Section 10. - Conceptual understanding and groundwater quality of the basin-fill aquifer in the San Luis Valley, Colorado and New Mexico

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Section 10.—Conceptual Understanding and Groundwater Quality of the Basin-Fill Aquifer in the San Luis Valley, Colorado and New Mexico

By Laura M. Bexfield and Scott K. Anderholm

in

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

Edited by Susan A. Thiros, Laura M. Bexfield, David W. Anning, and Jena M. Huntington

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Basin Overview

The San Luis Valley in southern Colorado and northern New Mexico (fig. 1) has extensive areas of irrigated agriculture overlying a shallow aquifer of relatively high intrinsic susceptibility to contamination that is used for public, domestic, and agricultural supply. Defined for the purposes of this study by the boundary of the basin-fill deposits within the San Luis surface-water basin (fig. 1), the San Luis Valley includes the internally drained San Luis closed basin at the far northern end of the area, along with the northernmost surface-water and alluvial basins drained by the Rio Grande, which enters the San Luis Valley from the west. By means of the Rio Grande, the San Luis Valley is hydraulically connected at its southern end to the Española Basin. Altitudes of the alluvial basins within the San Luis Valley, which cover about 4,900 mi^2, range from about 5,800 ft where the Rio Grande drains the valley at its southern end to nearly 8,900 ft along the margins of the San Juan Mountains on the west and the Sangre de Cristo Mountains on the east (fig. 1). This section will focus on that part of the San Luis Valley within Colorado and particularly on the Alamosa Basin (an alluvial basin that includes both the San Luis closed basin and areas drained by the Rio Grande), which contains most of the valley's agricultural area. The Alamosa Basin lies within the Southern Rocky Mountains Physiographic Province and is considered part of the Rio Grande aquifer system (Robson and Banta, 1995), but has hydrogeologic characteristics similar to those of alluvial basins in the Basin and Range aquifer system of the southwestern United States.

The San Luis Valley is categorized as having an arid to 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 1948–2006 was only 7.1 in. at Alamosa (Western Regional Climate Center, 2006a), although mean annual precipitation for 1957–2005 was 45.4 in. at Wolf Creek Pass in the San Juan Mountains, which border the basin to the west (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 11.0 in. over the alluvial basin area of the San Luis Valley as a whole (McKinney and Anning, 2009). About 44 percent of precipitation within the alluvial basin falls between July and September; winter storms make a large contribution to annual precipitation in the surrounding mountains. Evapotranspiration from a class-A pan during April through October for years 1960 to 1980 at Alamosa averaged 57 in. (Leonard and Watts, 1989). The mean monthly maximum temperature for 1948–2006 at Alamosa was 37.4°F in January and 82.1°F in July (Western Regional Climate Center, 2006a).

In 2000, the total population of the six major counties that lie within the San Luis Valley was about 75,300 (U.S. Census Bureau, 2001a, 2001c), a 33 percent increase from the population of about 56,600 in 1980. The largest cities and towns in 2000 were Alamosa, Colorado; Taos, New Mexico; and Monte Vista, Colorado (U.S. Census Bureau, 2001b, 2001d). Analysis of LandScan population data for 2000 (Oak Ridge National Laboratory, 2005) indicated a population of about 70,200 for the alluvial basin area of the San Luis Valley as a whole (McKinney and Anning, 2009). Areas classified as urban cover less than one percent of the valley. The National Land Cover Database dataset for 2001 (U.S. Geological Survey, 2003) indicated that the dominant land-use types are rangeland, which makes up about 70 percent of the area, and agriculture, which makes up about 20 percent. Most agriculture is concentrated in the western part of the Alamosa Basin (fig. 1). The high rate of evapotranspiration relative to precipitation requires that crops be irrigated throughout the growing season. The most abundant crops grown in the San Luis Valley are alfalfa, native hay, barley, wheat, potatoes, and other vegetables, with rotation of barley or alfalfa and potatoes being common (Anderholm, 1996).

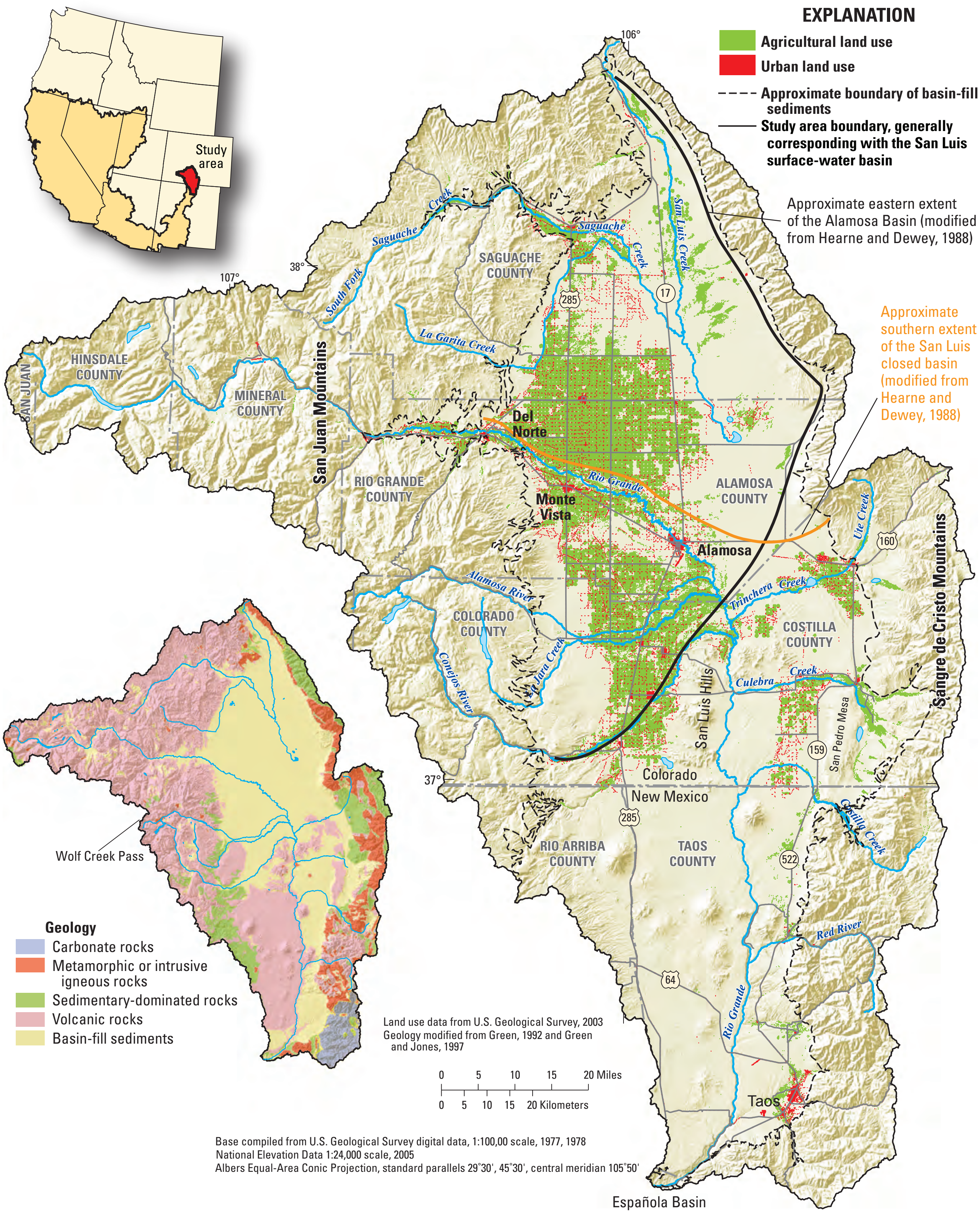


Figure 1. Physiography, land use, and generalized geology of the San Luis Valley, Colorado and New Mexico.

Irrigated agriculture is the largest water user within the San Luis Valley. Water-use estimates by the U.S. Geological Survey (USGS) for 2000 (http://water.usgs.gov/watuse/) indicate that water use for public supply was less than 1 percent of total use. About 54 percent of the water used for irrigated agriculture was surface water, which is diverted from the Rio Grande and smaller tributary streams. Most of the wells pumped for irrigation water are completed in the shallow unconfined aquifer, although the deeper confined aquifer also is commonly used as a source of irrigation water (Emery and others, 1969; Emery and others, 1971a, 1971b; Hearne and Dewey, 1988; Stogner, 2001). USGS estimates indicate that more than 90 percent of all water demand for public supply in the San Luis Valley in 2000 was met by groundwater withdrawals. Public-supply wells pump primarily from the confined aquifer (Emery and others, 1971b), whereas domestic wells commonly pump from the unconfined aquifer (Stogner, 2001). Development of water resources in the San Luis Valley for agricultural and urban purposes has substantially altered processes that recharge the groundwater system and has also affected groundwater movement and discharge.

Groundwater-quality issues that were identified for the San Luis Valley include both naturally occurring contaminants and anthropogenic compounds. As described later in this section, concentrations of dissolved solids are larger than the U.S. Environmental Protection Agency (USEPA) non-enforceable guideline of 500 mg/L (U.S. Environmental Protection Agency, 2009; each time a drinking-water standard or guideline is mentioned in this section, it denotes the citation “U.S. Environmental Protection Agency, 2009”) and as large as 20,000 mg/L in parts of the unconfined aquifer; dissolved-solids concentrations also can exceed 500 mg/L in upper parts of the confined aquifer. Nitrate concentrations in shallow groundwater of the unconfined aquifer exceed the background concentration of 3 mg/L (Stogner, 2001)—and even the USEPA drinking-water standard of 10 mg/L—across large areas in the western part of the Alamosa Basin, likely as the result of the application of fertilizer to crops. Naturally elevated concentrations of uranium and(or) gross alpha activities have been detected in groundwater from shallow monitoring wells completed in the unconfined aquifer, as have elevated arsenic concentrations. With respect to anthropogenic compounds, pesticides (both agricultural and nonagricultural herbicides and insecticides) have been detected at generally low concentrations in shallow parts of the unconfined aquifer beneath agricultural areas.

Water Development History

Although irrigated agriculture has been practiced in the Alamosa Basin at least since the arrival of Spanish settlers in the 1630s, irrigated acreage remained small until the 1880s (Hearne and Dewey, 1998). From about 1880 to 1890, extensive networks of canals and irrigation structures were built to divert water from the Rio Grande and its tributaries, resulting soon afterward in the diversion of all available natural flow from these streams to irrigate agricultural fields, primarily in the central part of the Alamosa Basin (Powell, 1958; Hearne and Dewey, 1988; Stogner, 2001). Several reservoirs also were constructed on the Rio Grande, the Conejos River, and other tributaries starting in the early 1900s to help match water supplies to irrigation needs, typically by storing water during spring months and releasing it to canals late in the summer (Colorado Division of Water Resources, 2004). Before the 1970s, a common method of irrigation using surface water was subirrigation, whereby sufficient water was applied to raise the water table to the root zone of the growing crops, about 1 to 3 ft below land surface (Powell, 1958; Hearne and Dewey, 1988; Stogner, 2001). However, subirrigation soon resulted in waterlogging and alkali damage of soils, forcing a shift in irrigated agriculture to higher land to the west by about 1915 (Powell, 1958). Another consequence of irrigating the west side of the basin with surface water was substantial rise in water levels, estimated to be as great as 50 to 100 ft across areas of the Rio Grande alluvial fan (Powell, 1958). The groundwater divide that separates the San Luis closed basin from areas to the south might have developed as a result of irrigation on the Rio Grande alluvial fan, and the location of the divide probably migrates north and south partly in response to changes in irrigation-return flow in the area (Hearne and Dewey, 1988).

