflow that entered the basin at depth along the northern margin. Despite the long residence times of the groundwater, concentrations of dissolved solids are moderate throughout much of this zone (specific-conductance values generally are less than 600 µS/cm) (fig. 9 and table 3) and exceed the USEPA's non-enforceable guideline of 500 mg/L in only some wells. Values of pH exceed 8 across broad areas of the West Central zone. The groundwater is generally well oxidized (fig. 10) and contains nitrate at concentrations below 2 mg/L; however, dissolved oxygen and nitrate are below detection in some wells (Plummer and others, 2004a). Groundwater of the West Central zone commonly has concentrations of arsenic greater than the USEPA drinking-water standard (fig. 11); these large concentrations generally are associated with volcanism in the Jemez Mountains and with desorption from metal oxides, especially in areas where pH exceeds about 8.5 (Bexfield and Plummer, 2003; Plummer and others, 2004a). In one well sampled by Plummer and others (2004a), the standard of 30 µg/L for uranium was exceeded.

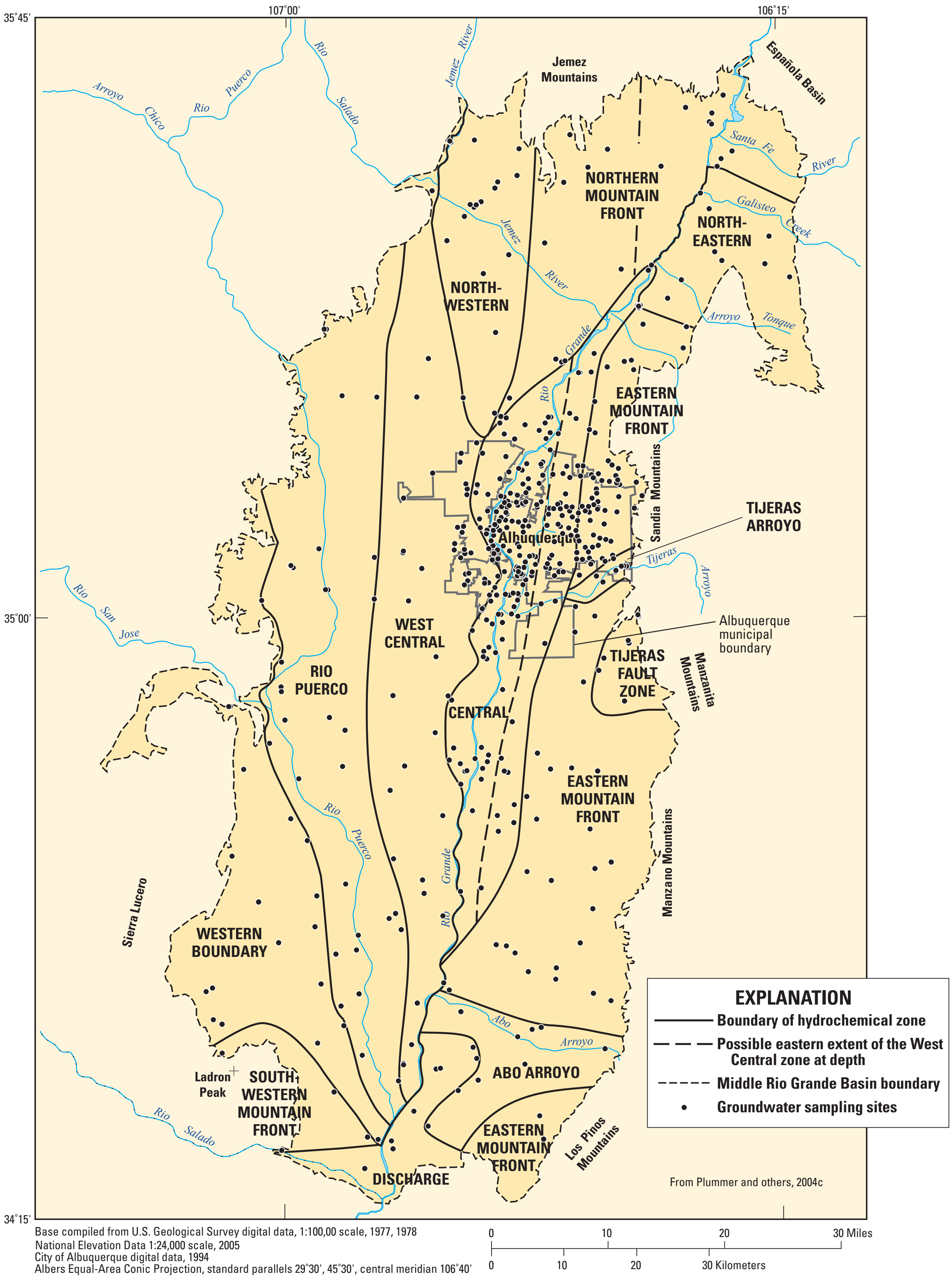


Figure 8. Hydrochemical zones and well sites in the Middle Rio Grande Basin, New Mexico.

Table 3. Median values of selected water-quality parameters by hydrochemical zone for the Middle Rio Grande Basin, New Mexico.

