USGS Professional Paper 1703—Ground-Water Recharge in the Arid and Semiarid Southwestern United States—Chapter D

Streamflow, Infiltration, and Ground-Water Recharge at Abo Arroyo, New Mexico

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Abstract

Abo Arroyo, an ephemeral tributary to the Rio Grande, rises in the largest upland catchment on the eastern side of the Middle Rio Grande Basin (MRGB). The 30-kilometer reach of channel between the mountain front and its confluence with the Rio Grande is incised into basin-fill sediments and separated from the regional water table by an unsaturated zone that reaches 120 meters thick. The MRGB portion of the arroyo is dry except for brief flows generated by runoff from the upland catchment. Though brief, ephemeral flows provide a substantial fraction of ground-water recharge in the southeastern portion of the MRGB. Previous estimates of average annual recharge from Abo Arroyo range from 1.3 to 21 million cubic meters. The current study examined the timing, location, and amount of channel infiltration using streamflow data and environmental tracers during a four-year period (water years 1997–2000). A streamflow-gaging station ("gage") was installed in a bedrock-controlled reach near the catchment outlet to provide high-frequency data on runoff entering the basin. Streamflow at the gage, an approximate bound on potential tributary recharge to the basin, ranged from 0.8 to 15 million cubic meters per year. Storm-generated runoff produced about 98 percent of the flow in the wettest year and 80 percent of the flow in the driest year. Nearly all flows that enter the MRGB arise from monsoonal storms in July through October. A newly developed streambed temperature method indicated the presence and duration of ephemeral flows downstream of the gage. During the monsoon season, abrupt downward shifts in streambed temperatures and suppressed diurnal ranges provided generally clear indications of flow. Streambed temperatures during winter showed that snowmelt is also effective in generating channel infiltration. Controlled infiltration experiments in dry arroyo sediments indicated that most ephemeral flow is lost to seepage before reaching the Rio Grande. Streambed temperature records confirmed this, providing evidence of only two flows reaching the Rio Grande during a three-year period (water years 1998–2000). Sub-channel chloride concentrations indicate that approximately half of the seepage loss eventually becomes ground-water recharge. Vertical profiles of pore-water chloride in transects adjacent to the channel indicate that basin-floor recharge outside the arroyo is negligible under current climatic conditions.

Introduction

Abo Arroyo is an impressive example of the ephemeral streams linking lateral upland catchments to the Rio Grande, the regional axial drainage of the extensional Rio Grande Rift. The arroyo's headwaters spread over a large, elevated catchment separated from the Middle Rio Grande Basin (MRGB) by the Manzano and Los Piños Mountains (fig. 1). The exposed Precambrian bedrock of these ranges forms the southeastern border, or mountain front, of the basin. Upstream of the mountain front, Abo Arroyo comprises a dendritic system of meandering canyons cut into Paleozoic sedimentary rocks. Base flow is small and restricted to a bedrock-controlled reach near the mountain front. Downstream of the mountain front, where it lacks substantial tributaries, the normally dry arroyo cuts into unconsolidated Cenozoic sands and gravels. Abo Arroyo crosses several distinct geomorphologic settings between the upland catchment and the Rio Grande. The exposed bedrock of the upland catchment and alluvial cliffs and terraces along the arroyo reflect millions of years of landscape evolution under hydraulic conditions often different from those today.

Sparse vegetation lines the arroyo banks within the MRGB. The channel floor, free of vegetation but strewn with boulders, evinces sporadic interruption of no-flow conditions by flash flood events. Understanding present-day ground-water recharge requires information about the spatial and temporal patterns of ephemeral flows, associated streambed infiltration, and subsequent losses of infiltrated water to evapotranspiration. Because bedrock at the mountain front is largely impermeable (Anderholm, 2000), recharge to MRGB ground water from the upland catchment is primarily restricted to infiltration from flows crossing into the basin. Water that enters the basin as sub-channel seepage from the small but persistent base flow just upstream of the mountain front may also be important.