Groundwater also has been used to irrigate crops in the Alamosa Basin since at least 1904, when water from the confined aquifer was noted to be of economic importance for agriculture in several areas of the basin (Powell, 1958). At the time of his study, Powell (1958) had documented 586 flowing wells and 61 pumped wells that were completed in the confined aquifer for use in irrigation. Irrigation water reportedly has been pumped from the unconfined aquifer since 1903 (Powell, 1958). However, utilization of water from the unconfined aquifer did not increase markedly until severe droughts of the 1930s and 1950s forced farmers to supplement surface-water supplies (Stogner, 2001). The number of irrigation wells completed in the unconfined aquifer rose from 176 by 1936 to about 1,300 by 1952 and more than 2,300 by 1980 (Powell, 1958; Stogner, 2001). By the late 1960s, subirrigation was no longer effective because the increase in withdrawals from the unconfined aquifer had lowered the water table (Stogner, 2001). A dramatic increase in the use of center-pivot sprinkler systems for irrigation started in the 1970s; the number of such systems rose from 262 in 1973 to 1,541 in 1980 and almost 2,000 in 1990 (Hearne and Dewey, 1988; Stogner, 2001). These systems, which generally rotate overhead sprinklers around a point in the center of a 160-acre field, allow more precise application of water. They generally use groundwater pumped from the unconfined aquifer and have largely replaced flood irrigation in the southern part of the San Luis closed basin, where they are particularly common (Anderholm, 1996).

The amount of surface water used to irrigate crops in the Alamosa Basin varies from year to year depending on total irrigated acreage and climatic factors that affect crop water requirements and surface-water availability (fig. 2) (Wilson, 2004). Irrigated acreage in the Colorado part of the Rio Grande drainage generally increased between 1950 and 2002, averaging about 581,000 acres (Wilson, 2004). The average annual surface-water diversion for irrigation between 1950 and 2002 was about 1,077,000 acre-ft; the annual supply-limited consumptive use averaged about 395,000 acre-ft (Wilson, 2004). The use of groundwater to help meet irrigation requirements increased steadily between 1950 and 2002, with the average annual diversion of groundwater at about 543,000 acre-ft and the average annual consumptive use at about 365,000 acre-ft (Wilson, 2004). During periods when surface water supplied to individual farms exceeds crop demands, some irrigation districts and ditch companies in the area encourage diversion of surface water into recharge pits at the edges of agricultural fields, thereby helping to maintain water levels in the unconfined aquifer (Miller and others, 1993).

Most of the water used for drinking, domestic purposes, and stock needs in the Alamosa Basin is groundwater. Powell (1958) reported that the first wells used for these purposes were completed in the unconfined aquifer; however, only four years after confined conditions were discovered by accident in 1887, an estimated 2,000 flowing wells had been completed in the confined aquifer, mostly for domestic water uses. At the time of his study, Powell (1958) documented a total of six public-supply wells completed in the confined aquifer, producing about 720 million gallons annually from depths ranging from 365 ft to 1,802 ft below land surface. Emery and others (1971b) found records of 11 wells completed in the confined aquifer and four wells completed in the unconfined aquifer in use for public supply in the Colorado portion of the San Luis Valley. All of the larger cities and several of the smaller towns in the area now rely on public-supply wells (Colorado Division of Water Resources, 2004); at least 76 municipal supply wells have been permitted in the Colorado part of the San Luis Valley (Harmon, 2000). Using city and county population estimates combined with representative per capita use by month and a consumptive use factor of 0.4, Wilson (2000) estimated total consumptive water use in 1995 for combined municipal, domestic, commercial, and public purposes to be about 5,800 acre-ft, which equates to withdrawals of about 14,000 acre-ft. Harmon (2000) indicated that about 600 wells had been permitted for domestic or related uses in the Colorado part of the San Luis Valley and estimated that these wells pump about 530 acre-ft/yr.

Groundwater also is pumped from the San Luis Valley in association with the Closed Basin Project. This project pumps water from the unconfined aquifer in areas of natural groundwater discharge in the San Luis closed basin and delivers the water to the Rio Grande through a series of channels and pipelines. The Closed Basin Project is designed to “salvage” water that otherwise would have been lost to “nonbeneficial” evapotranspiration by lowering the water table (Leonard and Watts, 1989; Harmon, 2000). The salvaged water is then used to help meet Colorado’s obligations under the Rio Grande Compact of 1929. Pumping for the Closed Basin Project averaged about 22,560 acre-ft/yr between 1986 (the first year of operation) and 1997, when 168 wells were included in the project (Harmon, 2000).

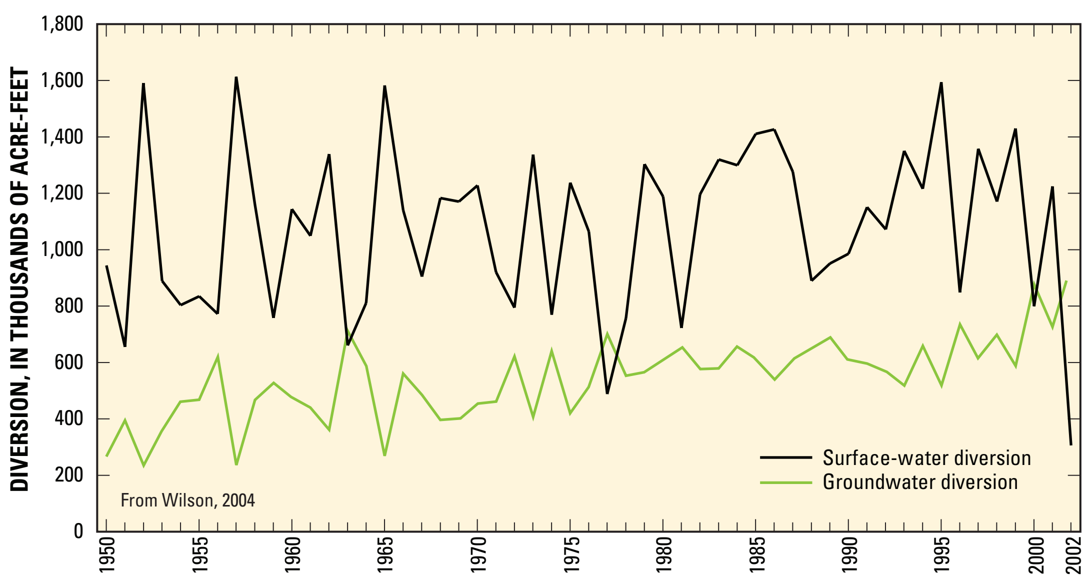


Figure 2. Estimated annual diversions of surface water and groundwater for irrigation in the Colorado part of the San Luis Valley, 1950 to 2002.

Hydrogeology

The San Luis Valley is a major physiographic and structural feature formed by crustal extension along the generally north-south trending Rio Grande Rift. The valley is downfaulted along the Sangre de Cristo Mountains that border the valley on the east and hinged along the San Juan Mountains that border the valley on the west (Emery and others, 1971a) (fig. 1). The Sangre de Cristo Mountains consist largely of Precambrian, Paleozoic, and Mesozoic igneous and metamorphic rocks, whereas the San Juan Mountains consist of a thick sequence of volcanic rocks that underlie and intertongue with sedimentary rocks within the San Luis Valley (Hearne and Dewey, 1988).

The Alamosa Basin at the north end of the San Luis Valley is divided into eastern and western subbasins, the Baca and Monte Vista grabens, respectively, by an uplifted fault block known as the Alamosa horst (fig. 3). Except where indicated, the following information on the valley-fill deposits of the Alamosa Basin is derived from the discussion by Leonard and Watts (1989), which incorporates the conclusions of several previous investigations. The maximum thickness of valley-fill deposits is about 10,000 ft in the western subbasin, about 5,400 ft over the Alamosa horst, and about 19,000 ft in the eastern subbasin. As mentioned previously, the Alamosa Basin includes the San Luis closed basin on the north. At the southern end, the Alamosa Basin is hydraulically separated from the Costilla Plains and the Taos Plateau by the San Luis Hills (Hearne and Dewey, 1988). Faults, which are common in the Alamosa Basin, might affect groundwater movement by acting as barriers to horizontal flow (Huntley, 1976) and(or) as conduits for vertical movement (Mayo and Webber, 1991).

The basin fill of the Alamosa Basin comprises alluvial sedimentary rocks and Tertiary volcanic rocks (fig. 3). The oldest sequence of alluvial sedimentary rocks is the Eocene to Oligocene deposits of the Vallejo Formation, which is present only in the western part of the basin and consists of reddish fluvial clay, silt, sand, and gravel. The Vallejo Formation is overlain by an eastward-thinning wedge of heterogeneous volcanic and volcaniclastic rocks of the Oligocene Conejos Formation (McCalpin, 1996; Mayo and others, 2007), which is in turn overlain by the Fish Canyon and Carpenter Ridge Tuffs of Oligocene age (Leonard and Watts, 1989; Mayo and others, 2007).

The basin-fill deposits of the Santa Fe and Los Pinos Formations, which range in age from Oligocene to Pliocene, are as thick as 10,000 ft in the eastern subbasin of the Alamosa Basin (McCalpin, 1996). The Los Pinos Formation forms an eastward thickening wedge along the eastern border of the San Juan Mountains, consisting of sandy gravel with interbedded volcaniclastic sandstone and tuffaceous material. The Santa Fe Formation, which is predominant in the eastern part of the Alamosa Basin and intertongues with the Los Pinos Formation, consists of buff to pinkish-orange clays with interbedded, poorly to moderately sorted silty sands.

The Alamosa Formation of Pliocene and Pleistocene age overlies the Santa Fe and(or) Los Pinos Formations across most of the Alamosa Basin. The Alamosa Formation, which is up to about 2,050 ft thick, consists of discontinuous beds of clay, silt, sand, and gravel of mixed fluvial, lacustrine, and eolian origin (Leonard and Watts, 1989; McCalpin, 1996); these deposits generally become more fine grained toward the topographic low of the San Luis closed basin. Within the Alamosa Formation, the position of the uppermost blue clay or fine-grained sand, the top of which is generally between 60 and 120 ft below land surface, typically is used to assign the division between the shallow, unconfined aquifer and the deeper, confined aquifer. Pleistocene and Holocene deposits that overlie the Alamosa Formation are similar in lithology and represent eolian reworking of valley floor deposits, alluvial fan deposition, and deposition in stream channels (McCalpin, 1996; Mayo and others, 2007).

Conceptual Understanding of the Groundwater System

The groundwater system of the San Luis Valley has been most thoroughly studied—and is most intensely utilized—in Colorado, and particularly in the Alamosa Basin. In general terms, the groundwater system of the Alamosa Basin includes two main aquifers—the shallow, unconfined aquifer that is present across the entire basin, and the deeper, confined aquifer that is present everywhere except along the basin margins. Although the division between the two aquifers usually is defined by the top of the uppermost blue clay or fine-grained sand in the Alamosa Formation, Hearne and Dewey (1988) emphasize that groundwater conditions in the basin are complex because the overall aquifer system is really a heterogeneous mixture of aquifers and leaky confining beds, each of limited areal extent. Two separate flow systems also are present in the basin—one in the San Luis closed basin and one in the part of the Alamosa Basin that is drained by the Rio Grande.

