Streamflow, Infiltration, and Recharge in Arroyo Hondo, New Mexico

By Stephanie J. Moore[1]

Abstract

Infiltration events in channels that flow only sporadically produce focused recharge to the Tesuque aquifer in the Española Basin. The current study examined the quantity and timing of streamflow and associated infiltration in Arroyo Hondo, an unregulated mountain-front stream that enters the basin from the western slope of the Sangre de Cristo Mountains. Traditional methods of stream gaging were combined with environmental-tracer based methods to provide the estimates. The study was conducted during a three-year period, October 1999–October 2002. The period was characterized by generally low precipitation and runoff. Summer monsoonal rains produced four brief periods of streamflow in water year 2000, only three of which extended beyond the mountain front, and negligible runoff in subsequent years. The largest peak flow during summer monsoon events was 0.59 cubic meters per second. Snowmelt was the main contributor to annual streamflow. Snowmelt produced more cumulative flow downstream from the mountain front during the study period than summer monsoonal rains.

The presence or absence of streamflow downstream of the mountain front was determined by interpretation of streambed thermographs. Infiltration rates were estimated by numerical modeling of transient vertical streambed temperature profiles. Snowmelt extended throughout the instrumented reach during the spring of 2001. Flow was recorded at a station two kilometers downstream from the mountain front for six consecutive days in March. Inverse modeling of this event indicated an average infiltration rate of 1.4 meters per day at this location. For the entire study reach, the estimated total annual volume of infiltration ranged from 17,100 to 246,000 m^3 during water years 2000 and 2001. During water year 2002, due to severe drought, streamflow and streambed infiltration in the study reach were both zero.

Introduction

In the semiarid climate of the Española Basin, a rapidly growing population relies on scarce ground-water and surface-water resources. The Tesuque aquifer, which provides a significant portion of drinking-water supplies to cities and rural residences, is recharged by several processes, including (1) direct recharge, (2) subsurface inflow from adjacent aquifers, and (3) focused recharge. Focused recharge results from streambed infiltration through the unsaturated zone to the underlying aquifer.

Focused recharge along ephemeral streams may provide a substantial source of recharge to the alluvial aquifer of the Española Basin, which is referred to as the Tesuque aquifer (Spiegel and Baldwin, 1963; McAda and Wasiolek, 1988; Duke Engineering and Services, 2001). However, the sporadic nature of streamflow of ephemeral streams in the Española Basin, as well as throughout the Southwest, has resulted in poor documentation of streamflow and streambed infiltration of ephemeral streams. Consequently, focused recharge is one of the most uncertain components of regional water budgets (Duke Engineering and Services, 2001). Information on the quantity and timing of streamflow and streambed infiltration in ephemeral streams would allow for improved estimates of the focused-recharge component of water budgets.

Purpose and Scope

This chapter presents the results of a three-year study of streamflow, infiltration, and recharge in Arroyo Hondo, New Mexico. Data were collected from October 1, 1999 through September 30, 2002 (water years 2000–02). Traditional and experimental methods were used to characterize streamflow in Arroyo Hondo. Traditional methods were used to characterize streamflow at a continuous-record streamflow-gaging station (stream gage). Experimental temperature-based methods were used to estimate the presence and duration of streamflow at selected sites along Arroyo Hondo. In addition, precipitation and soil-water content were collected at selected locations throughout the watershed. Streambed infiltration rates were estimated through use of an inverse modeling technique that fits simulated to measured subsurface temperatures. Cumulative streambed infiltration rates were estimated from streambed infiltration rates, channel widths, and the downstream extent and duration of streamflow. Environmental tracers (chloride and bromide) were used to investigate the presence of recharge at selected sites.

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Previous Investigations

Ground-water recharge is an important process in the Española Basin (Spiegel and Baldwin, 1963; Anderholm, 1994; Duke Engineering and Services, 2001). Many studies have been conducted on the various recharge processes in the Tesuque aquifer.

Direct recharge (also known as diffuse or areal recharge) occurs by infiltration of precipitation through the unsaturated zone to the saturated zone. Thick unsaturated zones and high evapotranspiration rates, both of which are common in the Española Basin, preclude large amounts of direct recharge. Previous investigators have attempted to quantify direct recharge in the Española Basin. Spiegel and Baldwin (1963, p. 192) estimated direct recharge to be 1.3 centimeters per year (cm/yr) in the Arroyo Hondo area. Lee Wilson and Associates (1978, p. 1–62) estimated direct recharge to be 0.7 cm/yr in the Santa Fe area. McAda and Wasiolek (1988, p. 30) estimated direct recharge to be 1.3 cm/yr in the Arroyo Hondo area. Duke Engineering and Services (2001, p. 131) assumed a direct recharge rate of zero.

Spiegel and Baldwin conducted a comprehensive study of geology and water resources in the Santa Fe area. They reported the average annual yield of surface-water runoff from the upper 17.35 square kilometers (km^2) of the Arroyo Hondo watershed to be 660,000 cubic meters (m^3; Spiegel and Baldwin, 1963, p. 188); this estimate was determined from crest-stage data collected from 1913 to 1922. They also reported (p. 188) that most streamflow in Arroyo Hondo recharges the regional ground-water aquifer (the Tesuque aquifer).

McAda and Wasiolek simulated ground-water flow in the Tesuque aquifer. They estimated 625,000 m^3 per year of recharge to the Tesuque aquifer from streambed infiltration in Arroyo Hondo (McAda and Wasiolek, 1988, p. 29–31). This value, which represented a long-term average, was initially based on that reported by Spiegel and Baldwin (1963), and was subsequently constrained during model calibration. McAda and Wasiolek applied streambed infiltration at a constant rate of 1,712 m^3/day throughout the year.

Anderholm applied the chloride mass-balance method to estimate mountain-front recharge (which includes subsurface inflow from the mountain block and focused recharge from streambed infiltration) in the Santa Fe area. He estimated 1,020,000 m^3 per year of mountain-front recharge in Arroyo Hondo (Anderholm, 1994, p. 37).

Hydrogeologic Setting

Arroyo Hondo is a small mountain-front stream located in the southeastern part of the Española Basin, in central New Mexico (fig. 1). Arroyo Hondo is typical of many mountain-front streams draining the western slopes of the Sangre de Cristo Mountains in that it is a gaining stream in its upper reaches and a losing stream in its lower reaches. Streamflow is generally perennial upstream and ephemeral downstream from the mountain front. The mountain front is defined as the contact between the mountain block (bedrock) aquifer and the alluvial aquifer system (the Tesuque aquifer) and is located approximately 2.1 km below streamflow-gaging station Arroyo Hondo near Santa Fe, N. Mex. (08317050; fig. 2). The Arroyo Hondo watershed comprises 156 km^2 upstream from its confluence with Cienega Creek; 17 percent (26 km^2) of its drainage area is located upstream from the mountain front. Elevations in the watershed vary from about 1,800 to 2,700 m above sea level (fig. 1).

The climate of the Española Basin and the Arroyo Hondo watershed is semiarid (fig. 3). At higher elevations, most precipitation falls as snow during winter months, whereas at lower elevations most precipitation falls as rain during the late summer and early fall (July through October) monsoon season. Normal precipitation in the Santa Fe area is 363 mm (fig. 4; Western Regional Climate Center, 2002); for purposes of this report, “normal” precipitation is defined as mean annual precipitation for 1972–2001 at the National Weather Service Cooperative Santa Fe 2 Station.

Arroyo Hondo can be divided into two reaches on the basis of the location of the mountain front (fig. 2). Upstream from the mountain front, the stream channel is well defined, narrow, and bedrock controlled. Precambrian gneiss and granite underlie most of the watershed and scattered areas of terrace deposits of Quaternary age flank the arroyo (Spiegel and Baldwin, 1963). A series of sedimentary and volcanic rocks of Tertiary age are exposed just upstream from the mountain front, including the reddish sandstone, conglomerate and mudstone of the Galisteo Formation, and latitic to andesitic volcanic flows and breccias (Spiegel and Baldwin, 1963). A perennial spring (fig. 2) discharges from the Galisteo Formation.

Downstream from the mountain front, the arroyo channel and arroyo valley widen as they cross the alluvial fan deposits of the Española Basin (Spiegel and Baldwin, 1963). The alluvial fan deposits are part of the Santa Fe Group, which includes the Tesuque Formation of Tertiary age and the Ancha Formation of Tertiary age. The older and thicker Tesuque Formation, which consists primarily of pinkish-tan, silty to conglomeratic sand and sandstone, is exposed along the 1.6-km reach of the arroyo immediately downstream from the mountain front. The younger Ancha Formation, which consists of silt, sand, and gravel, overlies the remainder of the watershed. The Arroyo Hondo streambed is composed of recent alluvium, which generally thickens in the downstream direction. The alluvium includes a mixture of silt, sand, and gravel; some large cobbles are present in the upper reaches, where gradients are steeper.

Perennial flow generally extends from the headwaters of the arroyo to the mountain front (Spiegel and Baldwin, 1963; McAda and Wasiolek, 1988) and is partially sustained by the spring discharging from the Galisteo Formation. However, during years of below normal precipitation, the arroyo may be dry between the stream gage and the mountain front except for that portion of the arroyo fed by discharge from