[Specifice conductance is given in microsiemens per centimeter at 25 degrees Celsius (µS/cm at 25°C). **Abbreviations**: µS/cm, microsiemens per centimeter; mg/L, milligrams per liter; µg/L, micrograms per liter; pmC, percent modern carbon]

Hydrochemical zone	Specific conduct-ance (µS/cm)	Field pH	Dissolved oxygen (mg/L)	Ca (mg/L)	Mg (mg/L)	Na (mg/L)	K (mg/L)	Alkalinity (mg/L as HCO_3)	SO_4 (mg/L)	Cl (mg/L)	F (mg/L)	SiO_2 (mg/L)
Northern Mountain Front	340	7.49	5.12	38.5	6.1	20.0	4.9	137	19.5	5.6	0.35	53.3
Northwestern	400	7.84	6.68	33.9	4.2	49.9	5.7	160	44.8	8.5	0.61	30.1
West Central	535	8.22	3.00	12.0	2.5	103	4.2	174	92.0	13.4	0.99	34.5
Western Boundary	4,572	7.70	4.09	135	56.4	589	15.2	300	793.	820	1.64	22.5
Rio Puerco	2,731	7.50	3.73	135	42.7	290	10.4	190	1,080	185.8	0.63	21.8
Southwestern Mountain Front	462	8.11	4.43	52.6	13.5	27.8	2.5	202	53.0	15.0	1.02	17.6
Abo Arroyo	1,055	7.45	6.23	92.5	34.4	49.2	3.1	148	346	25.9	0.90	24.0
Eastern Mountain Front	382	7.67	5.16	45.0	5.1	29.2	2.2	157	31.0	10.5	0.60	28.4
Tijeras Fault Zone	1,406	7.42	4.66	171	36.0	95.0	6.1	599	100	139	1.27	18.9
Tijeras Arroyo	677	7.39	6.97	89.4	24.5	29.3	3.8	240	115	56.6	0.60	19.5
Northeastern	1,221	7.50	6.44	141	29.5	81.8	4.8	208	390	22.7	0.51	38.5
Central	436	7.74	0.12	42.9	8.0	31.0	6.4	158	66.0	16.6	0.44	47.0
Discharge	1,771	7.70	0.08	93.0	31.0	190	10.5	157	290	280	1.40	39.0

Hydrochemical zone	Nitrate (mg/L as N)	As (µg/L)	Fe (mg/L)	Mn (mg/L)	Mo (µg/L)	Sr (mg/L)	U (µg/L)	V (µg/L)	δD (per mil)	$\delta^{18}O$ (per mil)	$\delta^{13}C$ (per mil)	^{14}C (pmC)
Northern Mountain Front	0.56	3.2	0.060	0.005	1.7	0.31	1.0	6.4	-77.7	-10.9	-8.50	33.4
Northwestern	2.44	9.8	0.030	0.002	3.4	0.57	2.7	15.6	-64.7	- 8.73	-6.93	29.6
West Central	1.24	23.2	0.028	0.002	8.2	0.20	3.7	27.9	-96.7	-12.7	-7.18	8.80
Western Boundary	0.86	1.8	0.213	0.041	9.9	2.09	4.4	5.7	-64.4	- 9.12	-4.70	6.19
Rio Puerco	0.88	1.0	0.130	0.015	7.0	3.92	6.0	3.4	-61.6	- 8.51	-7.65	36.4
Southwestern Mountain Front	1.12	0.2	0.030	0.007	3.0	0.86	0.9	1.0	-53.5	- 7.74	-5.76	40.0
Abo Arroyo	1.40	5.2	0.105	0.004	3.4	1.48	5.4	9.5	-65.2	- 9.05	-6.72	24.1
Eastern Mountain Front	0.31	2.0	0.031	0.003	2.0	0.32	3.6	7.5	-81.0	-11.4	-8.70	47.2
Tijeras Fault Zone	1.09	2.2	0.111	0.023	3.7	1.11	7.3	6.3	-74.2	-10.3	-0.98	9.70
Tijeras Arroyo	3.79	1.0	0.050	0.005	1.9	0.47	3.7	3.0	-75.7	-10.3	-6.80	72.8
Northeastern	0.64	2.7	0.170	0.004	6.7	1.72	8.5	3.8	-68.6	- 9.72	-6.40	28.5
Central	0.08	5.4	0.041	0.015	5.0	0.40	3.6	9.3	-95.4	-12.8	-8.87	61.0
Discharge	0.42	9.9	0.080	0.010	10.3	3.02	3.9	7.1	-90.8	-12.1	-7.00	10.8