Depths to water are fairly small throughout the Alamosa Basin. In 1969, Emery and others (1973) measured depths to water of 12 ft or less throughout much of the basin, although depths to water exceeded 12 ft along the basin margins. During 1997–2001, depths to water in the intensively cultivated area north of the Rio Grande ranged from less than 5 ft to more than 25 ft (fig. 4). Depths to water throughout the basin respond to seasonal variations in recharge and discharge (Emery and others, 1973; Leonard and Watts, 1989; Stogner, 2005).

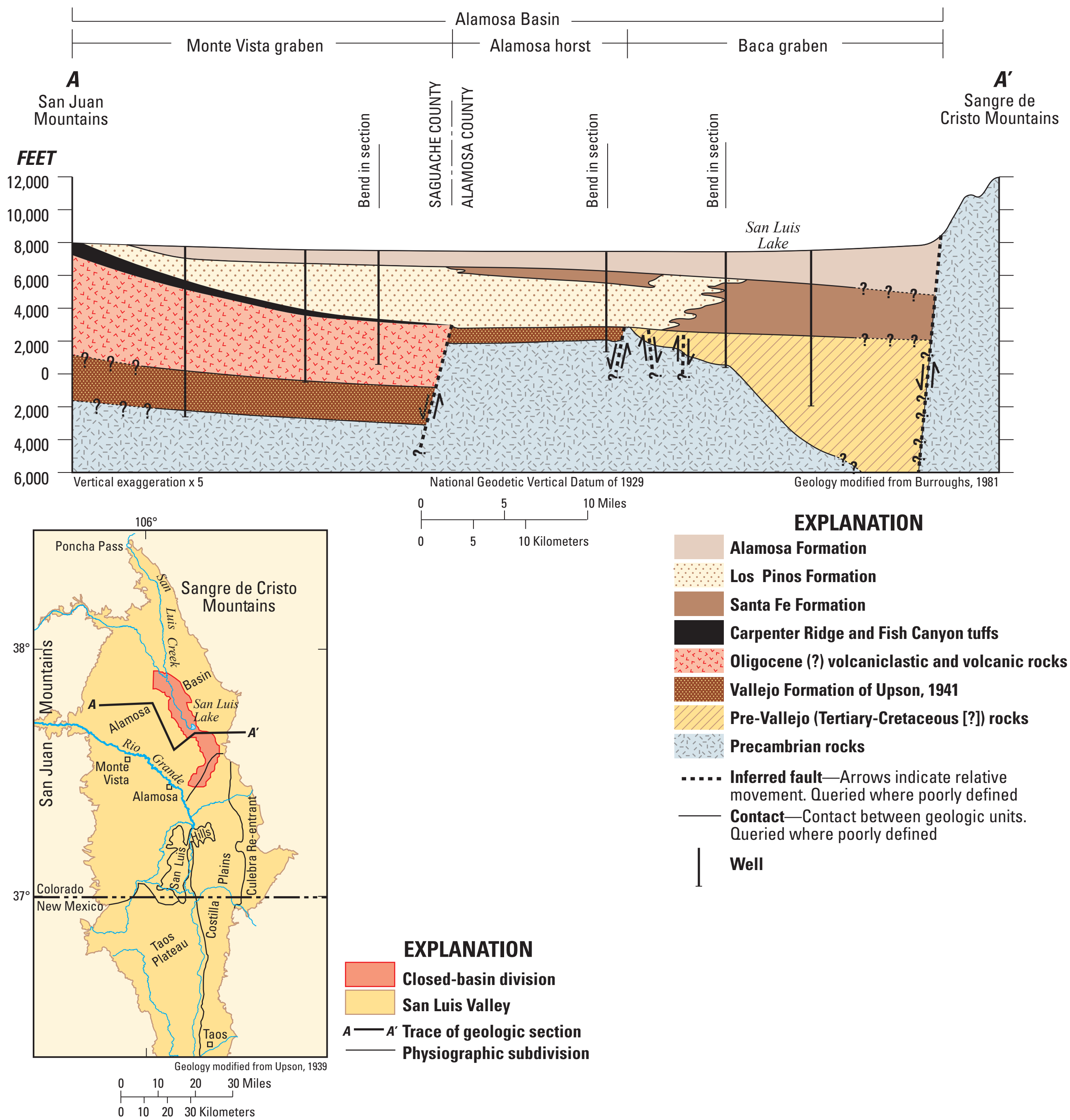


Figure 3. Generalized geologic section for the Alamosa Basin, Colorado.

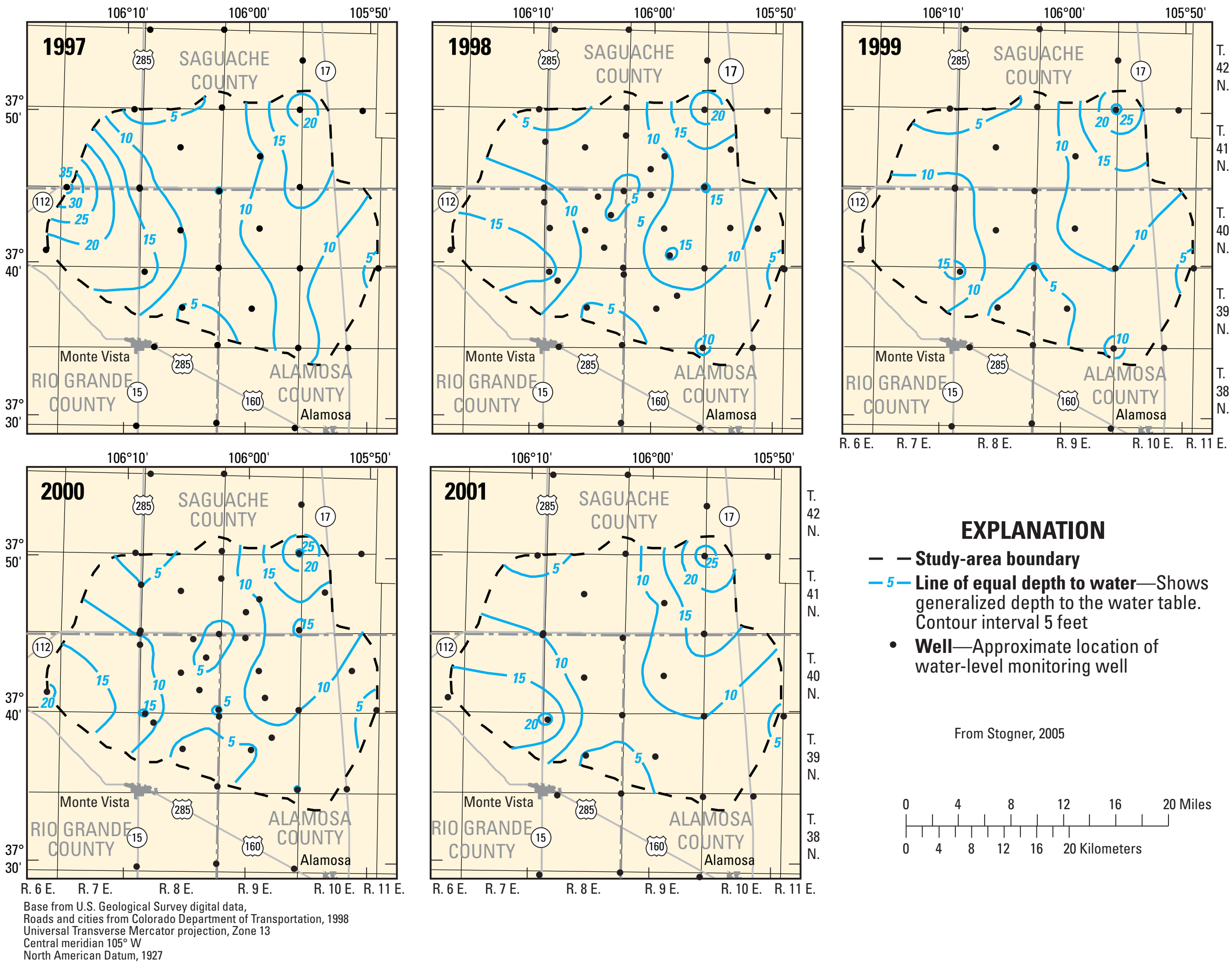


Figure 4. Depths to water in the unconfined aquifer in June 1997–2001 for part of the Alamosa Basin, Colorado.

On the basis of results of aquifer tests and specific-capacity tests, Emery and others (1973) estimated transmissivity values in the unconfined aquifer in most of the Alamosa Basin from about 700 ft^2/d near basin margins to about 30,200 ft^2/d in the western part of the basin, north of the Rio Grande; estimated transmissivity values in the confined aquifer generally ranged from about 13,400 to more than 160,800 ft^2/d. The Colorado Division of Water Resources (2004) groundwater-flow model (hereinafter, “the CDWR model”) for the Colorado part of the San Luis Valley assigns individual values of horizontal hydraulic conductivity to each of four layers in 26 “parameter zones” and to a single fifth layer that represents the lower Santa Fe Formation. Horizontal hydraulic conductivity values range from 0.1 ft/d for the lower Santa Fe Formation (layer 5) to 400 ft/d for coarse Rio Grande alluvium and alluvial fan deposits (both layer 1); most values range between 5 and 100 ft/d. Ratios of horizontal to vertical hydraulic conductivity in the CDWR model range from 2:1 to 10,000:1.

Water Budget

Investigators have developed water budgets for modern conditions in the groundwater system in various parts of the San Luis Valley. Three of these budgets represent overall inflow to and outflow from the area of study, rather than the groundwater system alone: Emery and others (1973) presented a budget for the Colorado part of the San Luis Valley, Huntley (1976) presented a budget for the San Luis closed basin, and Hearne and Dewey (1988) presented a budget for the Alamosa Basin. An estimated budget compiled for the CDWR groundwater-flow model of the Colorado part of the San Luis Valley represents inflow to and outflow from the groundwater system of the modeled area (table 1), and is, therefore, the focus of this discussion.

Also discussed in this section is a newly estimated predevelopment water budget for the groundwater system of the Colorado part of the San Luis Valley (table 1).

Table 1. Estimated modern water-budget components for the Colorado Division of Water Resources (2004) groundwater-flow model of the San Luis Valley, Colorado, and predevelopment water-budget components newly derived from documentation of the Colorado Division of Water Resources (2004) groundwater-flow model.