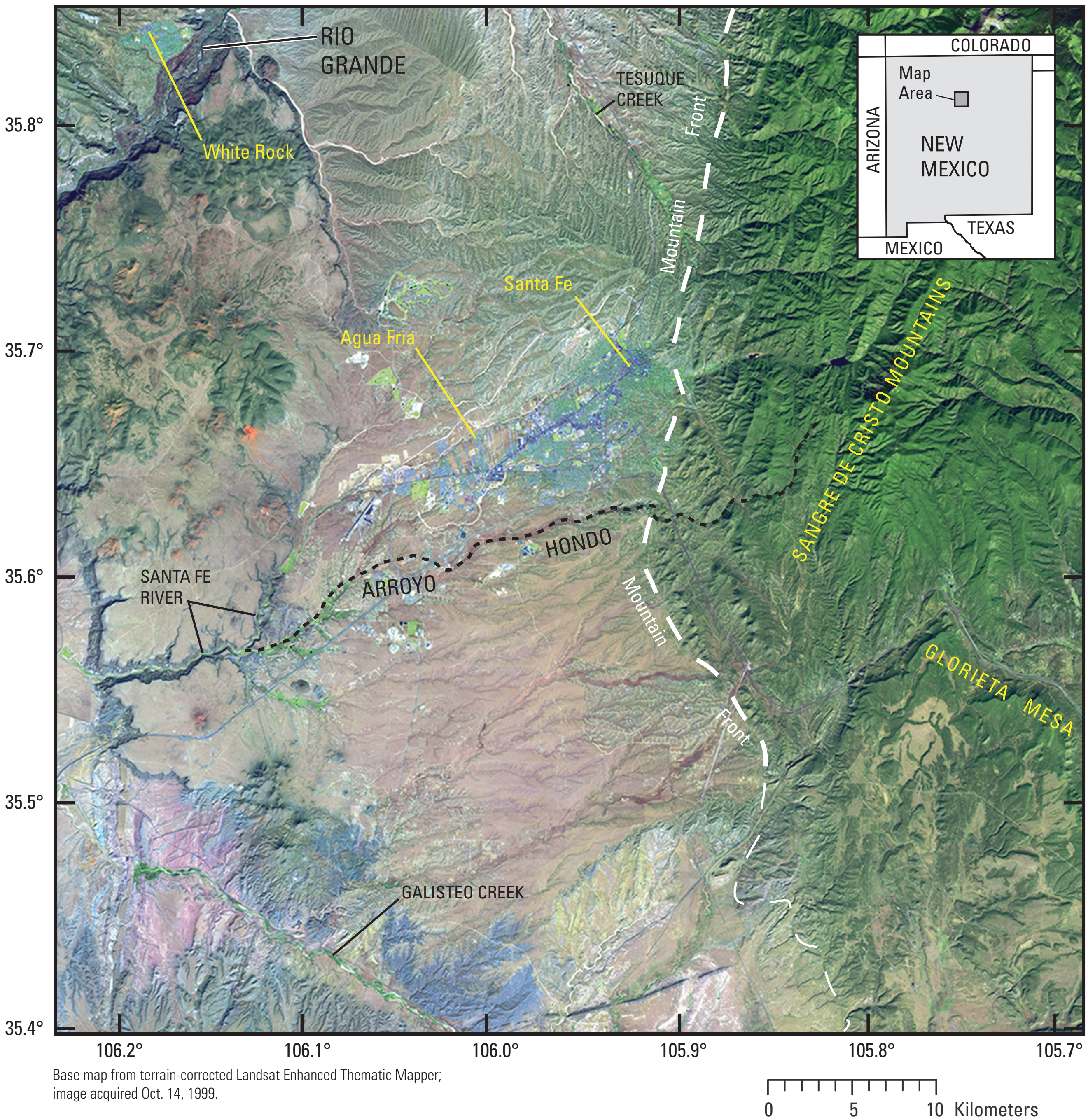

Figure 1. Arroyo Hondo, New Mexico, on the northeast rim of the Middle Rio Grande Basin. False-color satellite image shows active vegetation as deep shades of green (as in the volcanic highlands south of White Rock and in the crystalline Sangre de Cristo Mountains); sedimentary rocks as pastel shades of brown and green (younger and older Santa Fe clastics, respectively); pink (shale) and blue (volcaniclastics), near Galisteo Creek; and extrusive volcanics as dark gray with red (as in mounds north and south of junction of Arroyo Hondo with the Santa Fe River). The Middle Rio Grande Basin is at the base of cliffs dissected by the Santa Fe River, along the lower left edge of the image.

the spring. Downstream from the mountain front, the stream is ephemeral and flows only in response to runoff from snowmelt and intense summer thunderstorms (monsoons).

Depth to water varies spatially throughout the Arroyo Hondo watershed. A generalized longitudinal hydrogeologic section of part of the Arroyo Hondo watershed is shown in figure 5. Upstream from the mountain front, the water table is generally less than 50 m below land surface. Depth to the water table may exceed 90 m immediately downstream from the mountain front and generally decreases to the west.

Methods

Thermal and tracer-based methods were used to investigate streamflow, infiltration, and recharge in the Arroyo Hondo watershed. Instrumentation and data collection are discussed in this section. Methods of interpretation are discussed in subsequent sections of this chapter.

Study design was guided by general knowledge of streamflow in Arroyo Hondo (based on a literature review and initial reconnaissance of the study area) and of focused recharge processes in alluvial basins. Observations of channel morphology indicate that (1) streamflow is relatively frequent in the upper ephemeral reaches of Arroyo Hondo (in the 2.6 km immediately downstream from the mountain front; fig. 2) and (2) streamflow seldom extends continuously from the mountain front to its confluence with Cienega Creek (fig. 1). The thick, coarse-grained alluvium and frequent streamflows in the 2.6-km reach immediately downstream from the mountain front create ideal conditions for focused recharge.

Streamflow

Traditional and experimental methods were used to characterize streamflow in Arroyo Hondo. A continuous-record stream gage, Arroyo Hondo near Santa Fe, New Mexico (08317050), was installed in January 2000 to quantify streamflow in the perennial reach of the arroyo just upstream from the mountain front (fig. 2).

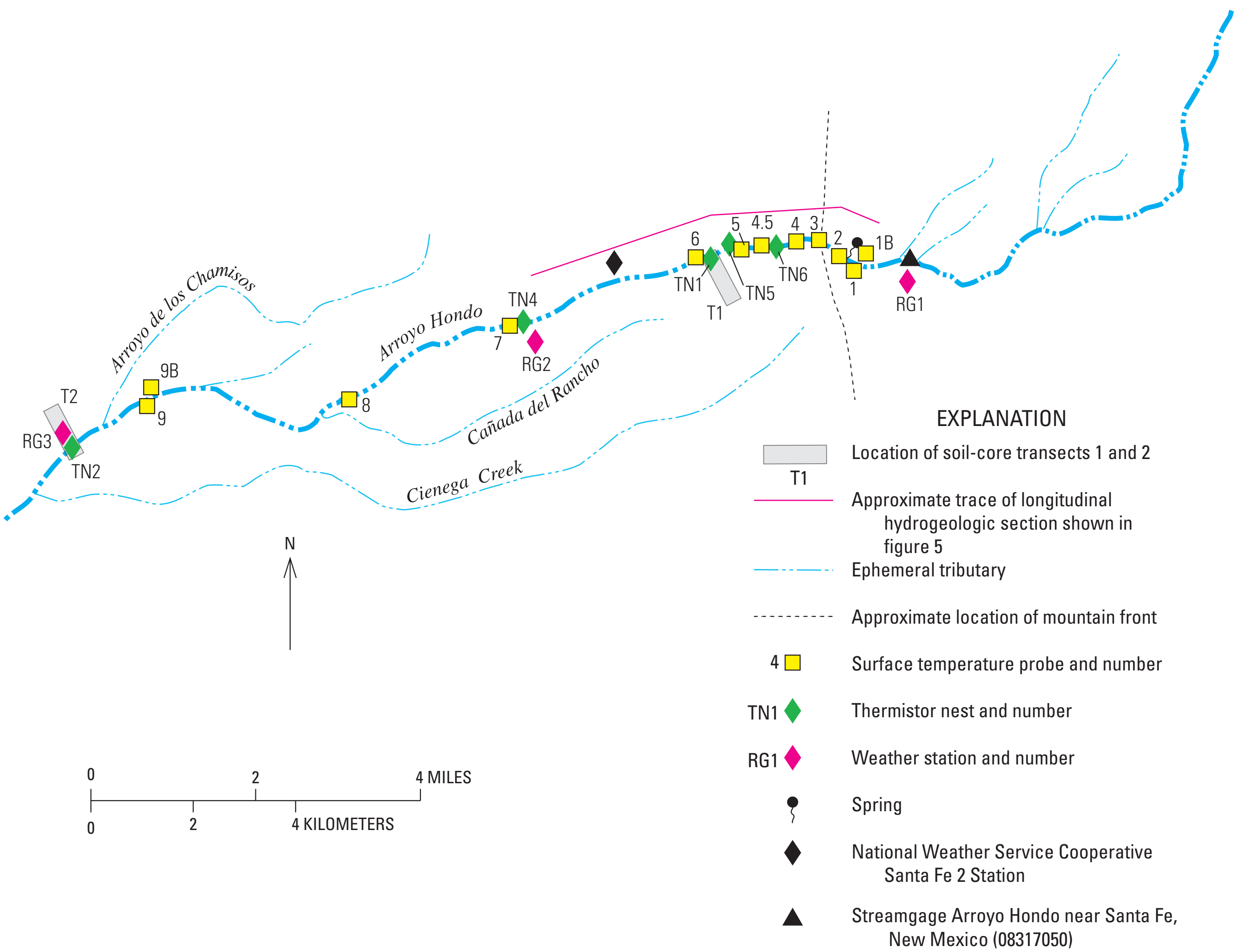

Figure 2. Schematic of the Arroyo Hondo, New Mexico study area.

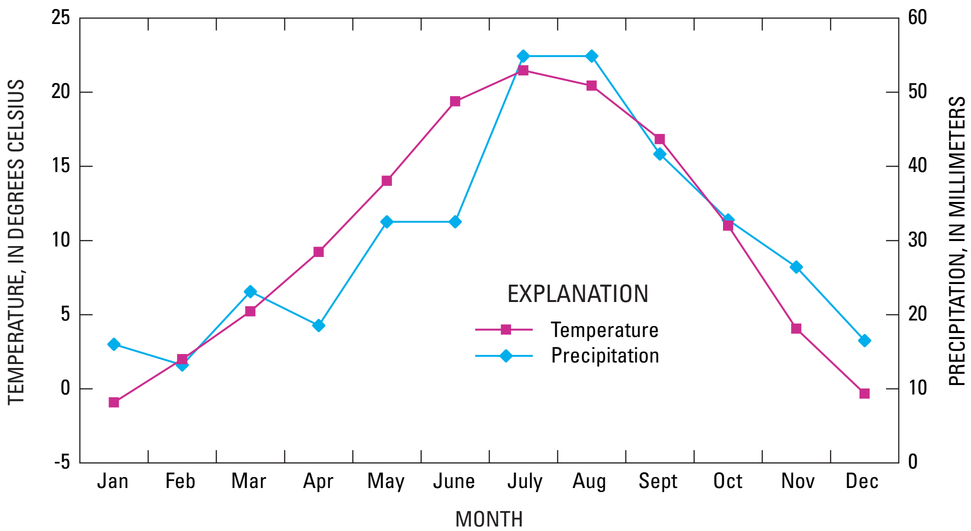

Figure 3. Mean monthly temperature and precipitation for the Arroyo Hondo, New Mexico study area. Data are from the National Weather Service Cooperative Santa Fe 2 station for 1972–2001. The location of the weather station is shown on figure 2.

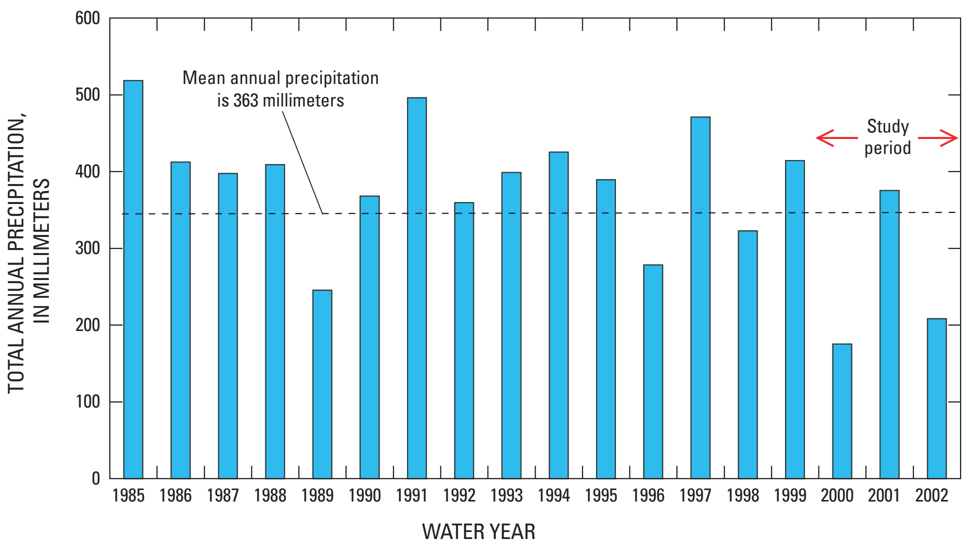

Figure 4. Total annual precipitation for the Arroyo Hondo, New Mexico study area. Data are from the National Weather Service Cooperative Santa Fe 2 station for water years 1985–2002. The location of the weather station is shown on figure 2.