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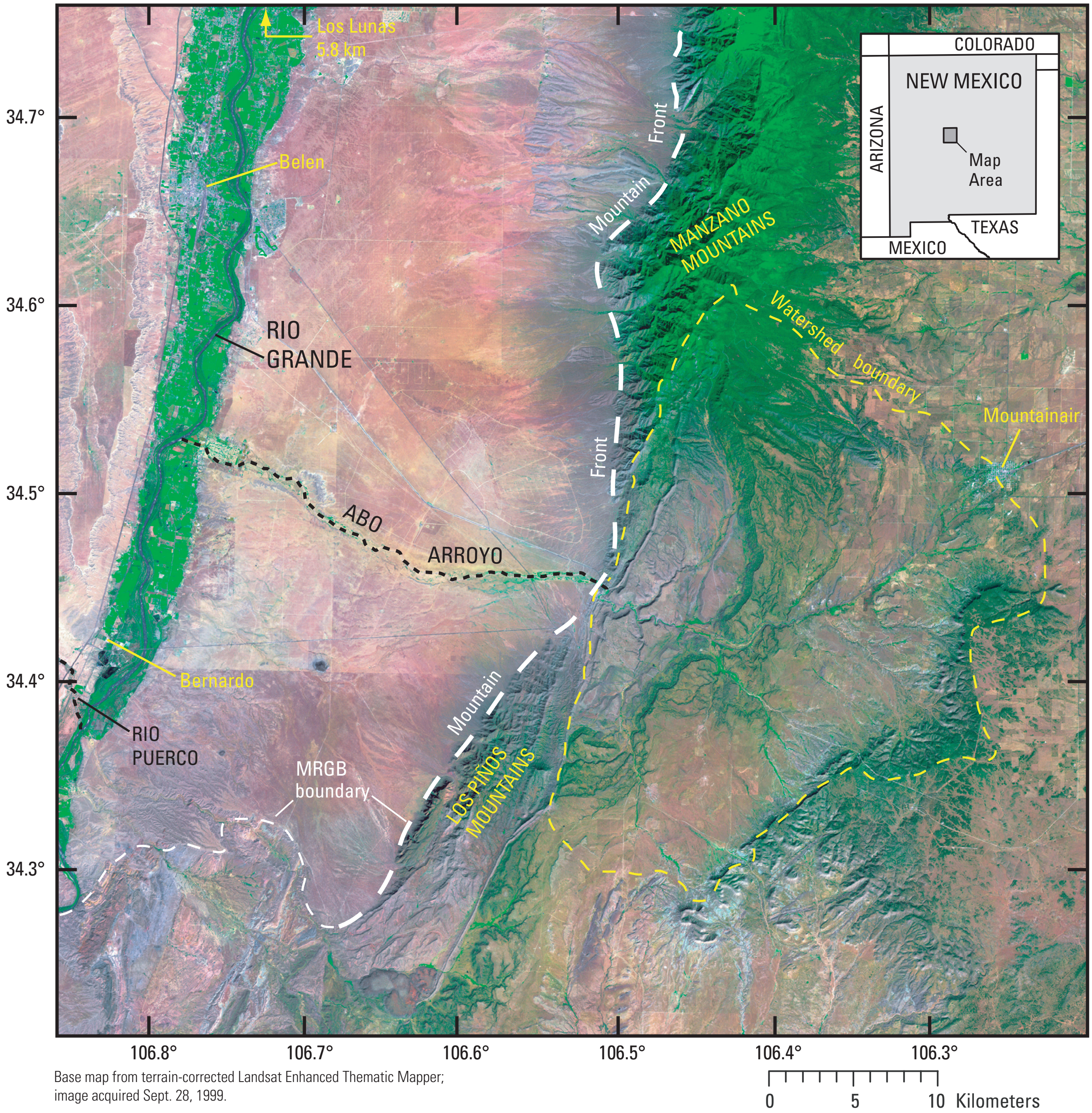

Base map from terrain-corrected Landsat Enhanced Thematic Mapper; image acquired Sept. 28, 1999.