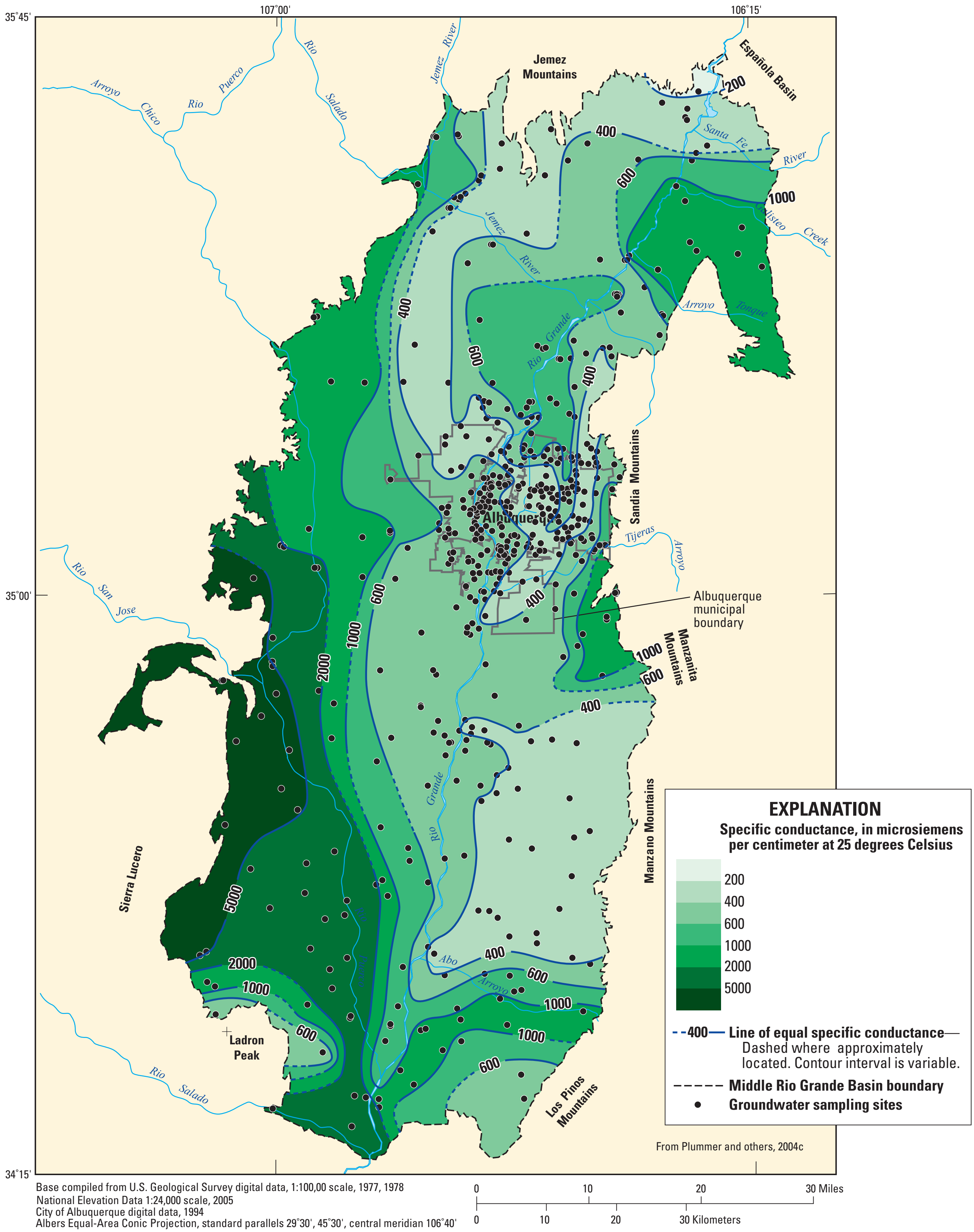


Figure 9. Specific conductance of groundwater in the Middle Rio Grande Basin, New Mexico.

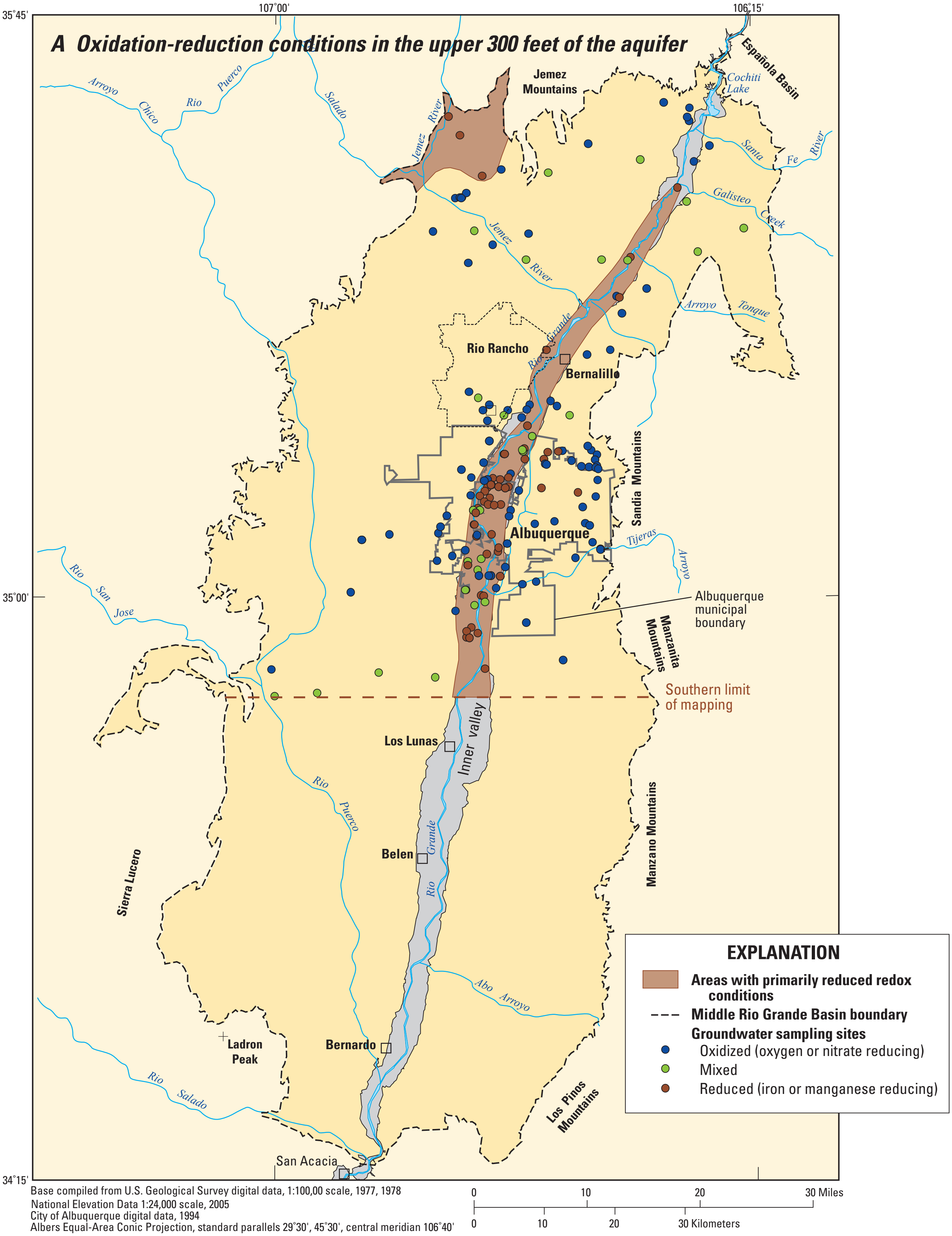


Figure 10. Oxidation-reduction conditions in the Middle Rio Grande Basin, New Mexico. (*A*) Conditions in the upper 300 feet of the aquifer, and (*B*) conditions in the deeper aquifer.