[All values are in acre-feet per year and are rounded to the nearest thousand. The predevelopment budget is intended only to provide a basis for comparison of the overall magnitudes of recharge and discharge between predevelopment and modern conditions, and does not represent a rigorous analysis of individual recharge and discharge components. Percentages of water-budget components are illustrated on figure 5. GIS, geospatial information system; CDWR, Colorado Division of Water Resources]

	Predevelopment	Modern (1970-2002)	Change from predevelopment to modern
Budget component		**Recharge**	
Canal and lateral leakage (including canals without GIS data)	0	290,000	290,000
Surface-water irrigation	0	291,000	291,000
Groundwater irrigation	0	158,000	158,000
Rim recharge (margin streams and creeks not explicitly modeled as streams)	[1]166,000	166,000	0
Precipitation	[2]50,000	70,000	20,000
Surface-water runoff from irrigation	0	17,000	17,000
Streams (natural streams, drains and canals modeled as streams)	[3]71,000	124,000	53,000
Constant flux (Subsurface inflow from eastern and western boundaries)	[1]113,000	113,000	0
Wells	0	2,000	2,000
Flowing wells and springs	0	45,000	45,000
Total recharge	[4]399,000	[4]**1,275,000**	**876,000**
Budget component		**Discharge**	
Streams (natural streams, drains and canals modeled as streams)	[4]57,000	77,000	20,000
Constant flux (Subsurface outflow through layers 1-3 of southern boundary)	[1]36,000	36,000	0
General head (flow from layer 4 of southern boundary)	[1]13,000	13,000	0
Wells	0	623,000	623,000
Flowing wells and springs	[1]4,000	75,000	71,000
Subirrigation meadow	0	97,000	97,000
Subirrigation alfalfa	0	32,000	32,000
Native evapotranspiration	[5]289,000	389,000	100,000
Total discharge	**399,000**	[4]**1,341,000**	[4]**942,000**
Change in aquifer storage (total recharge minus total discharge)	0	-66,000	-66,000

[1]Value assumed to have changed insignificantly between predevelopment and modern conditions; equivalent to value used in the CDWR (2004) groundwater flow model.

[2]Value calculated by adjusting the formula used in the CDWR (2004) groundwater flow model to include no irrigated lands; possible elevation differences between irrigated and non-irrigated lands were not considered.

[3]Value equivalent to results of "no pumping" scenario of the CDWR (2004) groundwater flow model.

[4]Values do not total up exactly because of rounding.

[5]Value estimated by applying a reduction that maintained the same ratio used in the CDWR (2004) model between stream gain and native evapotranspiration, while balancing total discharge with total recharge.

This budget is intended only to provide a basis for comparison of overall magnitudes of recharge and discharge between predevelopment and modern conditions, and does not represent a rigorous analysis of individual recharge and discharge components. The budget was developed by changing the CDWR model budget as deemed appropriate to remove influences of development on the system. All explicitly anthropogenic recharge sources were removed (that is, all recharge from irrigation and irrigation infrastructure). Rim recharge, which results from infiltration of water from the channels of stream along the basin margins that were not explicitly modeled as streams, and constant fluxes representing groundwater inflow along the basin margins were assumed to be unchanged. Precipitation input was adjusted by changing the 10 percent infiltration of precipitation assumed by the CDWR method for irrigated lands during the growing season to the 3 percent infiltration assumed by the same method for non-irrigated lands, without attempting to account for differences in precipitation resulting from elevation. Stream infiltration was adjusted to match the infiltration simulated by the "no pumping" scenario of the CDWR model. This quantity of infiltration is believed to be reasonable because most stream infiltration under natural conditions probably occurred in areas near the basin margins, where groundwater levels generally have not risen enough as a result of irrigation to substantially affect stream infiltration.

Discharge components of the CDWR water budget were removed or adjusted to represent predevelopment conditions. In particular, all components related to wells (both pumped and flowing), subirrigation, and flow to drains were removed. The constant flux and general head components representing flow into New Mexico at the south end of the model were assumed to be virtually unchanged. Because stream gains simulated by the "no pumping" scenario of the CDWR model are likely to be greatly influenced by the simulated application of irrigation water, these simulated gains were not used in the estimated predevelopment budget. Instead, the reduction in discharge required to balance the overall recharge to the groundwater system was applied to both stream gain and native evapotranspiration using the ratio between these two values in the original CDWR budget. This method, therefore, assumes that neither stream gain nor native evapotranspiration increased disproportionally to the other as a result of development; both discharge components would be likely to have increased in the study area as a whole because agricultural development occurred both within and outside the San Luis closed basin. A small spring discharge component was maintained to reflect average annual spring discharges estimated for the CDWR model. Individual components of recharge to and discharge from the groundwater system under both predevelopment and modern conditions are illustrated in the conceptual diagrams of regional groundwater flow in figure 5.

Under natural conditions, subsurface inflow—primarily from the relatively permeable rocks of the San Juan Mountains on the west—was one of the largest sources of recharge to the groundwater system of the Alamosa Basin (Huntley, 1976; Hearne and Dewey, 1988). Almost 90 percent of the total 113,000 acre-ft/yr groundwater inflow simulated by constant-flux boundaries (table 1) in the CDWR model is from the San Juan Mountains. The quantity of recharge to both the unconfined and confined aquifers from subsurface inflow probably has not changed substantially between predevelopment and modern conditions. Leakage of groundwater upward from the confined aquifer in the central part of the basin was an additional source of recharge to the unconfined aquifer under natural conditions; despite changes in hydraulic head caused by withdrawals from both aquifers, upward leakage continues to be a source of water to the unconfined aquifer. Using a hydrologic budget for the San Luis closed basin, Emery and others (1975) estimated leakage from the confined to the unconfined aquifer across the area to be about 0.6 ft/yr.

Although depths to water are small throughout most of the Alamosa Basin, low precipitation rates combined with high evaporation rates result in only a small contribution of precipitation to groundwater recharge (Emery and others, 1973; Leonard and Watts, 1989). For the CDWR model, higher percentages of infiltration were assumed for precipitation falling on irrigated lands during the growing season (10 percent) and for the sand dune area (21 percent) than for irrigated and non-irrigated lands outside the growing season (3 percent). Also, by taking elevation into account, the resulting value for recharge from precipitation was about 70,000 acre-ft/yr (table 1). Adjustments to represent predevelopment conditions, when no irrigation-wetted lands would be present to enhance infiltration, resulted in a value of about 50,000 acre-ft/yr (table 1). Some water—including precipitation—that infiltrates along the margins of the valley migrates downward to recharge the confined aquifer that underlies the central part of the valley (Leonard and Watts, 1989; Anderholm, 1996) (fig. 5).

Infiltration of surface water is an important source of recharge to both the unconfined and confined aquifers of the San Luis Valley. The Rio Grande, which had a mean annual discharge of about 648,000 acre-ft for the period 1909–2006 where it enters the Alamosa Basin near Del Norte (USGS digital data for 1909–2006), gains water along most of its course through the valley (Hearne and Dewey, 1988). However, several smaller streams enter the valley from the surrounding mountains and lose substantial quantities of water to the aquifer, particularly near the basin margins (fig. 5).

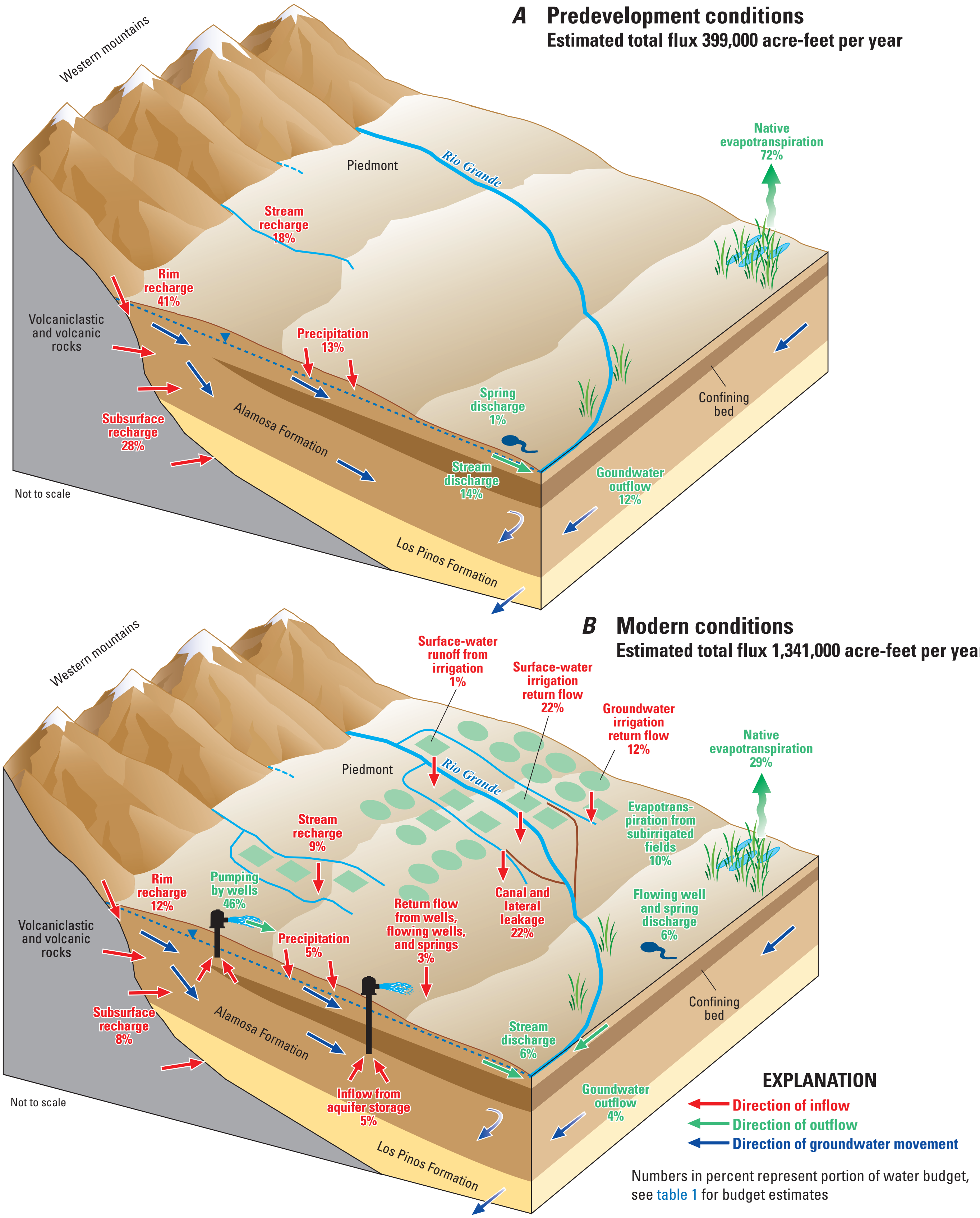


Figure 5. Generalized diagrams for the Alamosa Basin, Colorado, showing the basin-fill deposits and components of the groundwater system under (*A*) predevelopment and (*B*) modern conditions.

In the San Luis closed basin, these streams include Saguache, San Luis, and La Garita Creeks (Anderholm, 1996). In the part of the Alamosa Basin drained by the Rio Grande, important streams include the Conejos River, Alamosa River, and La Jara Creek, all originating in the San Juan Mountains, and Trinchera Creek, which flows out of the Sangre de Cristo Mountains. Along the margins of the valley, downward flow of water that originated as stream infiltration to the unconfined aquifer is a substantial component of recharge to the confined aquifer (Leonard and Watts, 1989; Anderholm, 1996).

Infiltration of water from streams flowing across the margins of the San Luis Valley was the primary source of surface-water recharge to the groundwater system under predevelopment conditions. For the CDWR model, this component of recharge was represented in part by a “rim recharge” term for all streams and creeks that were not explicitly represented in the model (table 1). This term, which should be unchanged between predevelopment and modern conditions, was estimated to be about 166,000 acre-ft/yr from information about precipitation rates and the drainage areas of surface-water basins along the valley margins. An unspecified portion of stream infiltration near the valley margins also is included in the approximately 124,000 acre-ft/yr of recharge from streams that are explicitly represented in the model (table 1); data provided in the CDWR model documentation indicate that about two-thirds of this amount likely represents infiltration from natural streams (as compared with canals and drains).