Figure 1. Abo Arroyo in the southeastern Middle Rio Grande Basin (MRGB) with its contributing watershed (upland catchment). False-color satellite image shows active vegetation as bright green, basin-fill and ancestral Rio Grande floodplain deposits as shades of pink, Paleozoic sedimentary rocks of Abo Canyon (east of the mountain front) as brown to purplish gray, basalt flows (most prominently at the south end of the Los Piños Mountains) as dark gray with red, and urban areas as speckled gray.

Traditional methods for gaging streams are ill suited to normally dry alluvial channels with infrequent, high-energy flows. Moving bedload is destructive and changes channel geometry. As a result, ephemeral streamflow data are scarce.

As a prominent example of an ungaged and undeveloped basin in the semiarid southwest, Abo Arroyo presented the opportunity to develop needed techniques for determining focused recharge from ephemeral flows. At the same time, the remoteness of Abo Arroyo presented challenges to instrument development and hydrologic conceptualization. The primary approach was to develop unattended temperature-based methods as a simple means for determining ephemeral streamflow and associated infiltration-induced recharge. Thermal techniques used at the other southwest ground water recharge sites trace their origins to this work. Abo Arroyo proved valuable for developing hydrologic concepts as well. The juxtaposition of hydraulic settings and their seasonal interactions provided a natural laboratory for studying a system dominated by ephemeral flow.

High frequency monitoring of streambed temperatures downstream of the mountain front, together with flow monitoring in the upland catchment, allowed detailed characterization of streamflow and recharge in time and space. The protocol for temperature-based determination of streamflow in arid environments evolved during the course of the study by model-guided trial and error. In addition to temperature-based monitoring, infiltration tests in dry arroyo sediments provided information on potential losses during flow events. Profiles of chloride and bromide in unsaturated-zone pore water provided supporting information on the amount of infiltrated channel water becoming ground-water recharge and on potential recharge from infiltrating precipitation adjacent to the channel. This latter work water indicated focusing of recharge beneath the active channel and long times of accumulation, or time since recharge last occurred, on terraces adjacent to the channel.

Hydrogeologic Setting

Abo Arroyo joins the Rio Grande about 65 km south of Albuquerque, between the towns of Belen and Bernardo (fig. 1). The altitude of the confluence is about 1,450 m. The 30-km study reach flows east to west, entering the MRGB through a narrow canyon separating the northern tip of the Los Piños Mountains from the southern tip of the Manzano Mountains. Maximum altitudes in these ranges reach 2,347 and 3,048 m, respectively. The arroyo crosses the mountain front at an altitude of 1,651 m. The watershed supplying the arroyo upstream of the mountain front has an area of about 650 km^2 (Anderholm, 2000).

The study reach begins near the mountain front (fig. 2). Once inside the MRGB, the arroyo cuts into the piedmont formed by coalescing alluvial fans issuing from the mountains (Hawley and others, 1982). The piedmont pinches out 5-10 km downstream of the mountain front, where Abo Arroyo cuts into a stepped sequence of abandoned fluvial terraces of the ancestral Rio Grande (Titus, 1963). The study reach terminates at its intersection with the active floodplain of the modern Rio Grande.