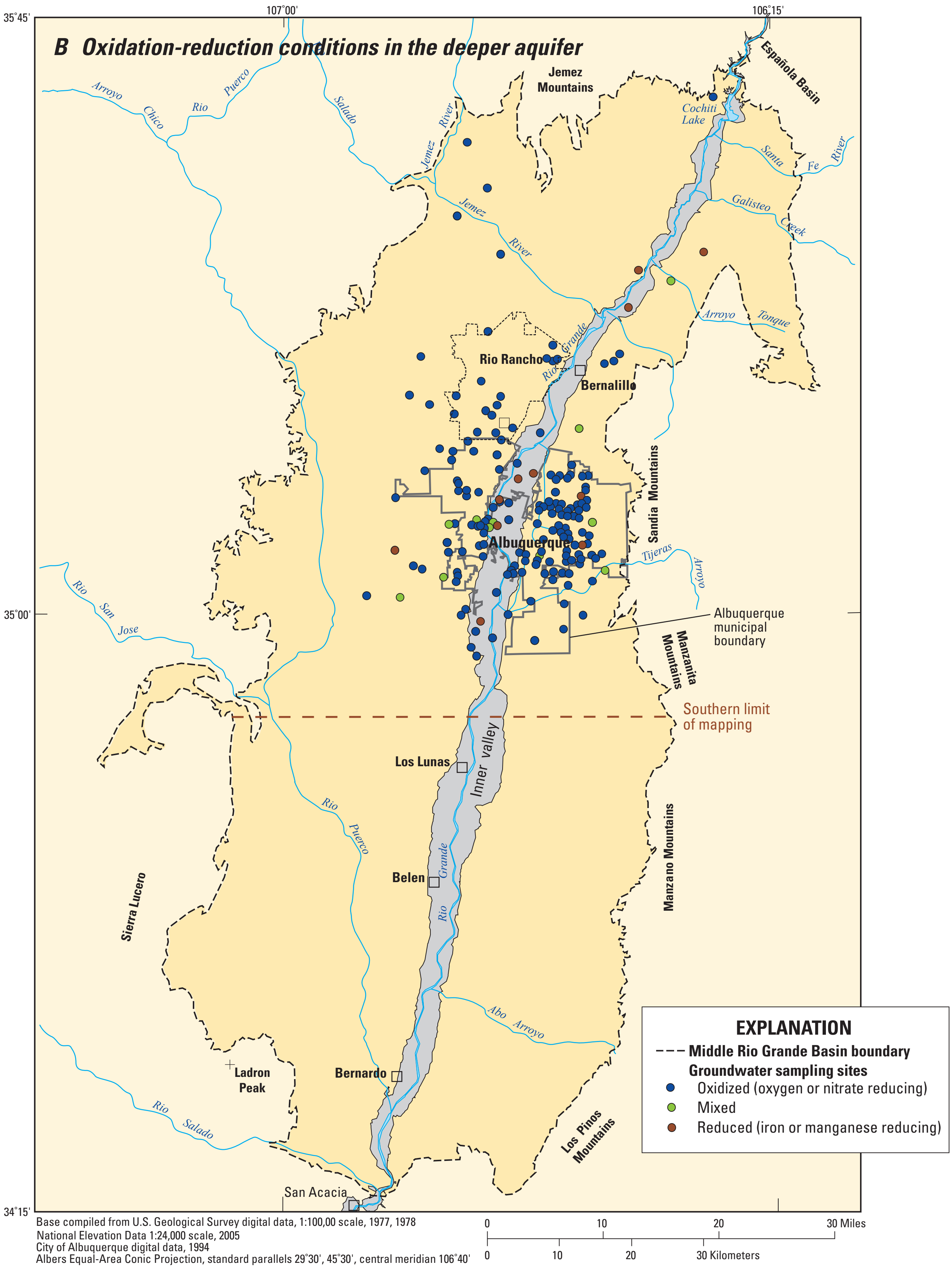


Figure 10. Oxidation-reduction conditions in the Middle Rio Grande Basin, New Mexico. (*A*) Conditions in the upper 300 feet of the aquifer, and (*B*) conditions in the deeper aquifer—Continued.