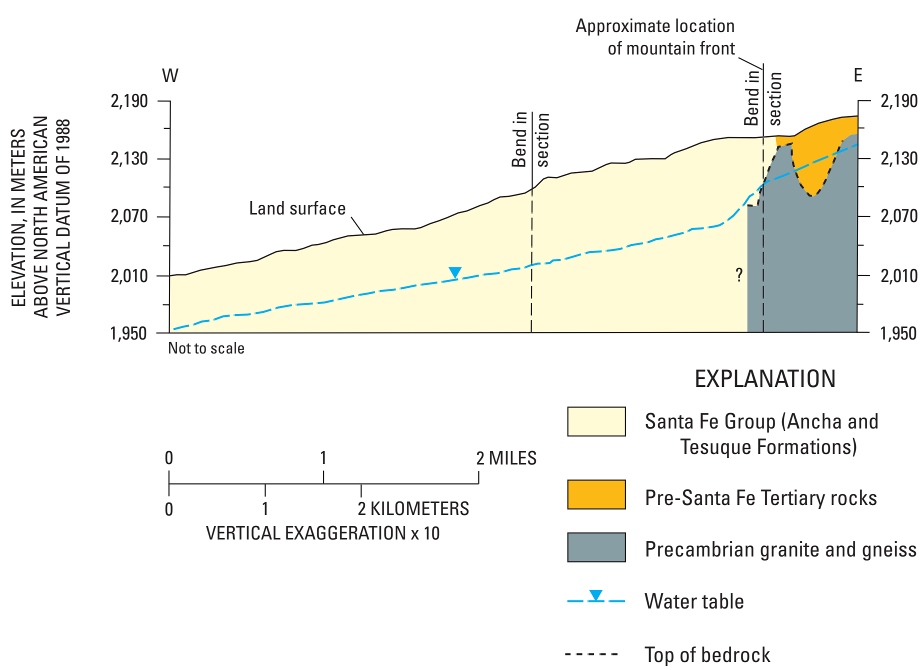

Figure 5. Generalized longitudinal hydrogeologic cross-section of Arroyo Hondo, New Mexico, modified from Spiegel and Baldwin (1963). The trace of the section is shown in figure 2.

Experimental temperature-based methods were used to determine the downstream extent and duration of streamflow (Constantz and others, 2002; Stewart, 2003). Twelve surface-temperature probes, which consist of a thermistor with a self-contained, single-channel data logger, were installed at selected locations in and near the arroyo channel. Each probe recorded temperature at 30-minute intervals; these data were used to construct a continuous thermograph for each location. Variations in the diurnal temperature signal were interpreted to determine if streamflow was present at a particular location in the arroyo, thus providing a continuous record of the downstream extent and duration of streamflow (Constantz and others, 2002; Stewart, 2003). During October 1999, nine surface-temperature probes (sites 1–9) were installed in the arroyo channel and two surface-temperature probes (sites 1B and 9B) were installed outside the active channel as benchmarks. Data from benchmark temperature probes helped to distinguish meteorological events (such as cold fronts and precipitation) from streamflow events. For surface-temperature sites in the perennial reach of the arroyo (sites 1–3), probes were placed on the channel surface and covered with large rocks to hold them in place. For those sites in the ephemeral reach of the arroyo (sites 4–9) and for benchmark sites adjacent to the arroyo channel (1B and 9B), probes were buried at depths ranging from 0.06 to 0.2 m. One additional surface temperature probe (site 4.5) was installed between sites 4 and 5 during March 2000 to gain additional streamflow information.

Three tipping-bucket rain gages with data loggers were installed in July 2000 along the arroyo (RG1–3; fig. 2) to measure spatial and temporal variations in precipitation. In addition to the general value gained from knowledge of spatial and temporal variations in precipitation, the data help to distinguish precipitation events from streamflow events (on the basis of temperature data).

Streambed Infiltration

Vertical sediment-temperature profiles have been used to estimate streambed infiltration rates (Lapham, 1987; Constantz and Thomas, 1996; Constantz and others, 2002; Constantz and others, 2003; Stewart, 2003). Thermistor nests, consisting of a self-contained data logger and four thermistors located at multiple depths in a vertical profile, were installed at selected locations in the ephemeral reach of the active channel (fig. 2). Temperature was recorded at 30-minute intervals. Thermographs constructed from data collected at each thermistor nest were used to indirectly estimate instantaneous infiltration rates during streamflow events. Thermistor nests TN1 and TN2 (fig. 2) were installed by using a truck-mounted, direct-push drill rig in October 2000. Thermistor nests TN4, TN5, and TN6 were manually installed in July 2002. At each nest, one thermistor was placed on the streambed surface and the other three thermistors were buried below the streambed surface at approximate depths of 0.3 m, 1.0 m, and 2.0 m.

Recharge

Environmental tracers (chloride and bromide) were used to investigate the presence or absence of recharge at selected sites. Soil cores were collected along transects T1 and T2 of Arroyo Hondo (fig. 2). At each transect, three soil cores were collected: one in the active channel (T1a and T2a), one 45–50 m from the active channel (T1b and T2b), and one 80–90 m from the active channel (T1c and T2c). Transect T1 is located 2.6 km downstream from the mountain front; soil cores T1a, T1b, and T1c were collected at 0, 45, and 80 m from the active channel. Transect T2 is located approximately 12 km downstream from the mountain front; soil cores T2a, T2b, and T2c were collected at 0, 50, and 90 m from the active channel. A truck-mounted, direct-push drill rig was used to collect 2.54-cm-diameter soil cores in October 2000. Each soil core extended from land surface to a depth of 5 to 7 m and was subsampled at intervals ranging from 0.15 to 0.91 m. Each subsample was analyzed for water content and chloride and bromide concentrations.

Streamflow

The magnitude, duration, and downstream extent of streamflow directly affect the quantity, duration, and distribution of streambed infiltration; that is, streambed infiltration is limited by the amount of streamflow in a particular stream, and the area over which streambed infiltration occurs is restricted to the portion of the stream where streamflow is present. Therefore, a detailed characterization of streamflow is necessary to improve understanding of streambed infiltration.

Temporal variations in streamflow are largely due to temporal variations in precipitation; therefore, variations in precipitation provide insight to variations in streamflow. Although the exact relation varies from one watershed to another, streamflow generally increases with increasing precipitation. To make reasonable comparisons between measured (or estimated) streamflow for different time periods, variations in precipitation for those same time periods need to be considered.

Precipitation during the study period was below normal for two of three years (Western Regional Climate Center, 2002; fig. 4). The normal streamflow (or a long-term average streamflow) is unknown for the stream gage at Arroyo Hondo because data were collected for only a three-year period during this study and no previous streamflow data exist.

The relation between streamflow and precipitation is demonstrated by streamflow records for two nearby stream gages located above diversions and (or) reservoirs on small, mountain-front streams in the Española Basin (table 1 and fig. 6) and referenced in the following discussions. These data show that streamflow is positively correlated with precipitation at all three stream gages (fig. 6).

Table 1. Annual streamflow and precipitation data in the Santa Fe area.

[NA, no data available]

Water year[1]	Total annual precipitation[2], in millimeters	Annual mean discharge[3], in cubic meters per minute			Total annual discharge[4], in millions of cubic meters		
		Tesuque Creek[5]	Arroyo Hondo[6]	Santa Fe River[7]	Tesuque Creek[5]	Arroyo Hondo[6]	Santa Fe River[7]
1937	NA	6.4	NA	NA	3.3	0.3	98
1938	NA	3.3	NA	NA	1.8	0.7	80
1939	NA	5.0	NA	NA	2.6	0.4	88
1940	NA	5.1	NA	NA	2.7	NA	NA
1941	NA	13.8	NA	NA	7.3	NA	NA
1942	NA	13.3	NA	NA	7.0	NA	NA
1943	NA	3.2	NA	NA	1.7	NA	NA
1944	NA	5.6	NA	NA	3.0	NA	NA
1945	356	6.8	NA	NA	3.6	NA	NA
1946	330	2.6	NA	NA	1.4	NA	NA
1947	262	3.3	NA	NA	1.7	NA	NA
1948	335	4.7	NA	NA	2.5	NA	NA
1949	425	6.0	NA	NA	3.2	NA	NA
1950	267	1.3	NA	NA	0.66	NA	NA
1951	211	1.3	NA	NA	0.69	NA	NA
1998	323	5.0	NA	NA	2.6	NA	NA
1999	414	5.0	NA	10.9	2.6	NA	5.7
2000	175	2.4	NA	3.6	1.3	NA	1.9
2001	375	5.3	0.9	11.4	2.8	0.47	6.0
2002	208	0.8	0.0	1.6	0.43	0.00	0.82

[1]Twelve-month period ending September 30th of designated year.

[2]Data prior to 1972 from the "Santa Fe" station; data from 1972 to present from the "Santa Fe 2" station (Western Region Climate Center, 2003).

[3]From U.S. Geological Survey digital data; also published in USGS Annual Data Reports (1937-2002).

[4]Calcuated as annual mean daily discharge times 365 days.

[5]U.S. Geological Survey streamflow-gaging station 08302500 (Tesuque Creek above diversions near Santa Fe, N. Mex.).

[6]U.S. Geological Survey streamflow-gaging station 08317050 (Arroyo Hondo near Santa Fe, N. Mex.).

[7]U.S. Geological Survey streamflow-gaging stations 08316000 (Santa Fe River near Santa Fe, N. Mex.; 1937–1951 data) and 08315480 (Santa Fe River above McClure Reservoir near Santa Fe, N. Mex.; 1998–2002 data).

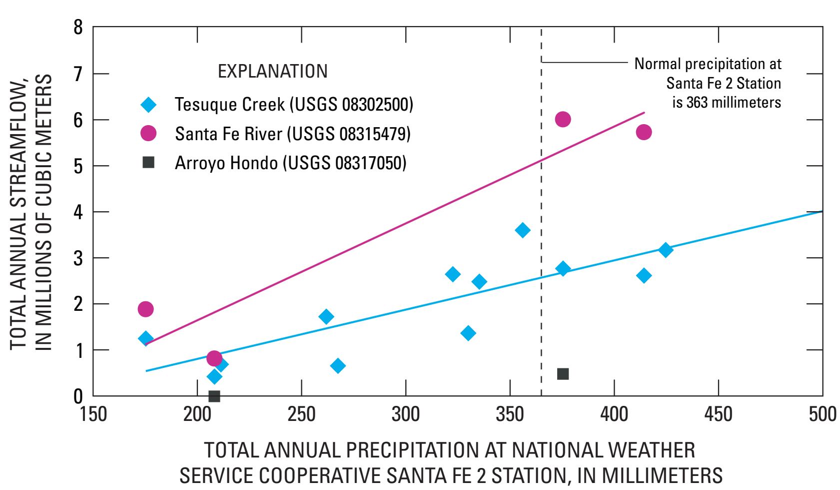

Figure 6. Relation between total annual streamflow and total annual precipitation at three USGS streamflow gaging stations in the Arroyo Hondo, New Mexico, study area. See figure 1 for stream locations.

Measured Streamflow

When the study began in October 1999, base flow in Arroyo Hondo was estimated to be less than 0.01 m^3/s at the stream gage. Streamflow at the gage ceased in May 2000, and the stream remained dry through the remainder of the water year (June through September) except for a few days of monsoon-induced streamflow events (monsoon events). Streamflow at the gage began again in late October 2000 and peaked in mid-March 2001 as a result of snowmelt. Streamflow at the gage ceased in June 2001. The stream remained dry throughout the remainder of the study period (fig. 7).

Total annual streamflow in Arroyo Hondo ranged from zero to 474,000 m^3 during the study period (water years 2000–02; fig. 7). Annual streamflow was largest (474,000 m^3) in WY 2001 when annual precipitation (375 mm) at the Santa Fe 2 weather station was 103 percent of normal. Annual streamflow was smallest in WY 2002 (zero m^3) when annual precipitation (208 mm) at Santa Fe 2 was 57 percent of normal. Below-normal precipitation in the Santa Fe area during WY 2002 resulted in the smallest streamflows on record at stream gages Tesuque Creek above diversions, near Santa Fe, N. Mex., and Santa Fe River above McClure Reservoir near Santa Fe, N. Mex. (fig. 6).