The development of irrigated agriculture has resulted in combined infiltration of applied irrigation water and canal leakage as the primary means through which surface water recharges the groundwater system—primarily the unconfined aquifer—under modern conditions (table 1 and fig. 5). Through surface-water diversions for irrigation, water from the Rio Grande is delivered throughout much of the Alamosa Basin; more than 180,000 acre-ft is diverted annually into the Rio Grande Canal that feeds the San Luis closed basin (Colorado Division of Water Resources, 2004). Most or all natural flow in tributaries is diverted for irrigation as well, resulting in recharge through canals and fields across broad areas, rather than at focused points along the mountain fronts. Leonard and Watts (1989) and Emery and others (1971a) state that return flow of irrigation water is now the single largest source of recharge to the unconfined aquifer in the Alamosa Basin. The CDWR model indicates that irrigation water applied to fields results in about 466,000 acre-ft/yr of recharge to the aquifer; canal and lateral leakage adds about 290,000 acre-ft/yr of recharge.

Agricultural and urban development has introduced additional sources of recharge to the groundwater system in the Alamosa Basin. Agricultural development has added infiltration of water that is pumped from the unconfined or confined aquifer and then applied to crops. Likely minor sources of recharge resulting from urbanization include seepage from septic tanks, sewer and water-distribution lines, and turf irrigation. Based on the estimated predevelopment flux through the groundwater system of about 399,000 acre-ft/yr through the Colorado part of the San Luis Valley (table 1), activities and practices associated with agricultural and urban development have more than tripled fluxes of water through the system.

Prior to the start of groundwater pumping, discharge from the unconfined aquifer of the Alamosa Basin took place primarily through evapotranspiration (Hearne and Dewey, 1988); in the San Luis closed basin, evapotranspiration was the only substantial means of discharge (Huntley, 1976 and 1979). Because the water table is close to the land surface throughout large areas of the Alamosa Basin, evapotranspiration can occur through direct evaporation of groundwater as well as through transpiration by phreatophytes. Most evapotranspiration is focused in the central, topographically low part of the Alamosa Basin, and particularly in the “ancestral sump” area of the San Luis closed basin (although groundwater pumping for the Closed Basin Project has recently lowered water levels and reduced evapotranspiration in this area). Because application of irrigation water has raised water levels across broad areas (Powell, 1958; Hearne and Dewey, 1988), evapotranspiration from the groundwater system of the San Luis Valley has increased overall as a result of agricultural development. The CDWR model simulates native evapotranspiration as about 389,000 acre-ft/yr and evapotranspiration from subirrigated meadows and crops as 129,000 acre-ft/yr. For the estimated predevelopment water budget of table 1, adjustment of the evapotranspiration component to balance groundwater inflows resulted in an estimated evapotranspiration of about 289,000 acre-ft/yr.

Direct groundwater discharge from the Alamosa Basin as underflow to areas to the south is believed to be small because of the relative impermeability of the San Luis Hills. Similarly, underflow from the southern tip of the San Luis Valley (as defined in fig. 1) to the Española Basin probably is relatively small; the hydrologic connection is primarily by means of the Rio Grande. Because the southern boundary of the CDWR model is the state line between Colorado and New Mexico, a component of groundwater underflow across that boundary is required to balance the model’s budget for the groundwater system. The value of 49,000 acre-ft/yr (table 1) for this underflow is not likely to have changed substantially between predevelopment and modern conditions. The CDWR model also simulates discharge to springs, which is one means of discharge from the confined aquifer of the valley. The relatively small discharge of 4,000 acre-ft/yr for two major springs that are not explicitly represented as streams was not changed for the estimated predevelopment budget of table 1. Natural discharge from the confined aquifer to the unconfined aquifer through upward leakage is not explicitly represented in the budgets of table 1.

Besides evapotranspiration by native vegetation, the other relatively large component of discharge from the groundwater system of the San Luis Valley under natural conditions was outflow from the unconfined aquifer to streams. This component applies only to areas south of the San Luis closed basin, where the Rio Grande (the major surface-water feature) generally gains water as it traverses the valley (Hearne and Dewey, 1988). The overall quantity of discharge to surface-water features has increased under modern conditions as a result of larger fluxes of water through the groundwater system and locally higher water levels associated with crop irrigation, although pumping has likely intercepted some groundwater that would otherwise have discharged to the Rio Grande. The CDWR model simulates about 77,000 acre-ft/yr of groundwater flowing to streams and agricultural drains. For the estimated predevelopment water budget of table 1, adjustment of the stream discharge component to balance groundwater inflows resulted in an estimated flow of about 57,000 acre-ft/yr to streams.

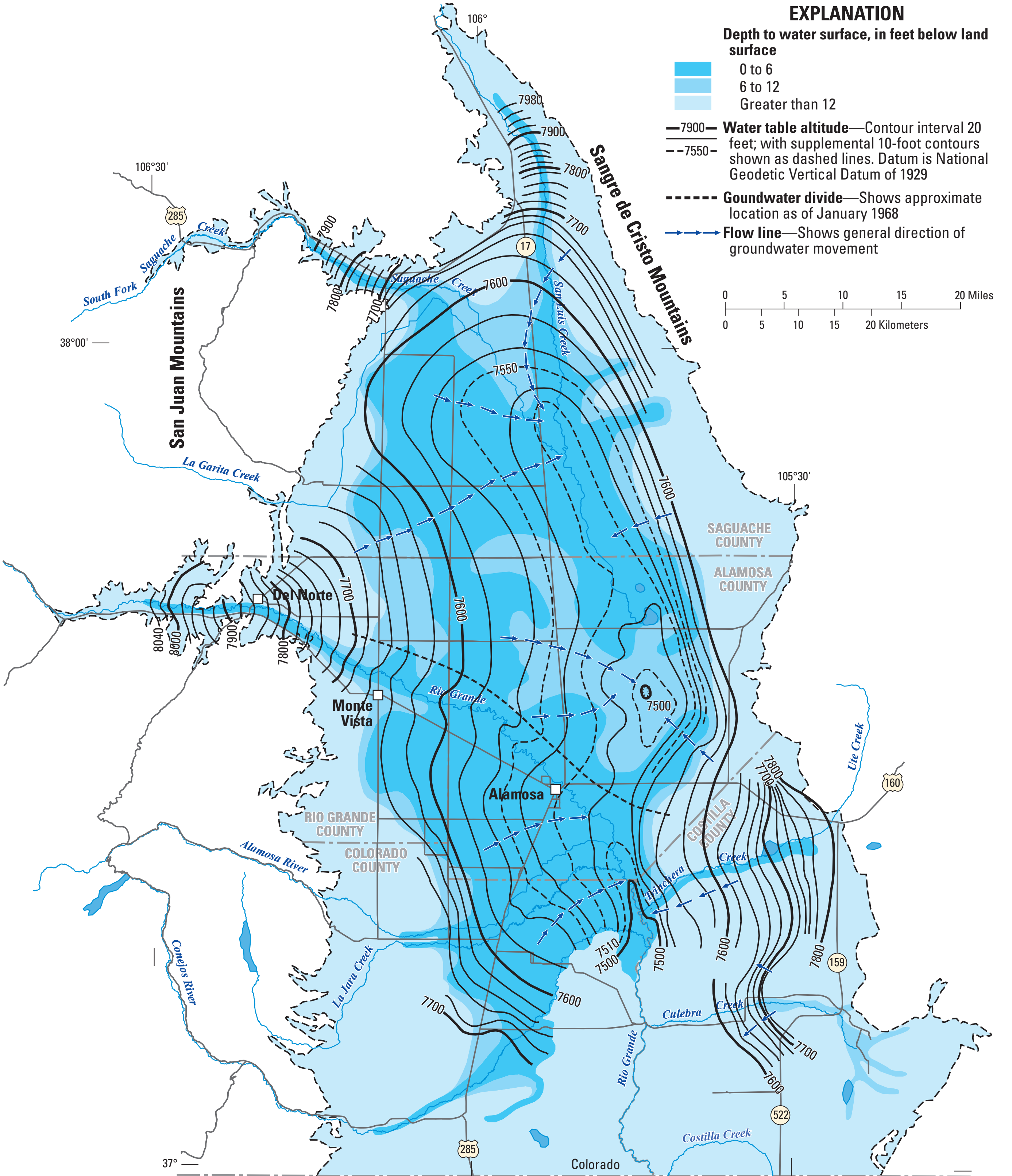
The substantial use of groundwater in the San Luis Valley since about the 1950s, primarily for crop irrigation, has resulted in pumping becoming the largest component of discharge from the groundwater system under modern conditions. Documentation for the CDWR model indicates that about 52 percent of all wells in the San Luis Valley are completed in the unconfined aquifer and about 25 percent are completed in the upper few hundred feet of the confined aquifer. Despite state-imposed moratoriums on the construction of new high-capacity wells in the confined aquifer in 1972 and in the unconfined aquifer in 1981 (Colorado Division of Water Resources, 2004), the CDWR model simulates discharge by "pumping" wells at about 623,000 acre-ft/yr (table 1). Flowing wells cause a much smaller net discharge of water from the aquifer because a portion of flowing well discharge is unconsumed and is assumed to recharge the unconfined aquifer. Ultimately, because a portion of the large quantity of groundwater applied to crops is lost to evapotranspiration, the net effect of application of groundwater for irrigation is a decrease in the quantity of groundwater in the basin (Anderholm, 1996). As a result of this development of the groundwater resource, the CDWR model simulates a 66,000 acre-ft annual reduction in the quantity of water in aquifer storage.

Groundwater Flow

Water-level maps for 1968 conditions (Emery and others, 1971a) (fig. 6) and 1980 conditions (Crouch, 1985) in the unconfined aquifer of the San Luis Valley illustrate that groundwater flows generally from the eastern, western, and northern margins of the valley (the primary predevelopment recharge areas) toward its central axis. In the San Luis closed basin, flow is toward the topographic low known as the "ancestral sump" area, where natural saline lakes and salt deposits provide evidence of a great quantity of evapotranspiration. Small quantities of groundwater might also flow across the southern boundary of the closed basin (Leonard and Watts, 1989). In the southern part of the Alamosa Basin, groundwater flows primarily toward the Rio Grande, where most discharge occurs, and southward toward the Costilla Plains and Taos Plateau. Contours of the potentiometric surface in the confined aquifer (Emery and others, 1973) indicate that horizontal groundwater-flow directions are similar to those in the unconfined aquifer. Although the vertical flow of groundwater is downward in the recharge area around the perimeter of the Alamosa Basin (Hearne and Dewey, 1988), in the central part of the basin, hydraulic heads in the confined aquifer are higher than in the unconfined aquifer, resulting in upward leakage (Emery and others, 1973; Hearne and Dewey, 1988).