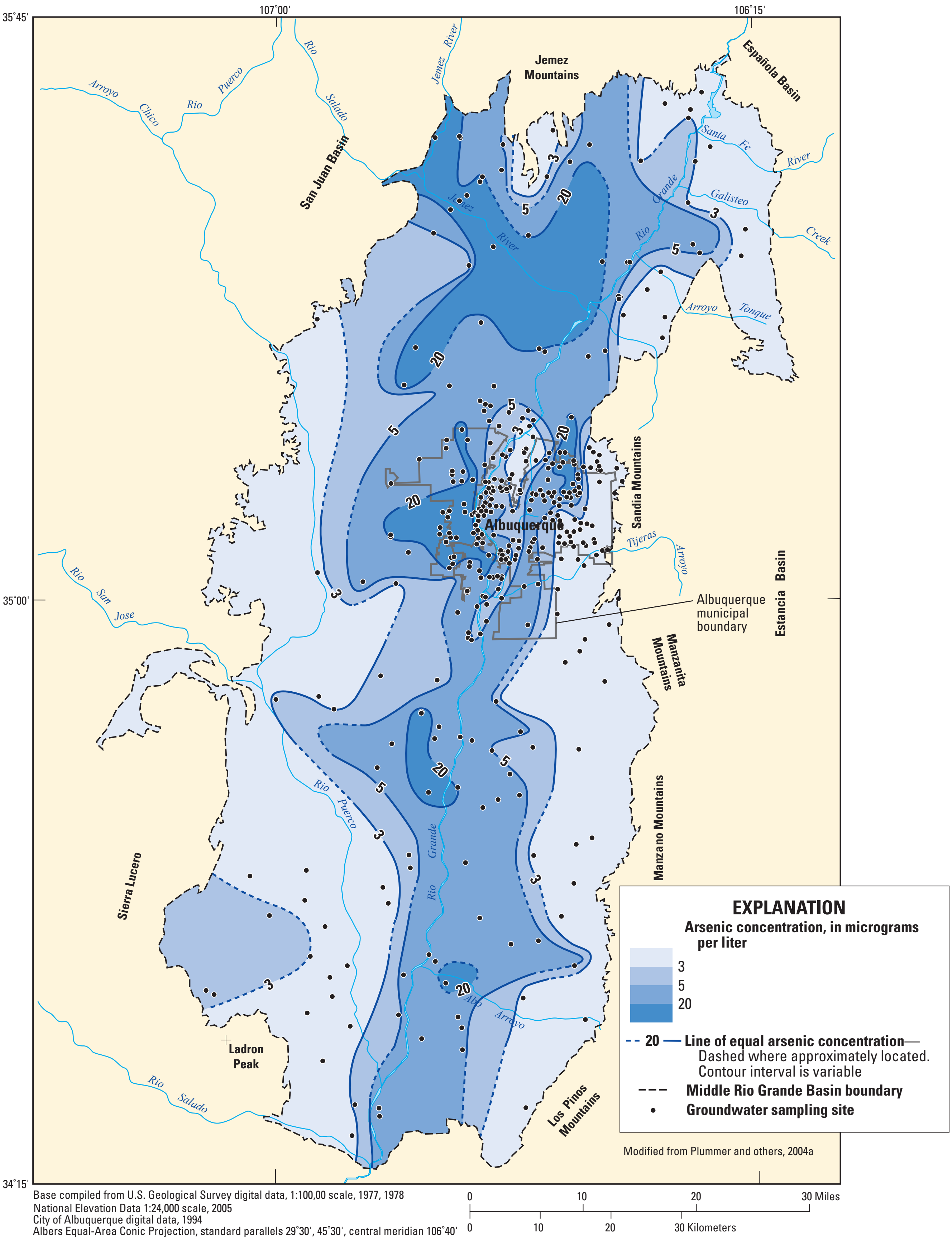


Figure 11. Concentrations of arsenic in groundwater in the Middle Rio Grande Basin, New Mexico.

Groundwater in the Central zone (fig. 8), representing recharge from the Rio Grande and its associated irrigation system, has mostly relatively small to moderate concentrations of dissolved solids (values of specific conductance generally less than 500 µS/cm) (fig. 9 and table 3) that reflect the local surface-water chemistry. Unlike groundwater throughout most of the basin, the water at shallow depths within the Central zone tends to have concentrations of dissolved oxygen and nitrate near or below detection limits (fig. 10*A*), which probably reflects a greater organic-carbon content for sediments within the Rio Grande inner valley and, therefore, greater oxygen and nitrate reduction. Plummer and others (2004a) did, however, detect nitrate at concentrations up to about 5 mg/L in some wells of the Central zone; also, some shallow groundwater had elevated concentrations of dissolved solids (values of specific conductance exceeding 800 µS/cm). Groundwater in the Central zone generally has small to moderate concentrations of arsenic (fig. 11), but concentrations exceed 10 µg/L in some areas, which is probably the result of local upwelling of deep, mineralized water along major faults or over structural highs (Bexfield and Plummer, 2003; Plummer and others, 2004a).

As defined by Plummer and others (2004a, 2004b), six hydrochemical zones are dominated by recharge through groundwater inflow along basin margins or major fault systems and(or) by arroyo infiltration: the Western Boundary, Rio Puerco, Northeastern, Tijeras Fault Zone, Tijeras Arroyo, and Abo Arroyo zones (fig. 8). Concentrations of arsenic tend to be small in all six of these hydrochemical zones (fig. 11 and table 3). With the exception of the Tijeras Arroyo zone, groundwater in these zones generally is not used for public supply because of relatively large concentrations of dissolved solids (values of specific conductance generally exceeding 1,000 µS/cm) (fig. 9 and table 3), probably as a result of either long residence times in more reactive pre-Santa Fe Group rocks (groundwater inflow) or high rates of evapotranspiration (arroyo infiltration). The relatively small area of groundwater that is noticeably influenced by infiltration from Tijeras Arroyo is generally suitable for use in public supplies, although relatively high concentrations of dissolved solids (larger than 500 mg/L) and nitrate (larger than 4 mg/L) occur in some wells in the zone (Plummer and others, 2004a). The larger concentrations of nitrate in the area might result from natural geologic sources (McQuillan and Space, 1995), septic-tank effluent from urbanization of the watershed (Blanchard, 2003), or both. The concentration of uranium in one well sampled by Plummer and others (2004a) in the Rio Puerco zone exceeded the drinking-water standard of 30 µg/L.

Potential Effects of Human Factors

As mentioned in previous sections, the long history of agricultural and urban development in the Middle Rio Grande Basin has resulted in several substantial changes to the hydrologic system, including the following: changes in the source, distribution, and chemical characteristics of recharge to the groundwater system (particularly within the Rio Grande inner valley); changes in the degree of groundwater/surface-water interaction and the magnitudes of associated fluxes of water entering and leaving the groundwater system (again, particularly in the inner valley); and changes in direction and magnitude of hydraulic gradients (particularly in and near Albuquerque). Observed and potential effects of these changes on groundwater quality in the basin are discussed in this section; previously documented effects of human activities on groundwater quality are summarized in table 4.