Daily mean streamflow (the mean of the computed streamflow for a particular day) at the Arroyo Hondo stream gage ranged from zero to 0.13 m^3/s during the study period (fig. 7). Daily mean streamflow was largest on March 10, 2001, during a snowmelt-induced streamflow event (snowmelt event). Streamflow on March 10 was steady throughout the day.

Instantaneous streamflow ranged from zero to approximately 0.59 m^3/s during the study period. The largest instantaneous streamflow occurred on July 1, 2000, during a monsoon event. Daily mean streamflow on July 1 was 0.03 m^3/s.

The previous two examples highlight important differences that are characteristic of snowmelt- and monsoon-induced streamflow events in Arroyo Hondo. Snowmelt events typically have relatively steady flows that often result in the largest daily mean streamflow for a particular year. Additionally, snowmelt events last longer and, therefore, result in larger total streamflow for a particular time period. Monsoon events may produce the highest peak streamflow for a particular year. However, streamflow during monsoon events is typically unsteady and of short duration (often lasting less than 24 hours), which results in a smaller total streamflow for a particular time period. Because snowmelt events result in a larger total streamflow than monsoon events, they likely result in a larger volume of streambed infiltration.

Use of Heat to Determine the Presence of Streamflow

Streambed infiltration can occur only in areas of a stream where streamflow is present. Therefore, knowledge of the distribution and timing of streamflow will improve understanding of streambed infiltration. Temperature variations in streambed sediments were used to determine the presence of streamflow (Constantz and others, 2002; Stewart, 2003).

The use of two different installation methods for temperature probes complicated the interpretation of streambed temperatures. Upstream from the mountain front, temperature probes were placed on the streambed of the active arroyo channel. At these sites, streamflow dampened the amplitude of the diurnal temperature signal because water buffered the temperature probe from the extremes of air temperature (fig. 8). Downstream from the mountain front, temperature probes were buried below the streambed at depths of 0.2 – 0.6 m. At these sites, infiltration of streamflow increased the amplitude of the diurnal temperature signal because advection (the dominant heat-transport mechanism during infiltration) transfers heat into the streambed more efficiently than conduc-

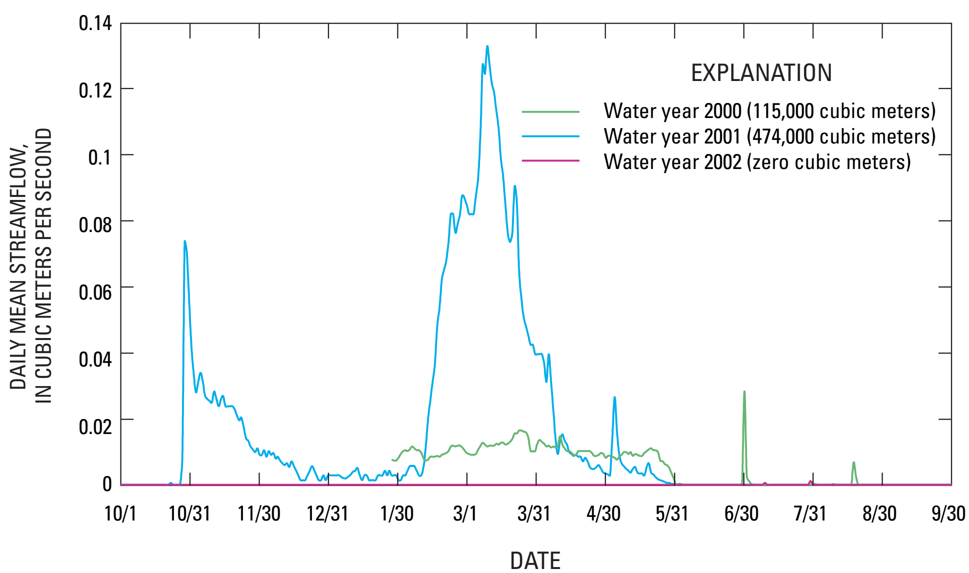

Figure 7. Daily mean discharge at streamflow-gaging station 08317050, Arroyo Hondo near Santa Fe, New Mexico, for water years 2000-02. The volume of total annual streamflow is shown in parentheses. The streamgage location is shown on figure 2.

tion (the dominant heat-transport mechanism in dry sediments; fig. 9). For temperature probes buried at depths less than 0.2 m, changes in the amplitude of the diurnal temperature signal caused by the presence of streamflow are less obvious. Additionally, the duration of monsoon events may be far less than 24 hours, in which case the diurnal temperature signal would be only briefly interrupted and the amplitude may not be significantly affected. Theoretically, some form of automated time-series analysis could be used to interpret results; however, because of complications described above, visual inspection was primarily used to interpret thermographs for each temperature probe.

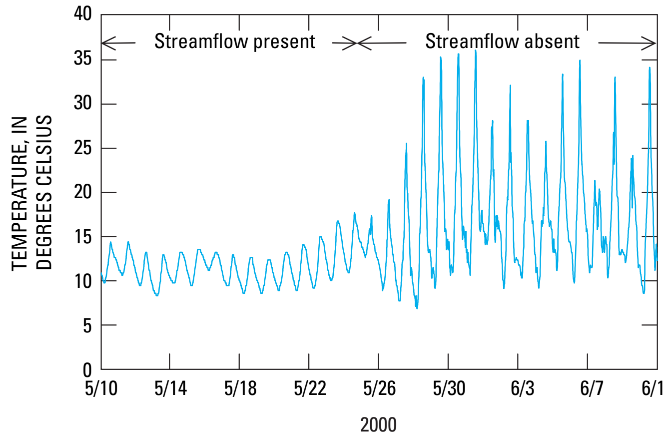

Figure 8. Streambed temperatures at a probe on the surface of the streambed, Arroyo Hondo study area, New Mexico.

Downstream Extent and Duration of Streamflow

The presence or absence of streamflow was determined through inspection of each thermograph. The presence or absence of streamflow was used to ascertain the minimum downstream extent of continuous streamflow for every day in the study period, as described in Constantz and others (2002) and Stewart (2003). The minimum downstream extent of streamflow and its relation to daily mean streamflow at the stream gage are shown for the two most active periods of streamflow during this study (figs. 10–11).

Monsoon rains resulted in four short periods of streamflow during WY 2000, three of which caused streamflow to extend beyond the mountain front (fig. 10). The largest monsoon event occurred in early July when instantaneous streamflow at the stream gage reached 0.59 m^3/s (not shown in fig. 10), daily mean streamflow reached 0.03 m^3/s, and the distal end of streamflow extended at least 3.8 km downstream from the stream gage.

Two monsoon events in early August 2000 produced streamflow at and downstream from the mountain front despite a daily mean streamflow of less than 0.01 m^3/s at the stream gage (fig. 10). In other words, streamflow was virtually absent at the gage but present downstream. This situation is likely due to the spatial distribution of the relatively spotty monsoon rains during the early August 2000 events. Precipitation may fall on only a portion of the watershed during a given storm. If the portion of the watershed receiving precipitation is located downstream from the stream gage, any streamflow resulting from that precipitation will not flow past the stream gage.

Arroyo Hondo was dry between the stream gage and the mountain front at the beginning of WY 2001 (October 1, 2000; fig. 11). Because of increasing precipitation, the distal end of streamflow reached the mountain front by late October

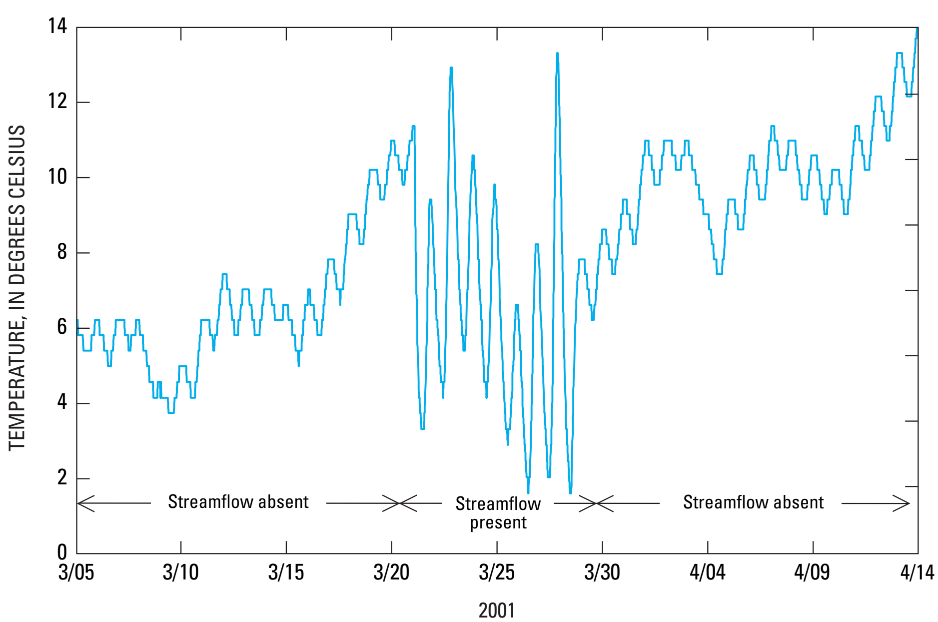

Figure 9. Streambed temperatures at a probe buried approximately 0.3 meter below the streambed, Arroyo Hondo study area, New Mexico.

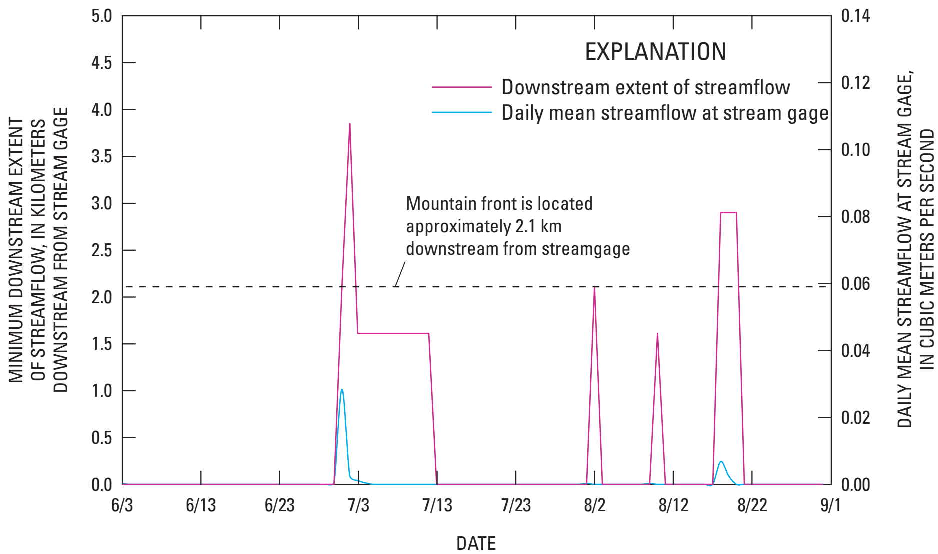

Figure 10. Minimum downstream extent and magnitude of flow at streamflow-gaging station 08317050, Arroyo Hondo near Santa Fe, N. Mex., during summer of 2000.