Groundwater pumping from the unconfined aquifer in the Alamosa Basin has caused some decline in water levels, particularly during years when surface water is in short supply for irrigation. Declines were apparent as early as 1980 in parts of the closed basin (Crouch, 1985). These declines are also evidenced by the reduction in groundwater storage simulated by the CDWR groundwater-flow model for the Colorado part of the San Luis Valley and by the calculations of Stogner (2005) indicating that the volume of water in the unconfined aquifer in part of the San Luis closed basin was about 10 percent less during 1997–2001 than it was during 1948–49. Maps of the 1997–2001 conditions in the unconfined aquifer in part of the closed basin (Stogner, 2005) illustrate that local water-level declines (and, therefore, decreases in saturated thickness) have occurred at least seasonally in this area.

With respect to the confined aquifer, Emery and others (1973) conducted an evaluation to determine whether substantial declines in hydraulic heads or changes in vertical gradients had occurred as a result of the removal of water through flowing wells or withdrawals for public supply. No evidence of widespread, long-term changes in heads or vertical gradients was found at that time. Although long-term water-level data are available for several wells in the confined aquifer of the San Luis Valley through at least 2000 (Colorado Division of Water Resources, 2004; Brendle, 2002), no subsequent investigations are known to have focused on reevaluation of this issue.



Base compiled from U.S. Geological Survey digital data, 1:100,00 scale, 1977, 1978
National Elevation Data 1:24,000 scale, 2005
Albers Equal-Area Conic Projection, standard parallels 29°30', 45°30', central meridian 105°50'

Modified from Emery and others, 1971a

Figure 6. Groundwater levels that represent 1968 conditions in the unconfined aquifer of the San Luis Valley, Colorado.

Studies of groundwater age in the Alamosa Basin indicate that water in the unconfined aquifer typically contains a substantial fraction of young recharge (fig. 7A) (see Section 1 of this report for a discussion of groundwater age and environmental tracers). Mayo and others (2007) found that the tritium content of groundwater in the unconfined aquifer generally decreased from the mountain fronts toward the valley, consistent with the direction of flow inferred from water levels. They concluded that 50–100 years was a reasonable estimate of travel time from the San Juan Mountain front to the "ancestral sump" area of the San Luis closed basin, a distance of about 30 mi. Using tritium, chlorofluorocarbons, and carbon-14, Rupert and Plummer (2004) concluded that many water samples from the unconfined aquifer in the area of the Great Sand Dunes represented mixtures of young (post-1941) and old recharge, and that it took more than 60 years for the old fraction of groundwater to travel from the mountain front to the far side of the dunes, a distance of about 7 mi. Stogner (2005) used data on hydraulic gradients and aquifer properties for his study area in the closed basin to estimate a theoretical travel time of 400 years for a distance of 23 mi. Unpublished USGS data for chlorofluorocarbons in groundwater near the water table beneath agricultural areas in the San Luis Valley indicate substantial components of young water, recharged within the past 12–40 years prior to sampling.

Carbon-14 ages estimated by Mayo and others (2007) for water in the confined aquifer are generally older than 5,000 years—even relatively close to the mountain fronts—and become progressively older toward the central part of the Alamosa Basin, exceeding 27,000 years in some areas (fig. 7B). Carbon-14 age estimates by Rupert and Plummer (2004) of 4,300 and 30,000 years for two wells completed in the confined aquifer near the Great Sand Dunes indicated a similar age range.

Effects of Natural and Human Factors on Groundwater Quality

Groundwater quality in the San Luis Valley is determined by the source and composition of recharge and the processes occurring along a flow path, which are particularly important in the unconfined aquifer of the Alamosa Basin. Studies by Emery and others (1973), Edelman and Buckles (1984), Williams and Hammond (1989), Anderholm (1996), Stogner (1997, 2001, 2005), and Mayo and others (2007) have illustrated patterns in concentrations of dissolved solids and(or) nitrate for various parts of the valley. Anderholm (1996) and Stogner (2001) also discuss detections of organic compounds associated with human activities (volatile organic compounds [VOCs] and[or] pesticides) in groundwater of the Alamosa Basin.

General Water-Quality Characteristics and Natural Factors

The natural sources of groundwater recharge along the perimeter of the San Luis Valley tend to have low concentrations of dissolved solids, nitrate, and trace elements and tend to be oxidized. Mayo and others (2007) indicated that streams entering the valley typically have concentrations of dissolved solids less than 100 mg/L. The concentrations of dissolved solids in mountain springs, which might be indicative of groundwater underflow into the San Luis Valley, tend to be less than 200 mg/L (Mayo and others, 2007). The low concentrations of dissolved solids of stream infiltration, groundwater inflow, and precipitation recharging along the valley perimeter are reflected in both the unconfined and confined aquifers in this area, where groundwater commonly has values of specific conductance less than 250 µmhos/cm and(or) concentrations of dissolved solids less than 250 mg/L (Emery and others, 1973; Mayo and others, 2007) (fig. 8). Groundwater near the valley perimeter also tends to have concentrations of nitrate less than about 3 mg/L as nitrogen (Emery and others, 1973), which is considered the background concentration for the area (Stogner, 2001). Anderholm (1996) found generally low concentrations of trace elements (less than drinking-water standards) in water from 35 wells completed in the unconfined aquifer, even in the central part of the valley. However, arsenic (believed to be from natural sources) was elevated above the USEPA drinking-water standard of 10 µg/L in three wells toward the center of the valley and above 5 µg/L in a total of seven wells. Uranium was naturally elevated above the USEPA drinking-water standard of 30 µg/L in two wells toward the center of the valley, with a maximum concentration of 84 µg/L. Gross alpha activity exceeded the drinking-water standard in eight wells in the same area, and concentrations of radon generally exceeded 1,000 pCi/L throughout the study area (the USEPA has proposed a drinking-water standard of 300 pCi/L, along with an alternate standard of 4,000 pCi/L that would apply in states where programs are in place to reduce radon levels in indoor air [U.S. Environmental Protection Agency, 2010]). In areas of the unconfined aquifer away from the valley center, Anderholm (1996) and Rupert and Plummer (2004) found concentrations of dissolved oxygen generally were greater than 1 mg/L and pH values generally were between about 7 and 8, consistent with data in Mayo and others (2007).

Dissolved-solids concentrations, water types, and redox conditions tend to change as groundwater moves toward the center of the San Luis Valley, particularly in the unconfined aquifer of the San Luis closed basin. In the "ancestral sump" area, concentrations can exceed 20,000 mg/L (Williams and Hammond, 1989; Mayo and others, 2007) (fig. 8A). The groundwater tends to change from a calcium bicarbonate type near the valley perimeter to a sodium bicarbonate type down

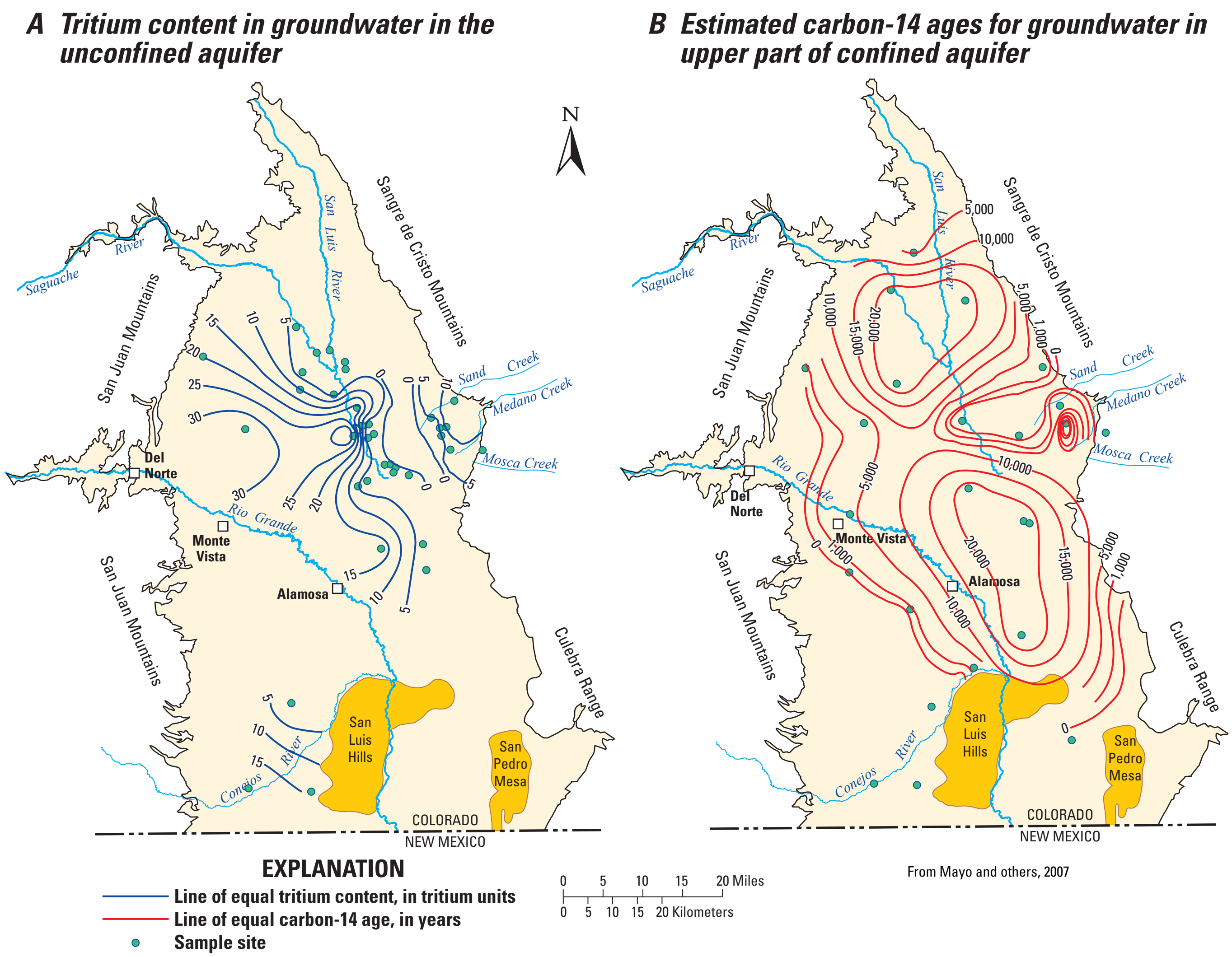


Figure 7. Distribution of (*A*) tritium content in groundwater in the unconfined aquifer and (*B*) estimated carbon-14 ages for groundwater in the upper part of the confined aquifer in the Alamosa Basin, Colorado.

gradient (Williams and Hammond, 1989), although water with elevated concentrations of sulfate and chloride also is found in the sump area (Mayo and others, 2007). Some investigators have concluded that the principal cause of the large increases in concentrations of dissolved solids in the sump area is evapotranspiration (Huntley, 1976; Williams and Hammond, 1989). Other investigators, while acknowledging that evapotranspiration is an important influence on the chemistry of groundwater in the sump area (particularly at very shallow depths), have concluded that dissolution of minerals including gypsum and halite is perhaps the most important factor in increasing concentrations of dissolved solids along flow paths in the unconfined aquifer of the valley (Emery and others, 1973; Mayo and others, 2007). Ion exchange has been cited as a major factor in the increase in the dominance of sodium in groundwater toward the sump area in the unconfined aquifer (Emery and others, 1973; Williams and Hammond, 1989; Mayo and others, 2007), although Emery and others (1973) also mention calcite precipitation as a factor. The likely effects of irrigated agriculture on dissolved-solids concentrations and elevated nitrate concentrations (particularly in the San Luis closed basin) in the unconfined aquifer will be discussed in the following section. Concentrations of dissolved oxygen in the unconfined aquifer tend to be less than 1 mg/L in parts of the study area nearest the ancestral sump (Anderholm, 1996); associated concentrations of manganese are larger here than in other parts of the study area, indicating a likely transition toward reduced conditions. Mayo and others (2007) found median pH values in the unconfined aquifer near the sump area to be 8 or above.