Irrigated agriculture and its supporting infrastructure have added to the sources and areal extent of groundwater recharge in the Rio Grande inner valley. During predevelopment, recharge in the inner valley occurred only along the wetted Rio Grande channel (although the position of the channel probably shifted frequently). Under modern conditions, recharge occurs not only along the now fixed channel of the river, but also along the unlined irrigation canals criss-crossing the inner valley and across the wider expanse of irrigated fields. Evapotranspiration of irrigation water applied to fields can increase the concentrations of dissolved solids in the excess irrigation water that recharges the groundwater system. This water can also potentially transport to the water table fertilizers and pesticides that were applied to fields. Substantial quantities of the excess irrigation water that reaches the groundwater system (or that runs off fields) can subsequently be captured by the groundwater drain system and transported back to the Rio Grande, along with increased dissolved solids and any agricultural chemicals. This water is then re-diverted into irrigation canals downstream. Agricultural development in the Middle Rio Grande Basin has, therefore, resulted in increased interaction between the groundwater and surface-water systems—in particular, increased fluxes occurring over broader areas—and introduced the means for potential transport of anthropogenic chemicals and increased dissolved solids to shallow groundwater in the inner valley.

One study is known to have been conducted to determine the effects of agricultural practices on shallow groundwater quality in the inner valley of the Middle Rio Grande Basin in particular. Bowman and Hendrickx (1998) found increases in specific conductance and concentrations of nitrate, along with low-level pesticide detections (1 µg/L or less), during the growing season directly beneath the agricultural field being studied in the southern part of the basin (table 4).

Table 4. Summary of documented effects of human activities on groundwater quality in the Middle Rio Grande Basin, New Mexico.

[<, less than; ft, feet; MRGB, Middle Rio Grande Basin; U.S. EPA, United States Evironmental Protections Agency.]

Groundwater-quality effect	Cause	General location(s)	Reference(s)
Elevated concentrations of nitrate	Agricultural fertilizer application	Shallow groundwater (depths < 100 ft) in current or former agricultural areas within the Rio Grande inner valley, including in Bernalillo, Socorro, and Valencia Counties [also found in an agricultural area of the Rio Grande inner valley in Dona Ana County to the south of the MRGB]	Nuttall (1997); Bowman and Hendrickx (1998); McQuillan and Parker (2000); Anderholm (2002)
Elevated concentrations of dissolved solids	Irrigation of agricultural fields	Shallow groundwater (depths < 100 ft) in current or former agricultural areas within the Rio Grande inner valley, including in Bernalillo and Socorro Counties [also found in an agricultural area of the Rio Grande inner valley in Dona Ana County to the south of the MRGB]	Bowman and Hendrickx (1998); McQuillan and Parker (2000); Anderholm (2002)
Detections of agricultural pesticides	Agricultural pesticide application	Shallow groundwater (depths < 100 ft) beneath an irrigated agricultural field in the Rio Grande inner valley in Socorro County [also found in an agricultural area of the Rio Grande inner valley in Dona Ana County to the south of the MRGB]	Bowman and Hendrickx (1998); Anderholm, 2002
Elevated concentrations of nitrate, dissolved solids, and chloride	Septic-tank effluent	Shallow groundwater (depths < 100 ft) in urbanized but unsewered areas, particularly in the Rio Grande inner valley near Albuquerque	McQuillan and Keller (1988); McQuillan and others (1989); Anderholm (1997)
Detections of detergent additives	Septic-tank effluent	Shallow groundwater (depths generally < 100 ft) in urbanized but unsewered areas, particularly in the Rio Grande inner valley near Albuquerque	Kues and Garcia (1995)
Detections of volatile organic compounds	Point sources, including mainly leaky underground storage tanks and industrial sites	Primarily in shallow groundwater (depths < 100 ft) in the Rio Grande inner valley in and near Albuquerque, but also locally at greater depths and (or) outside the inner valley	McQuillan and Keller (1988); Earp (1991); Anderholm (1997); U.S. Department of Energy (1999); McQuillan and Parker (2000); U.S. EPA (2005); U.S. EPA (2006b)
Detections of urban pesticides	Urban pesticide application	Shallow groundwater (depths < 100 ft) in the Rio Grande inner valley in and near Albuquerque	Anderholm (1997)

Bowman and Hendrickx (1998) concluded that these effects were rapidly mitigated by dilution with ambient groundwater and, therefore, that agricultural management practices did not pose a broad threat to the quality of shallow groundwater in the valley. A review of available nitrate data for groundwater beneath a variety of land uses in the Albuquerque area appears to support this conclusion by indicating that concentrations of nitrate were smaller in agricultural land-use settings than in urban or rangeland land-use settings (Anderholm and others, 1995). A plume of nitrate contamination in the South Valley area of southern Albuquerque is, however, believed to be associated with a former vegetable farm (Nuttall, 1997). Also, agricultural use of nutrients has reportedly caused nitrate pollution of groundwater in Bernalillo, Socorro, and Valencia Counties (McQuillan and Parker, 2000).