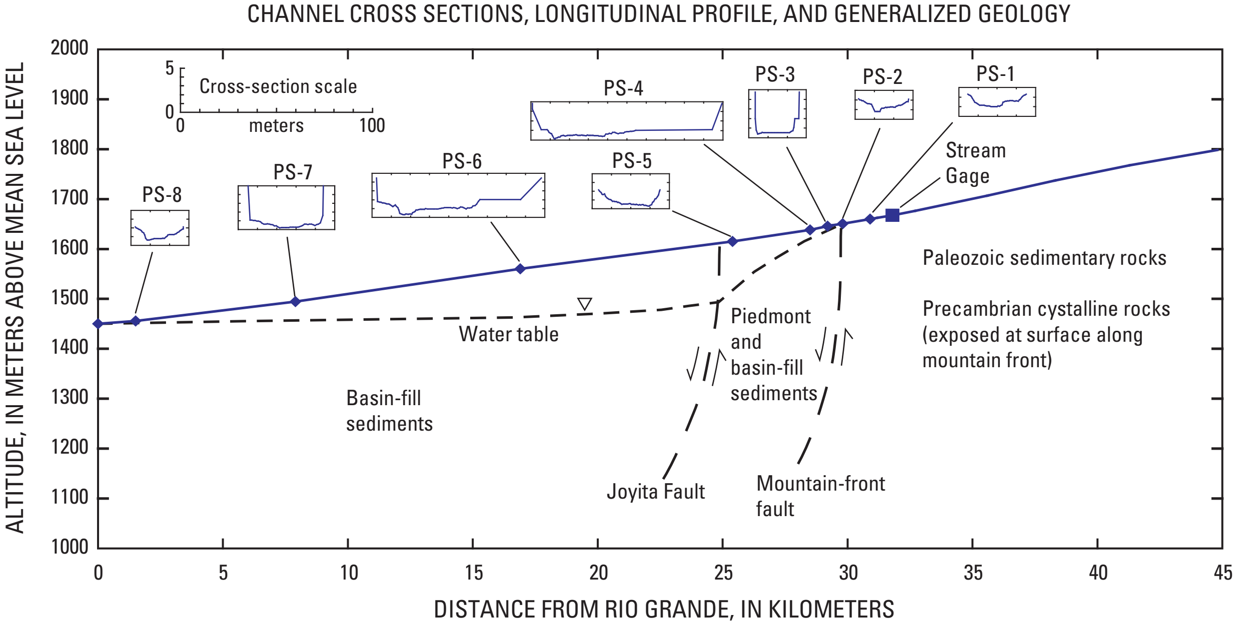

Figure 2. Longitudinal profile, and generalized geology of Abo Arroyo from its confluence with the the Rio Grande (altitude 1,450 meters) to an altitude of 1,800 meters, with channel cross-sections at probe-site (temperature monitoring) locations PS-1 to PS-8. Vertical exaggerations of the longitudinal profile and channel cross sections are 1:20 and 1:4, respectively. Longitudinal profile runs roughly west (left) to east (right). Channel cross-sections run north (left) to south (right). Water-table profile is from contour map of predevelopment levels (Bexfield and Anderholm, 2000). Locations of the Joyita and unnamed mountain-front faults are from figure 4 of Kernodle, McAda, and Thorn (1995).

Base flow is usually perennial just upstream of the mountain front, where the alluvium is thin. As the channel crosses onto the thick alluvium of the MRGB, base flow becomes nonexistent and flows are limited to short events caused by storm runoff from the upland catchment. Tributary inflows are negligible downstream of the mountain front. The unsaturated zone beneath the channel ranges from 30 to 120-m thick near the mountain front to 5 to 30-m thick near the Rio Grande (Titus, 1963; Bexfield and Anderholm, 2000).

Sediments transported into the arroyo derive primarily from Paleozoic sedimentary rocks in the upland catchment (fig. 1). The dominant source rocks are Pennsylvanian limestones and shales in the lower elevations near the mountain front, and Permian arkosic redbeds (mostly sandstones) in the higher elevations away from the mountain front (Spiegel, 1955; Dane and Bachman, 1965; Scholle, 2003). Contacts and bedding dip eastward in opposition to the channel gradient, impeding flow toward the MRGB. Within the basin, channel sediments range from boulders to fine sand near the mountain front to fine to medium sands near the Rio Grande (fig. 3). The downstream fining indicates a loss of transport power associated with high rates of channel infiltration. In the lower half of the study reach, at PS-6 and 7, the channel surface tended to crust when dry due to recessional deposition of small amounts of fines (fig. 2). Little crusting was observed upstream, where sediments were coarser.