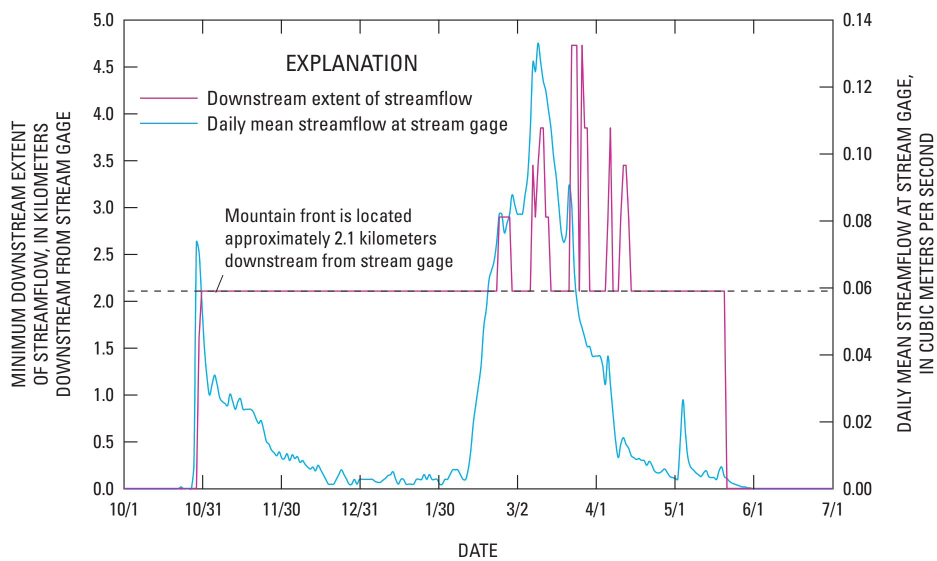

Figure 11. Minimum downstream extent and magnitude of flow at streamflow-gaging station 08317050, Arroyo Hondo near Santa Fe, N. Mex., October 2000 to June 2001.

2000 and persisted through the beginning of snowmelt in February 2001 (fig. 11). Rapid increases in daily mean streamflow resulted in the distal end of streamflow advancing further downstream (fig. 11). The distal end of streamflow reached its maximum downstream extent (at least 4.73 km below the stream gage) in late March, several days after the maximum daily mean streamflow of 0.13 m^3/s at the stream gage. The delay between the maximum downstream extent of streamflow and the maximum daily mean streamflow may be attributed to depleted soil moisture conditions (resulting from below-normal precipitation during WY 2000) that were likely present throughout the arroyo. The distal end of streamflow retreated upstream as daily mean streamflow steadily decreased.

For a given daily mean streamflow, monsoon events extend a greater distance downstream than snowmelt events (figs. 10–11). However, the duration of streamflow below the mountain front is greater for snowmelt events than for monsoon events, regardless of the magnitude of daily mean streamflow. Throughout the study period, snowmelt events produced more streamflow downstream from the mountain front than monsoon events; the increased extent of streamflow may be due to higher residual moisture contents in streambed sediments during spring than during summer months. Snowmelt events are more likely than monsoon events to result in streambed infiltration because (1) streamflow is of longer duration below the mountain front, (2) the total volume of streamflow is larger below the mountain front, (3) almost all streamflow is lost to infiltration, and (4) evapotranspiration rates are smaller during spring than summer and fall months.

Streambed Infiltration

Streambed infiltration rates were estimated through use of an inverse modeling technique that fits simulated to measured temperatures (Niswonger and Prudic, 2003). A variably saturated, two-dimensional, heat transport model (VS2DI) was used to simulate streambed infiltration during streamflow events (Hsieh and others, 2000). The model, which includes a graphical-user interface that runs the simulation model VS2DH (Healy and Ronan, 1996), has been successful in simulating heat and ground-water transport below streams (Ronan and others, 1998; Thomas and others, 2000).

Simulation of complex processes (such as streambed infiltration into unsaturated, layered sediments) is possible by using many simplifying assumptions. Further discussion of these assumptions and their consequences are available in Healy and Ronan (1996), Ronan and others (1998), Constantz and others (2002), and Niswonger and Prudic (2003). The manual trial-and-error calibration method was used for this study and the best fit (model solution) of simulated to measured temperatures was identified through visual inspection (Constantz and others, 2002; Niswonger and Prudic, 2003).

The best fit may not be unique because of the possibility that a suitable solution may be obtained by a variety of logical model configurations. While the model configuration and assumed properties of the best fit (described in the following sections) are reasonable, it is not suggested that this configuration is an accurate representation of actual conditions. Therefore, it is recognized that the best fit does not represent a unique solution and does not validate the assumed configuration and properties. Despite these limitations, model results are presented to provide an estimate of streambed infiltration and to provide insight into possible streambed infiltration processes.

Although data were collected at five thermistor nests, only one streamflow event was recorded because of below-normal precipitation conditions that persisted throughout the study period. During the spring snowmelt in 2001, the distal end of streamflow extended at least 4.73 km downstream from the stream gage. Thermistor nest TN1 (fig. 2) recorded streambed-sediment temperatures at the streambed surface, and at depths of 0.30, 0.94, and 2.1 m below land surface. The onset of streamflow, around midday on March 20, can be identified by the abrupt change in amplitude of the diurnal temperature signals (fig. 12); streamflow was present at this site for about 6 days. Streambed infiltration at TN1 was simulated by using VS2DI for this time period.

Model Configuration

The model configuration must be defined for the numerical simulation of streambed infiltration. Aspects of the model configuration include the geometry of the model domain, the hydraulic and transport properties of the streambed sedi-

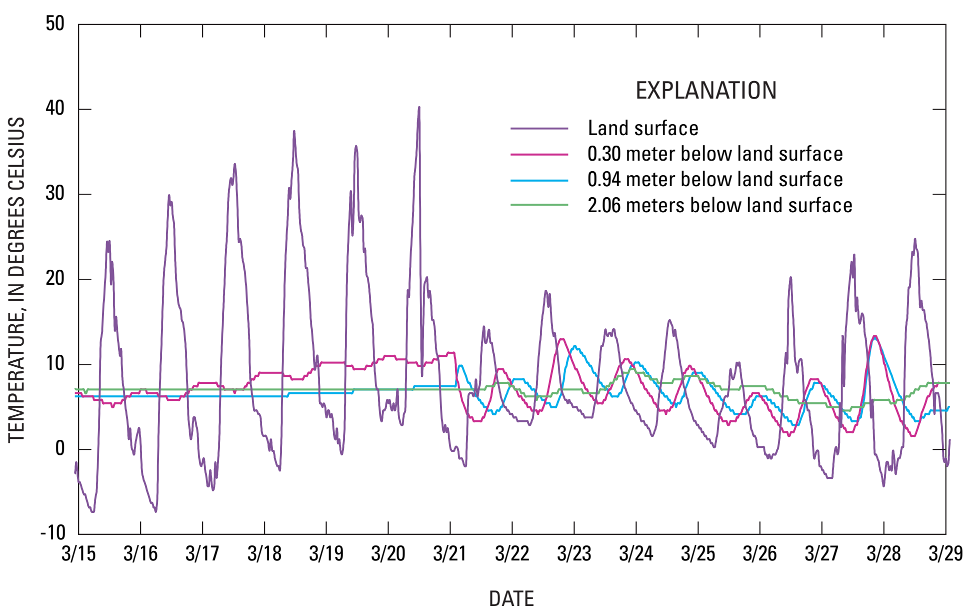

Figure 12. Temperatures at thermistor nest 1 (TN1) during March 2001, Arroyo Hondo study area, New Mexico. Streamflow began around midday on March 20, 2001. The location of TN1 is shown on figure 2.

ments, and the boundary and initial conditions. The model configuration is defined according to the conceptual framework of the system to be modeled; further details of model configuration are available in Hsieh and others (2000), and Niswonger and Prudic (2003).

This section describes the model configuration that resulted in the best fit of simulated to measured temperatures. Many aspects of the best-fit configuration were determined during the calibration process, as described in the next section.

The two-dimensional model domain is a longitudinal cross section of the streambed sediments (fig. 13). The model domain extends vertically from the streambed surface to the water table, which is located at 22 m below land surface for modeling purposes. The model domain is 30 m wide, with the streambed surface extending horizontally along the entire 30 m of the upper layer. Three observation points are centered horizontally in the model domain at depths corresponding to the locations of thermistors (0.30, 0.94, and 2.1 m below land surface). Grid spacing varies from 0.27 to 0.55 m in the horizontal direction and from 0.08 to 0.26 m in the vertical direction; the smallest cells are located near the observation points at the top and center of the model domain.

Boundary conditions (for temperature and pressure) were assigned for all boundaries of the model domain. The uppermost layer of cells in the model domain represents the stream and was defined by (1) a constant pressure head boundary and a (2) time-varying temperature boundary; temperatures at this boundary were varied according to those measured at the streambed surface at TN1. The water table was represented by the lowermost layer of cells in the model domain and was assigned a constant pressure head of zero meters and a constant temperature of 7°C. The two lateral boundaries of the model domain were designated as no-flow boundaries.

Initial hydraulic conditions were defined by an equilibrium profile (pressure head equals the negative elevation head above the water table), in which pressure head varied linearly with depth from zero m at the water table to –23 m at land surface. Initial temperatures in the model domain were specified at the observation points to be equal to measured temperatures at TN1. In the upper 2 m of the model domain, initial temperatures were assumed to be constant in the horizontal direction and to vary linearly with depth; below 2 m, initial temperatures were assumed to remain constant with depth.

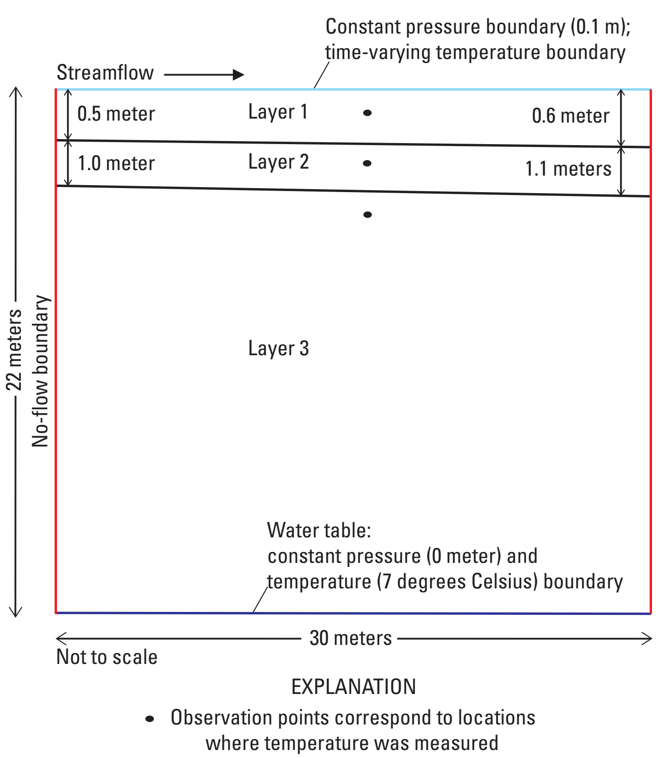

Figure 13. Schematic showing the best-fit model configuration, Arroyo Hondo study area, New Mexico.

Model Calibration

Model calibration was achieved through use of the manual trial and error approach (Constantz and others, 2002; Niswonger and Prudic, 2003). The objective of calibration is to obtain the best fit by minimizing the difference between simulated and measured temperatures. The best fit is identified through visual inspection of simulated and measured temperatures at the various observation points (fig. 13). The model (and, thus, the simulated streambed infiltration rate) is sensitive to particular hydraulic and transport properties. These properties, which include saturated hydraulic conductivity, anisotropy ratio, and longitudinal and transverse dispersivities, are varied during calibration in an attempt to minimize the difference between simulated and measured temperatures. Further details of the calibration process are available in Niswonger and Prudic (2003).