Results from a National Water-Quality Assessment (NAWQA) Program agricultural land-use study along about a 38-mi reach of the Rio Grande in the Rincon Valley (about 175 mi south of Albuquerque) showed low-level pesticide detections and elevated concentrations of nitrate (up to 33 mg/L) in shallow groundwater that were indicative of likely leaching of agricultural chemicals (Anderholm, 2002). Although this study did not address implications of these results for shallow groundwater quality in other areas of the Rio Grande Valley, the results indicate the potential for similar impacts in other areas with similar hydrogeology and agricultural practices, such as the Middle Rio Grande Basin. Surface-water data from the Anderholm (2002) study showed similar findings of elevated concentrations of nitrate (up to about 3 mg/L in groundwater drains) and low-level pesticide detections, indicating that agricultural practices also have had an effect on surface-water quality in the valley. A recent study of sources of salinity to the Rio Grande from its headwaters to Fort Quitman, Texas, found that a large contributor of river salinization is seepage of deep, sedimentary-origin brines to the river and drains under structural controls (the primary mechanism being movement along faults near the southern ends of structural basins) and that agriculture plays only a secondary role in salinization of the river (Phillips and others, 2003).

One effect of urbanization on the groundwater-flow system of the basin has been to alter flow directions and travel times, primarily in and around Albuquerque. Groundwater withdrawals for public supply and associated declines in hydraulic head have resulted in dominating east-west components of flow away from the Rio Grande inner valley near Albuquerque, in contrast to the primarily north-south flow through the valley area under predevelopment conditions. In some areas, declines in hydraulic head in the production zone have resulted in changes in vertical flow directions (at least during summer months), causing flow into the production zone from both shallower and deeper parts of the aquifer (Bexfield and Anderholm, 2002). Changes in head also have increased the magnitudes of both horizontal and vertical hydraulic gradients over broad areas, thereby decreasing groundwater travel times.

The changes in hydraulic gradients caused by groundwater withdrawals have the potential to affect groundwater quality. For example, changes in hydraulic gradients might exacerbate any existing groundwater-quality problems associated with land use by causing contaminants to spread more quickly across larger areas and to be drawn to greater depths in the aquifer. In particular, contaminants reaching the water table in the inner valley (where the aquifer is most susceptible) could be drawn toward major pumping centers to the east or west. Also, declining heads in the production zone could potentially cause deeper, more mineralized groundwater to move upward and degrade the quality of water used for public supply. A study of changes in 10 chemical parameters in groundwater from 93 City of Albuquerque public-supply wells over a 10-year period (1988–97) found that five parameters had a greater number of upward rather than downward trends among the wells; the opposite was true for the other five. For the five parameters—concentrations of dissolved solids, chloride, sulfate, sodium, and silica—that had more increasing than decreasing trends, the magnitudes of those trends were small (generally less than 1 mg/L), indicating no substantial regional changes in water quality during the time period of study (Bexfield and Anderholm, 2002). Concentrations of arsenic, which are believed to be elevated in deep, mineralized waters of the basin, had more decreasing than increasing trends.

Additional effects of urbanization have been to add potentially substantial new sources of recharge to the groundwater system—seepage from septic tanks, sewer and distribution lines, and turf irrigation, for example—as well as to change the chemical characteristics of some important sources of recharge, such as arroyo infiltration. In addition, urban land uses can result in local water-quality issues where (for example) contaminants produced or released at landfills, industrial operations, military operations, or underground storage tanks are transported to the water table. In the Middle Rio Grande Basin, seepage from various urban water sources would be expected to recharge the aquifer and affect groundwater quality almost exclusively in and near the inner valley of the Albuquerque area, where depths to water are generally within about 30 ft of land surface (Anderholm, 1987) and urban development is extensive. Indicators that groundwater quality has been affected by one or more urban activities would include elevated concentrations of nutrients and(or) dissolved solids and detections of pesticides and VOCs.

McQuillan and Keller (1988) report that septic-tank effluent has resulted in groundwater being contaminated with nitrate and(or) anaerobic respiration byproducts in Albuquerque, Belen, Bernalillo, Corrales, and Los Lunas (table 4). McQuillan and others (1989) concluded that elevated concentrations of dissolved solids, nitrate, and chloride in shallow groundwater in an area of the inner valley of southern Albuquerque were the result of residential development utilizing septic systems. In a study conducted in unincorporated areas of Bernalillo County, Kues and Garcia (1995) detected detergent additives—indicating the likely presence of domestic sewage—in 4 of 15 domestic wells sampled in the inner valley; detections were generally in wells with shallower known depths and were accompanied by relatively high concentrations of ammonia. Anderholm (1997) studied shallow groundwater quality in 30 wells in a NAWQA urban land-use study area in the inner valley near Albuquerque and concluded that infiltration of septic-system effluent had affected the groundwater quality in some areas (based on small concentrations of dissolved oxygen, large concentrations of dissolved organic carbon, and elevated concentrations of chloride).

Anderholm (1997) did not address the effects of specific land uses or of urban recharge sources besides septic-tank effluent on shallow groundwater quality in the inner valley. However, pesticides of primarily urban use were detected in several wells (all in areas of nonagricultural land use), which might reflect infiltration of turf irrigation water and(or) urban runoff from precipitation events (table 4). Elevated concentrations of nitrate and dissolved solids reported by Plummer and others (2004a) in some samples of young, shallow groundwater in the inner valley might be indicative of recent recharge of irrigation water, septic-tank effluent, or other urban recharge sources. Also, elevated concentrations of nitrate have been found in both perched and regional groundwater on Kirtland Air Force Base, southeast of Albuquerque (U.S. Department of Energy, 1999). The sources of elevated nitrate have not been conclusively determined, but suspected sources have included septic tanks and leach fields, waste storage and disposal sites, and landfills (U.S. Department of Energy, 1999).