The channel bottom supports little vegetation beyond scattered individuals of fast-growing species—mostly grasses—indicating frequent scour. Mixed vegetation lines the channel banks, with salt cedars (*Tamarix*) dominating the active floodplain upstream of the mountain front (fig. 3*A*) and near the floodplain of the Rio Grande (fig. 3*D*). Grasses, cacti, and shrubs form sparse cover on the elevated terrace adjacent to the channel (figs. 3*B*,*C*). Grasses are the most abundant plant adjacent to the channel, with shorter species near the mountain front giving way to taller species at lower elevations in the MRGB. Unexposed slopes in the upland catchment support piñon pines and junipers (figs. 3*A*,*B*)

Unconsolidated terrace sediments form dark red cliffs along the arroyo. In the middle of the study reach, the arroyo opens up to widths around 100 meters where channel banks have collapsed. The channel slope is relatively steep throughout the study reach, varying from 11 m/km near the mountain front to 6 m/km near the Rio Grande (fig. 2).

The primary land use within the Abo Arroyo section of the MRGB is rangeland. Irrigated crops grow at the downstream end of the study reach, forming a rectangular projection from the cultivated Rio Grande corridor. The upland catchment is almost entirely undeveloped (fig. 1).

Precipitation within the MRGB generally averages less than 300 mm/yr (Thorn and others, 1993). Precipitation increases in the bordering highlands due to orographic effects, reaching an estimated annual average of 760 mm along the crest of the Manzano Mountains (Anderholm, 2000). The largest amount of precipitation falls during the summer monsoon, with July, August, and September accounting for half the annual total (fig. 4). Winter precipitation at higher elevations consists primarily of snowfall, leading to occasional periods of snowmelt-supplied streamflow. Annual precipitation shows large year-to-year and sub-decadal fluctuations (fig. 5). Precipitation at Bernardo was 329 mm during the first year of the study, 54 percent above average, and 161 mm during the final year of the study, 25 percent below average. Even during the wettest years, potential evaporation (1,700 mm/yr) far exceeded precipitation (Stephens and Knowlton, 1986).

Previous Work

The desire to sustainably develop ground water has prompted repeated efforts to quantify recharge in the MRGB. Due to its large contributing area, the potential importance of Abo Arroyo was recognized by early ground-water modelers. Methods of estimating recharge, and estimates themselves, varied widely (fig. 6). The earliest estimate, a water-balance calculation by J. Dewey (reported by Kernodle and Scott, 1986), was about 19 million cubic meters per year (Mm^3 yr^{-1}). Subsequent estimates, based on outflow from the upland catchment (“basin yield”), ranged from 5 to 21 Mm^3 yr^{-1} (fig. 6). These estimates were based on nonlinear relationships—among precipitation, catchment area, and basin yield—that were developed with data from similar, gaged catchments. Basin-yield estimates assume that all streamflow exiting the upland catchment becomes ground-water recharge.

Anderholm (2000) derived an estimate of 1.6 Mm^3 yr^{-1} on the basis of an assumed steady-state mass-balance between meteoric chloride entering the catchment (in precipitation and dry deposition) and chloride leaving the catchment (in recharge to the basin aquifer). This approach used ground water near the mountain front to approximate the chloride concentration of recharge. Nimmo and others (2001) derived a nearly identical estimate by sampling the unsaturated hydraulic conductivity beneath the channel, applying Darcy’s law, and distributing the calculated recharging fluxes on the basis of broad geomorphic setting (Rio Grande floodplain, ancestral fluvial terrace, and piedmont slope).

Sanford and others (2004) matched water levels, ages, and solute compositions in a numerical model of the MRGB aquifer by adjusting hydraulic properties and recharge rates. This work, which drew on extensive geochemical characterization of Plummer and others (2004), successfully simulated the shape of the MRGB water table, including a prominent trough-like feature that had not previously been explained. Simulated recharge rates for the last glacial maximum were higher than today’s rates by ten to twenty times. The boundary of the numerical model was midway between the mountain front and the Rio Grande. Estimated current recharge in the modeled portion of the arroyo was 1.3 Mm^3 yr^{-1}.