For this study, the model configuration progressed from simple to more complex during the calibration procedure. Initially, the two-dimensional model domain was defined as a perpendicular cross section of the stream channel (streamflow perpendicular to the model domain). The model domain consisted of a single layer (that is, hydraulic and transport properties were consistent for every point in the model domain).

The best fit was achieved by using a longitudinal cross section of the stream channel (streamflow parallel to the model domain) that consisted of three layers of varying hydraulic and transport properties (fig. 13). The geometry of the layers was not based on actual physical conditions of the streambed sediments; however, the configuration used for these simulations seems reasonable given that alluvial sediments are deposited in a layered fashion. The longitudinal cross section of the stream channel likely resulted in an improved fit because of the anisotropic nature typical of streambed sediments that results in a small component of horizontal flow (Niswonger and Prudic, 2003).

Sensitivity Analyses

Sensitivity analyses were performed to ensure that two simplifying assumptions (discussed below) used to assign boundary and initial conditions did not affect the estimated average infiltration rate. One assumption involves initial hydraulic condition for the model domain, which was defined as an equilibrium profile with the water table located 22 m below land surface. The water table is probably deeper than 22 m (fig. 5), but the exact location of the water table is not known. To investigate how the exact position of the water table (and associated changes in the equilibrium profile) affects infiltration rates, the depth of the water table was varied from 22 to 55 m. Results of these simulations indicate that the average infiltration rate was insensitive to the exact location of the water table.

The second assumption involves boundary conditions for the upper surface of the model domain. Boundary conditions for the upper surface were defined as a constant pressure head of 0.1 m because attempts to measure and record stream stage at TN1 were unsuccessful and the actual time-varying pressure head was unknown. Sensitivity analysis showed that the average infiltration rate was not affected by varying pressure head over its probable range of 0.05 to 0.2 m, which was determined through site inspection of high-water marks following the streamflow event.

Simulated Infiltration Rates

The best fit of simulated and measured temperatures (fig. 14) resulted in an effective saturated hydraulic conductivity of approximately 3 m/d and an estimated average infiltration rate of 1.4 m/d. The model domain required to achieve this fit consisted of three layers (fig. 13) and varying hydraulic and transport properties (table 2).

The estimated average infiltration rate (1.4 m/d) seems reasonable when compared with rates reported for the Santa Fe River (shown in fig. 1). Constantz and others (2002, p. 52–7) reported an initial streambed infiltration rate of 2.0 m/d, followed by a steady streambed infiltration rate of 0.1 m/d; both rates were determined by using VS2DI inverse-modeling techniques. Constantz and others (2002, p. 52–8) also reported an initial streambed channel loss of 1.0 m/d at the same location on the Santa Fe River, followed by a steady loss of 0.4 m/d; these rates were estimated by using more traditional surface-water techniques.

Cumulative Streambed Infiltration

The estimated average streambed infiltration rate was used in conjunction with the downstream extent of streamflow to estimate cumulative streambed infiltration along Arroyo Hondo. The following simplifying assumptions were used: (1) the average streambed infiltration rate for the 2.6-km reach immediately downstream from the mountain front is 1.4 m/d and (2) the wetted area of the active channel for any given day can be estimated from the minimum downstream extent of streamflow. For every day during the study period, the wetted area of the active channel can be estimated from channel widths measured at each surface temperature probe site and channel lengths. Because the actual downstream extent of streamflow is not known, minimum and maximum wetted channel areas were estimated.

The minimum wetted area for a given day was estimated as the sum of (1) the wetted channel area between the mountain front and the most downstream probe site with streamflow present, and (2) 5 percent of the wetted channel area of the next downstream segment (a segment is the reach of the channel between any two probe sites). The additional 5 percent of the wetted channel area was included because it is unlikely that streamflow ceased immediately downstream from a particular probe location. The maximum wetted channel area was estimated as the sum of (1) the wetted channel area between the mountain front and the farthest downstream probe site with streamflow present, and (2) 95 percent of the wetted channel area of the next downstream segment.

Minimum and maximum cumulative daily streambed infiltration values were calculated for every day in the study period. Minimum and maximum cumulative annual streambed infiltration values were estimated as the sum of all daily values for a particular water year.

Cumulative streambed infiltration was estimated to range from 17,100 m^3 to 230,000 m^3 during WY 2000 and from 58,500 m^3 to 246,000 m^3 during WY 2001. During WY 2002, cumulative streambed infiltration was zero. For purposes of comparison, estimates of cumulative streambed infiltration are shown in figure 15 along with streamflow measured during the study period, previous estimates of streamflow (Spiegel and Baldwin, 1963), and previous estimates of streambed infiltration (McAda and Wasiolek, 1988).

Estimates of cumulative streambed infiltration do not equal measured streamflow, except during WY 2002 (fig. 15). The differences are likely due to the simplifying assumptions used to estimate cumulative infiltration. For example, the streambed infiltration rate is unlikely to be constant throughout the upper ephemeral reach of Arroyo Hondo because infiltration rates are strongly influenced by the hydraulic conductivity of streambed sediments. Therefore, any variations in the hydraulic conductivity of streambed sediments, including variations in grain size and layering of sediments, would result in variations in the streambed infiltration rate. Additionally, estimates of wetted channel width (and thus wetted channel area) were assumed to remain constant from one streamflow event to another, although the active channel width probably varied from one streamflow event to another.

For every year of the study period, estimates of cumulative streambed infiltration are lower than previous estimates of streamflow and streambed infiltration (fig. 15). McAda and Wasiolek (1988) reported 625,000 m^3 per year of recharge from streambed infiltration; this value represents an aver-

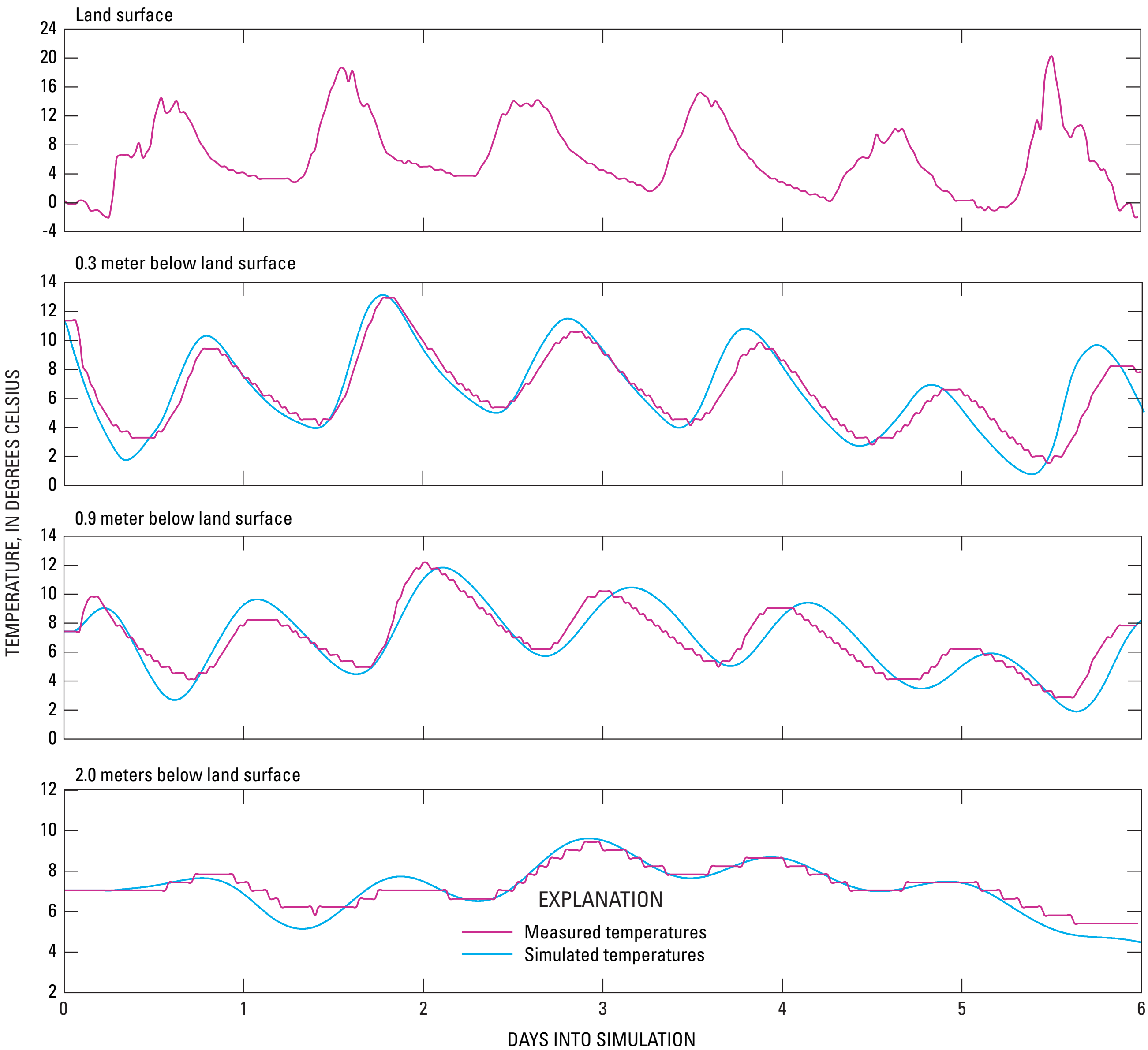

Figure 14. Measured and simulated temperatures at thermistor nest 1 (TN1) during March 2001 streamflow event, Arroyo Hondo study area, New Mexico. The location of TN1 is shown on figure 2.

Table 2. Selected hydraulic and transport properties used to simulate streambed infiltration.

Property (symbol)	Unit	Layer 1	Layer 2	Layer 3
Saturated hydraulic conductivity (K_{hh})	Meters per second	2.4×10^{-5}	3.5×10^{-5}	7.0×10^{-3}
Anisotropy ratio (K_{zz}/K_{hh})	Dimensionless	0.60	0.60	0.40
Porosity (η)	Dimensionless	0.38	0.38	0.38
Longitudinal dispersivity (α_L)	Meters	0.10	0.03	0.01
Transverse dispersivity (α_T)	Meters	0.10	0.03	0.01

age recharge rate. Normal precipitation, which represents a 30-year average value, for the Santa Fe area is 363 mm, which is 43 percent higher than mean annual precipitation (253 mm) measured during this study period. The annual water yield reported by Spiegel and Baldwin (660,000 m^3; 1963) was based on crest-stage gage data collected from 1913 to 1922. Based on long- term precipitation records for the Santa Fe 2 and Santa Fe weather stations, mean annual precipitation from 1913 to 1921 was approximately 379 mm per year (Western Regional Climate Center, 2002), which is about 50 percent higher than mean annual precipitation during the study period. Lower precipitation rates during this study may account for the smaller measured streamflow and, in part, for smaller estimates of cumulative streambed infiltration.

Recharge

Environmental tracers (chloride and bromide) were used to investigate the presence (or absence) of long-term recharge at selected locations in the Arroyo Hondo watershed. The basic principles of the chloride-mass balance method were applied to interpret environmental tracer data collected from soil cores in Arroyo Hondo.

Because chloride is water soluble, it moves through the unsaturated zone with infiltrating water. Therefore, large amounts of chloride in the unsaturated zone indicate that recharge is not occurring, and small amounts of chloride in the unsaturated zone indicate that recharge is occurring (Anderholm, 1994, p. 21–28; Izbicki and others, 2000, p. 206). Results of the chloride mass-balance method are valid only if the underlying assumptions are met (Scanlon, 2000).