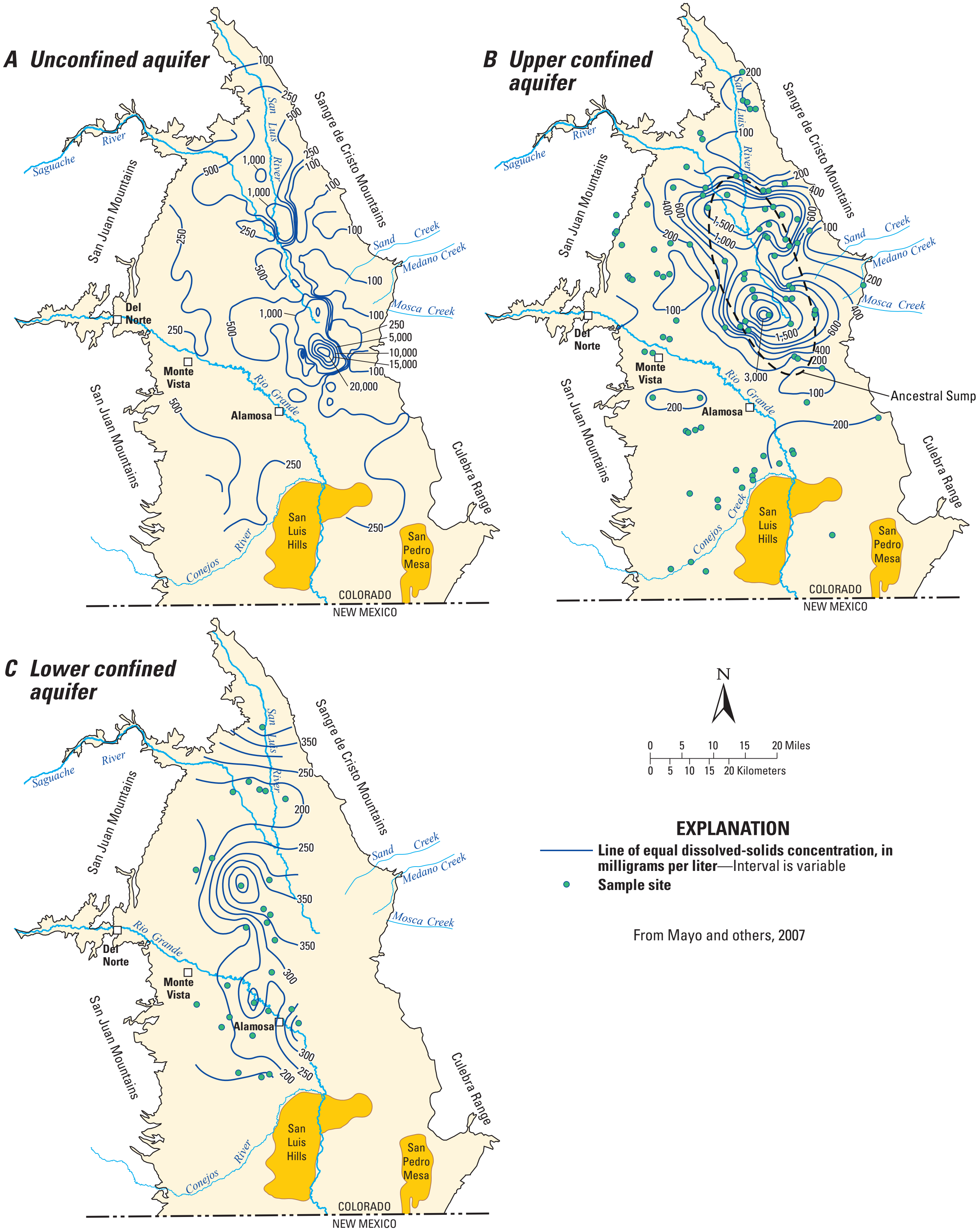


Figure 8. Distribution of dissolved-solids concentrations for the (*A*) unconfined, (*B*) upper confined, and (*C*) lower confined aquifers of the Alamosa Basin, Colorado.

Throughout most of the valley, concentrations of dissolved solids in the confined aquifer are less than those in the unconfined aquifer (fig. 8). Similar to the unconfined aquifer, changes in water chemistry also occur along flow paths in the confined aquifer of the San Luis Valley, although the changes tend to be less dramatic in the deeper confined aquifer. Increases in concentrations of dissolved solids and sodium are observed in the upper part of the confined aquifer in the "ancestral sump" area of the San Luis closed basin (fig. 8*B*). Because the confined aquifer is too deep to be affected by evapotranspiration and probably is little influenced by other near-surface processes, these changes in chemistry have been attributed to reactions with aquifer materials, including mineral dissolution and cation exchange (Emery and others, 1973; Mayo and others, 2007). Mayo and others (2007) concluded that methanogenic driven ion-exchange reactions are important in the upper confined aquifer in the sump area, where they and Emery and others (1973) detected methane and(or) hydrogen sulfide gas, which indicates reduced conditions. Even outside the ancestral sump area, Rupert and Plummer (2004) found concentrations of dissolved oxygen below 0.5 mg/L and the presence of manganese in two wells completed in the upper confined aquifer; pH values were 8.5 and 8.7. Mayo and others (2007) reported median pH values for the upper confined aquifer ranging from 8.3 in the sump area to 7.8 in other areas. For the lower confined aquifer, Mayo and others (2007) found that concentrations of dissolved solids were less than 250 mg/L throughout most of the San Luis Valley (fig. 8*C*); they reported median pH values ranging between 7.9 and 8.6 for different areas of the valley.

Potential Effects of Human Factors

As mentioned in previous parts of this section, the long history of agricultural development in the San Luis Valley has resulted in several substantial changes to the hydrologic system, including changes in the source, distribution, quantity, and chemical characteristics of recharge to the groundwater system. Groundwater levels and gradients also have been affected by the application of irrigation water to crops and by associated groundwater pumping. Observed and potential effects of these changes on groundwater quality in the San Luis Valley are discussed in this section. The discussion focuses in particular on the unconfined aquifer of the Alamosa Basin because this is the part of the groundwater system that has been most greatly affected by changes associated with human activities. In contrast, the confined aquifer is believed to have poor hydraulic connection with the land surface (Edelmann and Buckles, 1984) because of its depth, protective confining layer, and generally upward hydraulic gradients. Documented effects of human activities on groundwater quality in the unconfined aquifer of the Alamosa Basin are summarized in table 2.

Table 2. Summary of documented effects of human activities on groundwater quality in the Alamosa Basin, Colorado.

Groundwater-quality effect	Cause	General location(s)	Reference(s)
Elevated concentrations of nitrate	Agricultural fertilizer application	Unconfined aquifer beneath agricultural areas of the Alamosa Basin	Emery and others (1973); Edelmann and Buckles (1984); Anderholm (1996); Stogner (1997, 2001, and 2005)
Elevated concentrations of dissolved solids	Irrigation of agricultural fields	Unconfined aquifer beneath agricultural areas of the Alamosa Basin	Emery and others (1973); Huntley (1976); Edelmann and Buckles (1984); Williams and Hammond (1989)
Detections of agricultural pesticides	Agricultural pesticide application	Unconfined aquifer (including some domestic wells) beneath agricultural areas of the Alamosa Basin	Durnford and others (1990); Austin (1993); Anderholm (1996)
Detections of volatile organic compounds	Not determined	Only one documented detection near the water table beneath a primarily agricultural area of the San Luis closed basin	Anderholm (1996)
Detections of non-agricultural pesticides	Not determined	Only one documented detection near the water table beneath a primarily agricultural area of the San Luis closed basin	Anderholm (1996)

Irrigated agriculture and its supporting infrastructure have added to the sources and areal extent of groundwater recharge across much of the Alamosa Basin. Water from the Rio Grande was not a source of recharge under predevelopment conditions, but is now delivered by canals throughout much of the Alamosa Basin (including the San Luis closed basin) for irrigation. Water from tributaries that used to infiltrate only along the valley perimeter also is diverted for irrigation and now enters the groundwater system through infiltration from canals, fields, and recharge pits. Irrigation of crops with surface water by subirrigation has raised the water table in some areas, resulting in increased evapotranspiration. Evapotranspiration of irrigation water applied to fields can increase the dissolved-solids concentrations of the excess irrigation water that recharges the groundwater system. This water can also potentially transport to the water table the fertilizers and pesticides that were applied to fields. The advent of groundwater pumping from the unconfined aquifer to increase water supplies for irrigation in the Alamosa Basin (particularly the San Luis closed basin) has resulted in recycling of the groundwater on relatively short time scales, further increasing its exposure to evapotranspiration and agricultural chemicals. Agricultural development in the Alamosa Basin has, therefore, resulted in increased fluxes over broader areas and has introduced the means for potential transport of anthropogenic chemicals and increased dissolved solids to the unconfined aquifer throughout much of the basin.

Although the effects have not been quantified, several investigators have stated that irrigation-return flow has likely resulted in increased concentrations of dissolved solids in the unconfined aquifer of the Alamosa Basin (Emery and others, 1973; Huntley, 1976; Edelmann and Buckles, 1984; Williams and Hammond, 1989). Because applied irrigation water undergoes evapotranspiration and dissolves minerals from the soil and sediments as it recharges, irrigation-return flow contains more solutes than the applied irrigation water. Increases in concentrations of dissolved solids as a result of the irrigation cycle are likely to be most pronounced in areas of the basin where groundwater is a primary source of irrigation water and is recycled multiple times for this purpose. A study by Anderholm (1996) of shallow groundwater quality beneath areas of intense agriculture in the Alamosa Basin indicated wide local variations in concentrations of dissolved solids (ranging in value from 75 mg/L to 1,960 mg/L) superimposed on a general increase in concentrations from west to east. On the basis of ratios among various major ions, Anderholm (1996) found that compositions of several of the groundwater samples were similar to that of surface water that had been concentrated by evaporation; such samples might be indicative of irrigation water containing solutes that have been concentrated during recharge.

The effects of irrigated agriculture on concentrations of nitrate in the unconfined aquifer have been well documented, particularly in the San Luis closed basin (Emery and others, 1973; Edelmann and Buckles, 1984; Anderholm, 1996; Stogner, 1997, 2001, and 2005). Stogner (2001) noted that use of inorganic nitrogen fertilizers in the San Luis Valley began in the 1940s and increased dramatically starting in the 1960s, and that observed distributions of nitrate in shallow groundwater have been consistent with the overall pattern of fertilizer use though time. Early concentrations of nitrate reported by Scofield (1938) for 38 shallow wells in the San Luis Valley were all 0.3 mg/L or less. In subsequent samples collected during 1946–1950, Powell (1958) detected concentrations of nitrate of 3.2 mg/L or more in about 5 percent of wells.