VOCs indicative of urban recharge sources also have been detected in the basin, primarily in shallow groundwater of the inner valley (table 4). In the South Valley area of Albuquerque, McQuillan and Keller (1988) make reference to about 10 sites at which groundwater was contaminated by VOCs—particularly chlorinated solvents—that are associated with industrial development (which began in the area in the 1950s) and to 20 or more sites of groundwater contamination with petroleum products. McQuillan and Keller (1988) indicate that groundwater contamination in the South Valley area was once limited to depths of about 100 ft or less, but that pumping has drawn contamination to increasingly greater depths. All three sites of groundwater contamination with VOCs that are on the USEPA Superfund list in the Middle Rio Grande Basin are within the inner valley near Albuquerque (U.S. Environmental Protection Agency, 2006), although VOCs also have been detected in groundwater beneath upland areas, including on Kirtland Air Force Base (U.S. Department of Energy, 1999). A network consisting mostly of shallow wells within the inner valley that is monitored by the City of Albuquerque Environmental Health Department (Earp, 1991) has yielded detections of chlorinated solvents and(or) petroleum products in several wells. Although point sources—particularly leaky underground storage tanks—appear to account for most of the cases of groundwater contamination with VOCs in New Mexico (McQuillan and Parker, 2000) and the South Valley area of Albuquerque in particular (McQuillan and Keller, 1988), urban runoff has the potential to contribute VOCs to the aquifer. In the Albuquerque area, stormwater that does not infiltrate locally runs off into a storm-drain system that typically carries the water to concrete-lined drainage channels and(or) natural arroyo channels (Kelly and Romero, 2003; City of Albuquerque, 2007); these channels carry the untreated stormwater to the Rio Grande when flow is sufficient.

The NAWQA urban land-use study by Anderholm (1997) detected low levels of chlorinated solvents and(or) petroleum products or additives in five shallow monitoring wells in the inner valley (table 4). A separate NAWQA study of the quality of deeper groundwater from domestic wells in the Rio Grande inner valley of the Middle Rio Grande Basin and basins to the south detected no VOCs (Bexfield and Anderholm, 1997). However, a NAWQA study of the vulnerability of public-supply wells in the Albuquerque metropolitan area to contamination found very small (subparts per billion) concentrations of VOCs in some supply wells both inside and outside of the inner valley (Carter and others, 2007). Also, concentrations of VOCs have approached or exceeded drinking-water standards in some deep public-supply wells near known chemical releases, resulting in well closures (U.S. Environmental Protection Agency, 2010). As McQuillan and Keller (1988) suggest, the substantial water-level declines that are common in the vicinity of active public-supply wells in the Albuquerque area likely contribute to movement of contaminants beyond the shallow zone of the aquifer. McQuillan and Parker (2000) also state that an increasing number of contamination cases are being discovered in New Mexico in areas where the depth to groundwater is more than 200 ft.

Summary

The Middle Rio Grande Basin is an extensive alluvial basin with a large thickness of relatively unconsolidated aquifer sediments, generally long groundwater travel times, and only local areas of substantial intrinsic groundwater susceptibility to contamination. The groundwater system is hydraulically connected to the through-flowing Rio Grande, which is within an inner valley where depths to water are generally less than 30 ft. Groundwater conditions in the basin-fill aquifer generally are unconfined, although they are semiconfined at depth. Under natural conditions, the aquifer is recharged primarily through infiltration of surface water along the Rio Grande and its major tributaries, mountain-front processes, and subsurface inflow along the basin margins. Because of low precipitation rates relative to evapotranspiration and generally large depths to groundwater, there is little or no direct areal recharge from precipitation across most of the basin. The estimated rate of natural recharge (130,000 acre-ft/yr) is small relative to the volume of the aquifer in the basin, resulting in groundwater travel times that commonly exceed 10,000 years.

A long history of agricultural and urban land uses has had a substantial effect on the groundwater-flow system of the Middle Rio Grande Basin. The estimated annual flux of water entering and leaving the groundwater system has more than quadrupled since predevelopment. Most of this increased flux occurs in the inner valley as a result of the effects of irrigated agriculture and its associated infrastructure, which has also spread recharge across broader areas and affected its chemical composition. Changing hydraulic gradients that have resulted from large groundwater withdrawals for public supplies in and around Albuquerque have induced greater infiltration from the Rio Grande, in addition to changing horizontal and vertical groundwater-flow directions and locally increasing groundwater-flow velocities. Urbanization also has resulted in new sources of recharge (such as septic tanks) and affected the chemical composition of existing sources of recharge.

Groundwater chemistry in the Middle Rio Grande Basin is determined primarily by the source and composition of recharge. Evapotranspiration, geology, and other natural factors in recharge areas have resulted in relatively large concentrations of some contaminants (particularly dissolved solids and arsenic). Human activities have affected the quality of groundwater in some areas, although the general lack of areal recharge results in low susceptibility of the aquifer to anthropogenic contamination across much of the basin. Groundwater susceptibility and vulnerability is highest in the inner valley, where the occurrence of recharge combines with shallow depths to water and intense agricultural and urban activity. Within the inner valley, detections of elevated concentrations of dissolved solids, nitrate, pesticides, and VOCs have been associated with urban and(or) agricultural sources, including septic tanks, industrial activities, and fertilizer use. In most cases, anthropogenic contaminants have migrated only relatively short distances and have been detected only at relatively shallow depths, probably because generally low groundwater fluxes and high horizontal to vertical anisotropy tend to result in slow horizontal and vertical migration, respectively. In some areas, however, increased horizontal and vertical gradients resulting from urban groundwater withdrawals have caused more extensive migration of contaminants, which has affected the quality of water in a small number of public-supply wells. Also, detections of tracers of young groundwater and(or) anthropogenic contaminants in some areas that are located at substantial distances from primary recharge sources and that have relatively large depths to groundwater could imply the existence of local sources of recharge that have not been well characterized. Such detections also could imply that these areas are more susceptible to contamination than most historical studies would appear to indicate.

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