Interpretation of Environmental Tracers

Variations in water content and chloride concentrations are shown in figure 16, in addition to variations in bromide concentrations. Chloride and bromide concentrations have similarly shaped profiles in each soil core (fig. 16). Chloride-bromide ratios varied from zero to 100. Discussion in this section is restricted to chloride concentrations; however, bromide concentrations are presented for comparison.

Volumetric water contents along transect 1 varied from 1 to 25 percent (fig. 16). Water contents were generally less than 10 percent in the upper 3 m of cores T1a and T1c; the largest water contents were about 5 m below land surface. The largest water content in core T1b occurred 1 m below land surface; water contents decreased to less than 10 percent

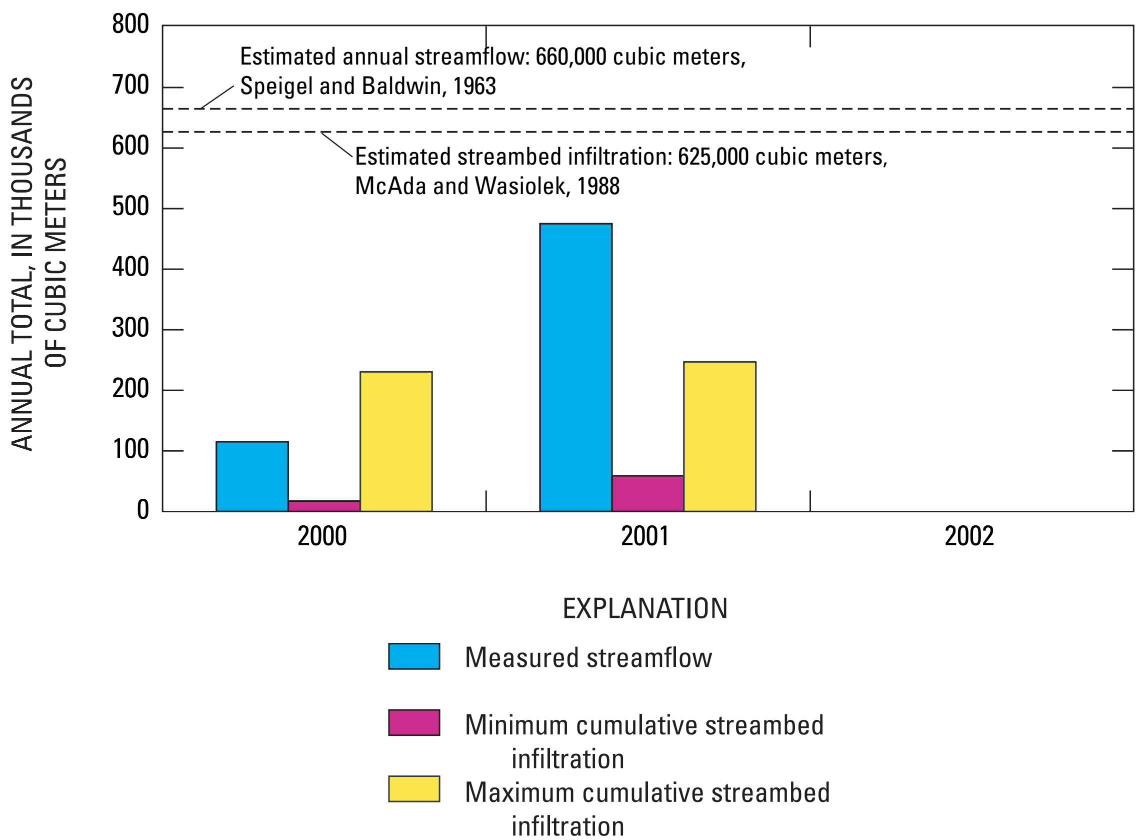

Figure 15. Measured streamflow, estimates of cumulative streambed infiltration, and previous estimates of streamflow and streambed infiltration, Arroyo Hondo study area, New Mexico.

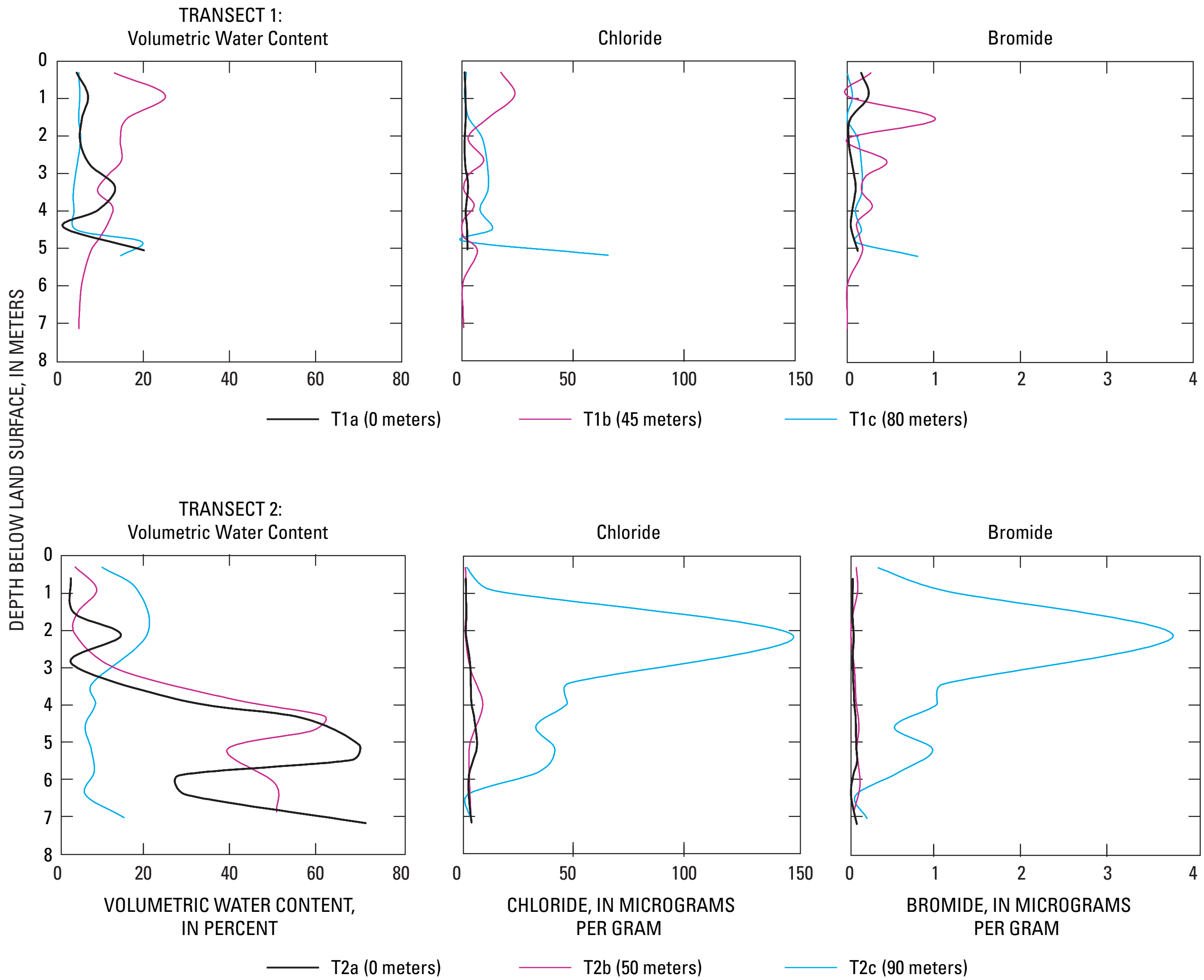

Figure 16. Volumetric water content and chloride and bromide concentration profiles for soil cores collected along transects 1 and 2 of the Arroyo Hondo study area, New Mexico. Distance from the arroyo channel is shown in parentheses. The locations of the transects are shown on figure 2.

at 7 m below land surface. Along transect 2, water contents varied from 2 to 70 percent. Water contents were less than 20 percent in the upper 3 m of cores T2a and T2b and increased to a maximum of 70 percent below 4 m. A thin layer (less than 0.3 m thick) of saturated, coarse-grained sand was penetrated between 5 and 6 m in cores T2a and T2b; a thin layer of silt was immediately below this layer. This layering may account for the unusually large volumetric water contents below 4 m in cores T2a and T2b. In core T2c, water contents were largest (about 20 percent) in the upper 3 m and smallest (less than 10 percent) in the lower 4 m.

Chloride concentrations ranged from less than 0.1 to 65 µg/g along transect 1 and from less than 0.1 to 147 µg/g along transect 2 (fig. 16). Core T1a, located in the active channel of the upper ephemeral reach, had the smallest chloride concentrations. Core T2c, located 90 m from the active channel in the lower ephemeral reach, had the largest chloride concentrations.

Chloride concentrations in core T2c (fig. 16) form a distinctive bulge-shaped profile that is typical of desert soils and indicate that direct recharge does not occur at that particular location. Chloride concentrations increase from 1.5 µg/g near land surface to a maximum of 147 µg/g at about 2 m below land surface, and then gradually decrease with depth to approximately 2 µg/g at about 7 m below land surface. Anderholm (1994, p. 21–23) reported similarly shaped profiles at three locations (“mesa sites”) within the Española Basin. Previous investigators have reported similar profiles in various arid regions including South Australia (Allison and others, 1985), western Texas (Scanlon, 1991), and the Mojave Desert (Izbicki and others, 2000; Stonestrom and others, 2003). The mass of chloride stored in the upper 7 meters of core T2c is 609.24 g/m2. Given a mean annual chloride deposition rate of 0.105 g/m2 (Anderholm, 1994, p. 18), this amount of chloride would take an estimated 5,800 years to accumulate (table 3). This

Table 3. Results of environmental tracer applications at selected locations in the Arroyo Hondo watershed.

Core identification	Transect location	Distance from active channel, in meters	Accumulation time[1], in years	Recharge[2]
T1a[3]	Upper ephemeral reach[4]	0	170	Yes
T1b	Upper ephemeral reach[4]	45	800	Possible low rate
T1c	Upper ephemeral reach[4]	80	1,300	Possible low rate
T2a[3]	Lower ephemeral reach[5]	0	350	Yes
T2b	Lower ephemeral reach[5]	50	350	Yes
T2c	Lower ephemeral reach[5]	90	5,800	Negligible

[1]The time required for the mass of chloride stored in the core to accumulate, as calculated from application of the chloride mass-balance method.

[2]Environmental tracers indicate only the presence or absence of recharge. The type of recharge (direct or focused) cannot be determined by using this method.

[3]Located in the active ephemeral channel.

[4]Transect T1 is located appoximately 2.6 kilometers downstream from the mountain front.

[5]Transect T2 is located approximately 12 kilometers downstream from the mountain front.

indicates that recharge is not presently occurring at the valley margin in the lower reaches of Arroyo Hondo.

Chloride concentrations in cores T1b and T1c are difficult to interpret because their profiles do not clearly indicate whether or not recharge is present (fig. 16). Chloride concentrations in core T1b are largest (18–24 µg/g) from zero to 1 m below land surface, decrease from 1 to 2 m, and remain less than about 9 µg/g. Chloride concentrations in core T1c are smallest (1.1 to 3.0 µg/g) from zero to 1.5 m, then increase to approximately 11 µg/g from about 2 to almost 5 m. A single sample from core T1c indicates an abrupt increase in chloride (and bromide) concentrations at about 5 m below land surface; the significance of this increase is unknown. The mass of chloride stored in the upper 5 m of cores T1b and T1c is 85 and 134 g/m2, respectively. The times required to accumulate these amounts of chloride are estimated to be 800 and 1,300 years, respectively (table 3). Although the chloride concentrations in cores T1b and T1c are small relative to those in T2c (fig. 16), the time required to accumulate the mass of chloride stored in T1b and T1c suggests that if recharge is occurring at these locations, it is at small rates.