Emery and others (1973) were among the first to map the common occurrence of concentrations of nitrate exceeding 10 mg/L as nitrogen in the unconfined aquifer of the closed basin; they attributed these elevated concentrations to heavy applications of chemical fertilizer during the previous decade. Similar patterns of nitrate concentration were observed by Edelmann and Buckles (1984), who additionally determined that concentrations of nitrate tended to be smaller toward the base of the unconfined aquifer. Anderholm (1996) detected concentrations of nitrate of 8.5 mg/L or more in several wells completed near the water table both north and south of the Rio Grande, and stated that the elevated concentrations were indicative of fertilizer leaching. Stogner (2005) used changes in the distribution of concentrations of nitrate through time (fig. 9) to estimate changes in nitrate mass in the unconfined aquifer beneath an intensively cultivated area of the closed basin. Stogner (2005) estimated that nitrate mass increased from about 6,900 tons in the 1940s to 34,000 tons in the late 1960s, and to 75,000 tons in the late 1990s.

The conclusion that agricultural practices are primarily responsible for the observed long-term increases in nitrate concentration and mass in the unconfined aquifer of the San Luis Valley is supported by the field experiments of Eddy-Miller (1993) and LeStrange (1995), which documented nitrogen leaching from irrigated fields. Stogner (1997, 2001) indicated that changes in farm-management practices (including changes in irrigation scheduling and reductions in the amount of fertilizer applied) that could reduce nitrate leaching are being encouraged in the San Luis Valley. Using study results indicating that net reductions in nitrate leaching of about 50 percent could be achieved by improved management practices (Sharkoff and others, 1996), Stogner (2005) calculated that resulting declines in the total mass of nitrate in the unconfined aquifer would be measurable within 10 to 15 years.

In addition to nitrate, pesticides have recently been studied in the unconfined aquifer of the San Luis Valley because of their potential to leach to groundwater. The pesticides Bravo, Sencor, Eptam, and(or) 2,4-D were detected at trace or low levels (7 µg/L or less) in samples from up to 10 of 34 irrigation wells sampled during the 1990 growing season by Durnford and others (1990), although the investigators indicated that sample or well-bore contamination may have affected these findings. On the basis of results from associated modeling of groundwater vulnerability in the area to pesticide contamination, Durnford and others (1990) concluded that farm-management practices and individual pesticide properties were important factors in determining contamination potential. Samples collected during the summer of 1993 from the

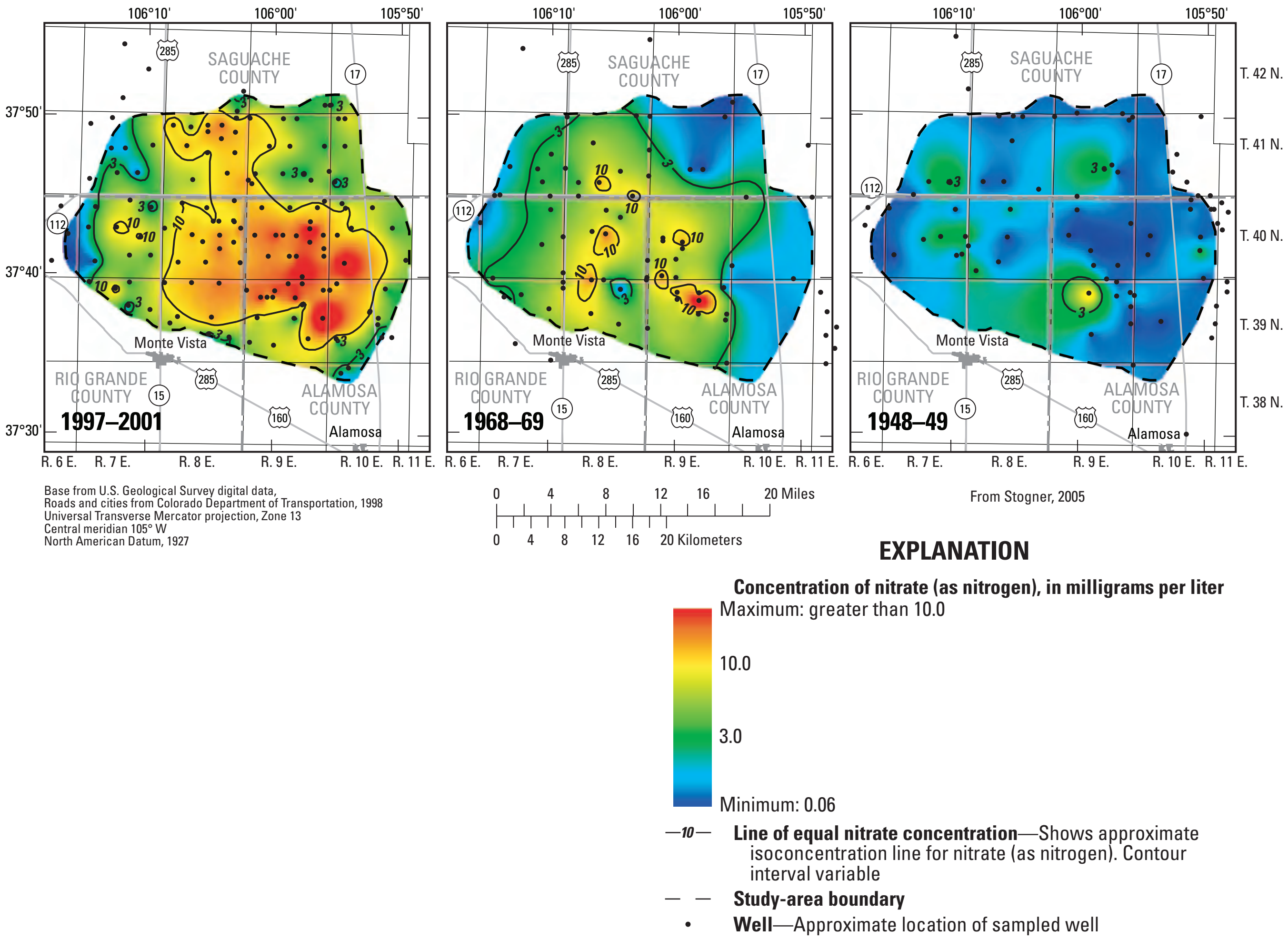


Figure 9. Estimated distribution of the concentration of nitrate (as nitrogen) in groundwater from the unconfined aquifer during 1997–2001, 1968–69, and 1948–49 for part of the Alamosa Basin, Colorado.

35 water-table wells studied by Anderholm (1996) showed only trace amounts (0.072 µg/L or less) of metribuzin, prometon (a nonagricultural herbicide), metolachlor and(or) *p,p´*-DDE in five wells, leading Anderholm (1996) to conclude that there was no widespread contamination of the unconfined aquifer by pesticide compounds. Samples collected between May and August of 1993 by the Colorado Department of Health and Environment from 93 domestic wells completed in the unconfined aquifer showed 2,4-D, hexazinone, and(or) lindane in three wells at concentrations up to 0.29 µg/L (Austin, 1993). Taken together, these studies appear to indicate that the unconfined aquifer of the San Luis Valley has been less affected by pesticide leaching than by nitrate leaching, perhaps because the pesticides used in the area are less mobile and persistent.

Potential effects of urbanization and septic tanks on water quality in the unconfined aquifer of the San Luis Valley are not known to have been specifically investigated. In one shallow well in the agricultural area studied by Anderholm (1996), however, one VOC (methyl *tert*-butyl ether) was detected at a concentration of 6 µg/L; the nonagricultural herbicide prometon was also detected in one well at a concentration of 0.01 µg/L. Given shallow depths to water and the occurrence of recent recharge throughout much of the San Luis Valley, there would appear to be potential for urban activities to affect shallow groundwater quality in the area.

Another activity with the potential to locally affect groundwater quality within the Alamosa Basin is metals mining, which is conducted in parts of the San Juan Mountains. Mine drainage has affected surface-water quality in the Alamosa River and in Little Kerber and Kerber Creeks, which enter the San Juan closed basin from the west (Emery and others, 1973). Balistrieri and others (1995) concluded that elevated concentrations of arsenic, cobalt, chromium, copper, nickel, and zinc in the Alamosa River downstream from its confluence with the Wightman Fork were likely associated with mine drainage; wetlands within the San Luis Valley that receive water from the Alamosa River also contained elevated concentrations of several of these elements. The potential effects of recharge from these sources on local groundwater quality are not known to have been studied.

Summary

The San Luis Valley in Colorado and New Mexico, which includes the Alamosa Basin, is an extensive alluvial basin with an unconfined aquifer having high intrinsic susceptibility and vulnerability to contamination as a consequence of small depths to water and widespread areal recharge, much of which now results from irrigated agriculture. The San Luis closed basin at the northern end of the valley is internally drained, whereas the groundwater system farther south is hydraulically connected to the Rio Grande, which gains water along most of its course through the area. Except near the basin margins, depths to water in the Alamosa Basin are commonly less than about 25 ft, and a thick fine-grained layer having its top at about 60 to 120 ft below land surface defines the division between the shallow, unconfined aquifer and a deeper, confined aquifer. Most wells are completed in the Alamosa Formation—consisting of discontinuous beds of clay, silt, sand, and gravel of mixed fluvial, lacustrine, and eolian origin—or in overlying deposits of similar lithology. Under natural conditions, groundwater recharges primarily along the basin margins as mountain-front recharge or groundwater underflow and discharges primarily in the central part of the basin as evapotranspiration. Because precipitation is small compared with evaporation, the direct infiltration of precipitation makes only a relatively minor contribution to aquifer recharge.

A long history of intensive agricultural land use has had a substantial effect on the groundwater-flow system in the unconfined aquifer of the Alamosa Basin. The estimated annual flux of water entering and leaving the groundwater system in the Colorado part of the San Luis Valley has more than tripled since development began. Most of this increased flux is the result of the effects of irrigation and its associated infrastructure, which has spread recharge across broad areas. Irrigation of croplands also has affected the chemical composition of recharge through evapotranspiration and recycling of shallow groundwater, which is pumped for application to crops at rates that make it the main component of discharge from the aquifer under modern conditions. Rates of evapotranspiration have also increased in some areas, primarily as the result of a rise in the water table resulting from irrigation. Even though groundwater withdrawals from both the unconfined and confined aquifers for irrigation and public supply have resulted in declines in aquifer storage, no large-scale changes in hydraulic gradients have been documented. Because the population of the basin remains small, urbanization has so far had little effect on the groundwater system.

Groundwater chemistry in the Alamosa Basin is determined by the source and composition of recharge and by processes occurring along a flow path, which are particularly important in the unconfined aquifer. Concentrations of dissolved solids are naturally high in the central part of the basin as a result of mineral dissolution and evapotranspiration, but also have increased in some areas because of irrigated agriculture. Naturally occurring concentrations of uranium and radon also might restrict the suitability of groundwater for consumption in some areas. Concentrations of nitrate, which were less than 3 mg/L throughout the basin prior to agricultural development, have increased to more than 10 mg/L over broad areas (particularly in the San Luis closed basin) as a result of the leaching of fertilizers applied to crops. Pesticides have been detected in shallow groundwater beneath agricultural areas, but not ubiquitously and generally in only trace concentrations. The occurrence of tracers of young water in shallow wells over broad areas of the Alamosa Basin is indicative of the susceptibility and vulnerability of the unconfined aquifer to contamination. In contrast, the confined aquifer is probably not substantially affected by near-surface processes, as indicated by generally upward hydraulic gradients and estimated groundwater ages on the order of thousands of years.

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