Chloride concentrations in cores T1a, T2a, and T2b are relatively small (less than 9 µg/g) and generally show little variation with depth (fig. 16), indicating that recharge is presently occurring at these locations. Chloride concentrations in core T1a, located in the active channel of the upper ephemeral reach, vary from 1.1 to 2.8 µg/g. Chloride concentrations in core T2a, located in the arroyo channel of the lower ephemeral reach, vary from 1.1 to 6.1 µg/g. Chloride concentrations in core T2b, located 50 m from the arroyo channel, vary from 0.86 to 8.4 µg/g. Chloride profiles of cores T2a and T2b show a small bulge with maximum chloride concentrations at 4 and 5 m below land surface, respectively. Previous studies show that similar profiles with small chloride concentrations and little variation with depth indicate the presence of recharge (Anderholm, 1994; Izbicki and others, 2000). Anderholm (1994) reported similar profiles for two locations in active arroyo channels in the Española Basin.

Implications of Environmental Tracers

Interpretations of environmental tracers (table 3) generally agree with the conceptual model of recharge in the Arroyo Hondo watershed. Focused recharge is presently occurring in the upper ephemeral reaches of Arroyo Hondo (T1a). Direct recharge is presently occurring in the lower ephemeral reaches of Arroyo Hondo (T2a), and in other permeable areas of the Arroyo Hondo watershed (T2b). In the less permeable areas of the Arroyo Hondo watershed (T2c), recharge is not presently occurring.

Tracers indicate that recharge is occurring in the active channel of Arroyo Hondo (T1a and T2a) and at a site located

50 m from the active channel (T2b). Characterization of streamflow and investigation of streambed infiltration during this study (see sections on Streamflow and Streambed Infiltration) validate the presence of focused recharge in the active channel of the upper ephemeral reach (T1a). Results of this study suggest that focused recharge is not occurring in the active channel of the lower ephemeral reach; however, previous investigators have reported small amounts of direct recharge throughout the Arroyo Hondo watershed (Spiegel and Baldwin, 1963; Lee Wilson and Associates, 1978; McAda and Wasiolek, 1988).

Summary

This chapter presents the results of a three-year study of streamflow, infiltration, and recharge in Arroyo Hondo, New Mexico. Data were collected from October 1999 through October 2002 (WY 2000–02). Traditional and experimental methods were used to characterize streamflow in Arroyo Hondo. Traditional methods were used to characterize streamflow at a continuous-record stream gage. Experimental temperature-based methods were used to estimate the presence and duration of streamflow at selected sites along Arroyo Hondo. Streambed infiltration rates were estimated by using an inverse modeling technique that fits simulated to measured subsurface temperatures. Cumulative streambed infiltration rates were estimated from streambed infiltration rates, channel widths, and the downstream extent and duration of streamflow. Two environmental tracers (chloride and bromide) were used to investigate the presence of recharge at selected sites. Precipitation during the study period was below normal for two of three years.

Total annual streamflow in Arroyo Hondo ranged from zero to 474,000 m^3 during the study period. Annual streamflow was largest (474,000 m^3) in WY 2001 when annual precipitation at the Santa Fe 2 weather station was 103 percent of normal. Annual streamflow was smallest in WY 2002 (zero m^3) when annual precipitation at Santa Fe 2 was 57 percent of normal. Below-normal precipitation in the Santa Fe area during WY 2002 resulted in the smallest streamflows on record at streamflow-gaging stations Tesuque Creek above diversions near Santa Fe, N. Mex., and Santa Fe River above McClure Reservoir near Santa Fe, N. Mex. Snowmelt-induced streamflow events result in a larger total streamflow than monsoon-induced streamflow events.

Twelve surface-temperature probes were installed at selected locations in and near the arroyo channel; thermographs were constructed from data provided by surface-temperature probes. For each probe site, the presence and duration of streamflow was determined through inspection of thermographs. This information was used to ascertain the minimum downstream extent of continuous streamflow for every day in the study period. For a given daily mean streamflow (at the stream gage), monsoon-induced streamflow events extend a greater distance downstream from the mountain front than snowmelt-induced streamflow events. However, the duration of streamflow below the mountain front is greater during snowmelt-induced streamflow events than during monsoon-induced streamflow events. Throughout the study period, snowmelt-induced streamflow events produced more streamflow downstream from the mountain front than monsoon-induced streamflow events; the increased extent of streamflow may be due to higher residual moisture contents in streambed sediments during spring than during summer months. Snowmelt events are more likely than monsoon events to result in streambed infiltration because (1) a greater duration of streamflow below the mountain front, (2) a larger total volume of streamflow below the mountain front, (3) almost all streamflow is lost to infiltration, and (4) evapotranspiration rates are smaller during spring than summer and fall months.

A variably saturated, two-dimensional, heat transport model (VS2DI) was used to simulate streambed infiltration during streamflow events. The best fit of simulated and measured temperatures resulted in an effective saturated hydraulic conductivity of approximately 3 m/d and an estimated average infiltration rate of 1.4 m/d. The model domain required to achieve this fit consisted of three layers with varying hydraulic and transport properties. The estimated average infiltration rate (1.4 m/d) seems reasonable when compared with rates reported for the Santa Fe River.

Several simplifying assumptions were used to estimate cumulative streambed infiltration rates. Cumulative streambed infiltration was estimated to range from 17,100 m^3 to 230,000 m^3 during WY 2000, and from 58,500 m^3 to 246,000 m^3 during WY 2001. Cumulative streambed infiltration during water year 2002 was zero. Estimates of cumulative streambed infiltration do not equal measured streamflow, except during WY 2002; the differences are likely due to the simplifying assumptions used to estimate cumulative infiltration.

For every year of the study period, measured streamflow and estimates of cumulative streambed infiltration are lower than previous estimates of streamflow (660,000 m^3) and streambed infiltration (625,000 m^3). Below-normal precipitation during WY 2000–02 may account for the smaller measured streamflow and, in part, for smaller estimates of cumulative streambed infiltration.

Two environmental tracers (chloride and bromide) were used to investigate the presence of long-term recharge at selected locations in the Arroyo Hondo watershed. Interpretations of environmental tracers generally agree with the conceptual model of recharge (based on results of this study and those of previous investigations) in the Arroyo Hondo watershed. Tracers indicate that recharge is occurring in the active channel of Arroyo Hondo (T1a and T2a) and at a site located 50 m from the active channel (T2b). Characterization of streamflow and investigation of streambed infiltration conducted during this study indicate that focused recharge resulting from streambed infiltration is occurring in the upper portion of the ephemeral reach of Arroyo Hondo.

References Cited

Allison, G.B., Stone, W.J., and Hughes, M.W., 1985, Recharge in karst and dune elements of a semi-arid landscape as indicated by natural isotopes and chloride: Journal of Hydrology, v. 76, p. 1–26.

Anderholm, S.K., 1994, Ground-water recharge near Santa Fe, north-central New Mexico: U.S. Geological Survey Water-Resources Investigations Report 94–4078, 68 p.

Constantz, J., Stewart, A.E., Niswonger, R., and Sarma, L., 2002, Analysis of temperature profiles for investigating stream losses beneath ephemeral channels: Water Resources Research, v. 38, no. 12, p. 52(1)–52(13).

Constantz, J., and Thomas, C.L., 1996, The use of streambed temperature profiles to estimate the depth, duration, and rate of percolation beneath arroyos: Water Resources Research, v. 32, no. 12, p. 3597–3602.

Constantz, J., Tyler, S.W., and Kwicklis, E.K., 2003, Temperature-profile methods for estimating percolation rates in arid environments: Vadose Zone Journal, v. 2, p. 12–24.

Duke Engineering and Services, 2001, Water supply study, Jemez y Sangre Water Planning Region, New Mexico: Charlotte, North Carolina, Duke Engineering and Services, 235 p.

Healy, R.W., and Ronan, A.D., 1996, Documentation of computer program VS2DH for simulation of energy transport in variably saturated porous media—Modification of the U.S. Geological Survey's computer program VS2DT: U.S. Geological Survey Water-Resources Investigations Report 96–4230, 36 p.

Hsieh, P.A., Wingle, W., and Healy, R.W., 2000, VS2DI—A graphical software package for simulating fluid flow and solute or energy transport in variably saturated porous media: U.S. Geological Survey Water-Resources Investigations Report 99–4130, 16 p.

Izbicki, J.A., Radyk, J., and Michel, R.L., 2000, Water movement through a thick unsaturated zone underlying an intermittent stream in the western Mojave Desert, southern California, USA: Journal of Hydrology, v. 238 (3–4), p. 194–217.

Lapham, W.W., 1987, Use of temperature profiles beneath streams to determine rates of vertical ground-water flow and vertical hydraulic conductivity: U.S. Geological Survey Water-Supply Paper 2337, 35 p.

Lee Wilson and Associates, 1978, Santa Fe County water plan, Santa Fe County, New Mexico: Santa Fe, Lee Wilson and Associates, 162 p.

McAda, D.P., and Wasiolek, Maryann, 1988, Simulation of the regional geohydrology of the Tesuque aquifer system near Santa Fe, New Mexico: U.S. Geological Survey Water-Resources Investigations Report 87–4056, 71 p.

Niswonger, R.G., and Prudic, D.E., 2003, Modeling heat as a tracer to estimate streambed seepage and hydraulic conductivity, *in* Stonestrom, D.A., and Constantz, J., eds., Heat as a tool for studying movement of ground water near streams: U.S. Geological Survey Circular 1260, 96 p.

Ronan, A.D., Prudic, D.E., Thodal, C.E., and Constantz, J., 1998, Field study and simulation of diurnal temperature effects on infiltration and variably saturated flow beneath ephemeral streams: Water Resources Research, v. 34, no. 9, p. 2137–2153.

Scanlon, B.R., 1991, Evaluation of moisture flux from chloride data in desert soils: Journal of Hydrology, v. 128, p. 137–156.

Scanlon, B.R., 2000, Uncertainties in estimating water fluxes and residence times using environmental tracers in an unsaturated zone: Water Resources Research, v. 36, no. 2, p. 395–409.

Stonestrom, D.A., Prudic, D.E., Laczniak, R.J., Akstin, K.C., Boyd, R.A., and Henkelman, K.K., 2003, Estimates of deep percolation beneath irrigated fields, native vegetation, and the Amargosa River channel, Amargosa Desert, Nye County, Nevada: U.S. Geological Survey Open-File Report 03–104, 83 p.

Spiegel, Zane, and Baldwin, B., 1963, Geology and water resources of the Santa Fe area, New Mexico: U.S. Geological Survey Water-Supply Paper 1525, 258 p.

Stewart, A.E., 2003, Temperature based estimates of streamflow patterns and seepage losses in ephemeral channels: Stanford, Calif., Stanford University, Ph.D. dissertation, 248 p.

Thomas, C.L., Stewart, A.E., and Constantz, J., 2000, Determination of infiltration and percolation rates along a reach of the Santa Fe River near La Bajada, New Mexico: U.S. Geological Survey Water-Resources Investigations Report 00–4141, 65 p.

Western Regional Climate Center, 2003, Santa Fe 2, New Mexico, Period of record climate summary: http://www.wrcc.dri.edu/cgi-bin/cliMAIN.pl?nmsaf2, last accessed April 2003.