Hydrochemical zonation of ground water clearly shows the imprint of Abo Arroyo recharge. Figure 7, adapted from Plummer and others (2004), synthesizes data in the southeastern MRGB. A region of relatively cool ground water lies

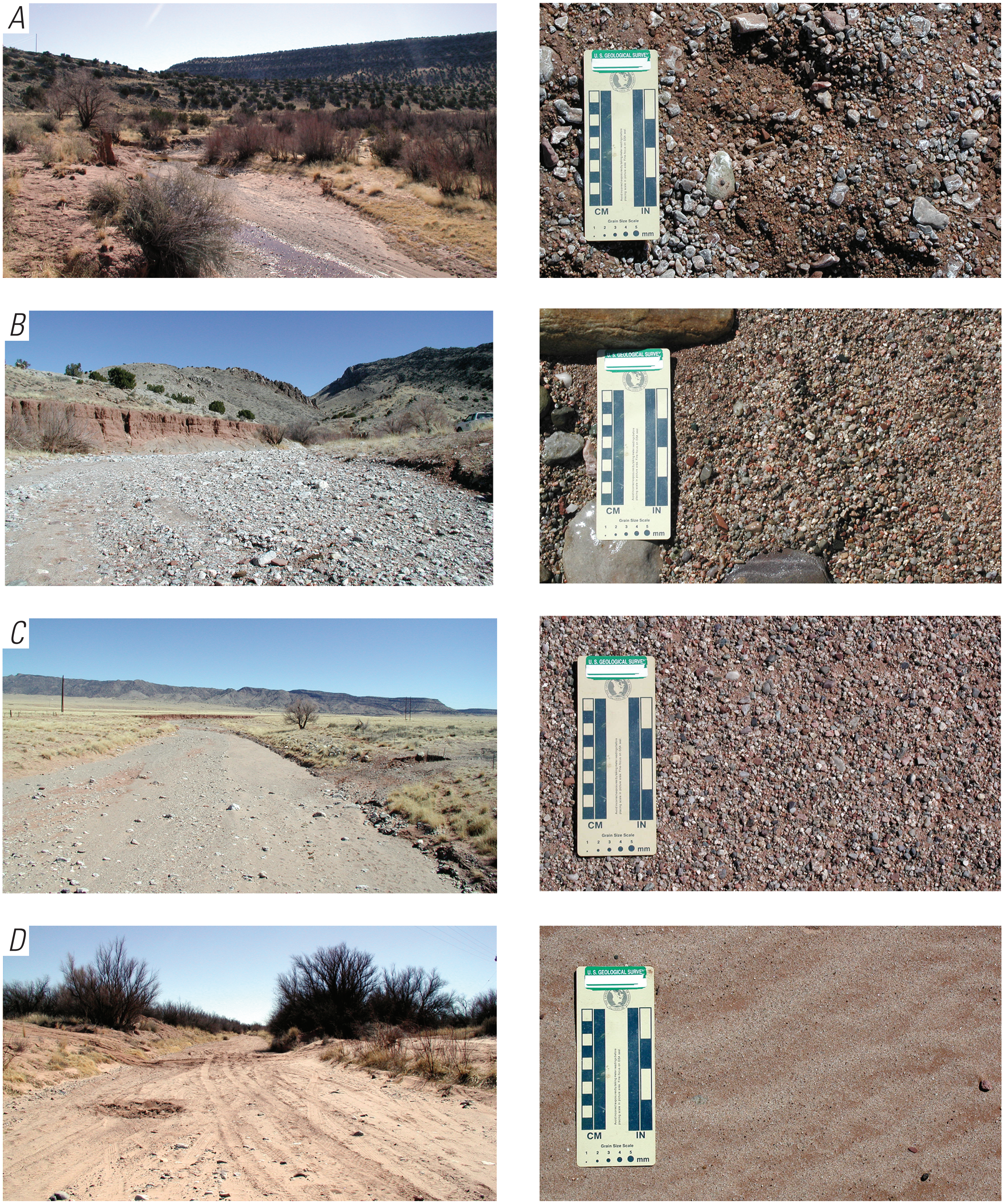

Figure 3. Photographs of Abo Arroyo sediments fining in the downstream direction, March 2003. *A,* Near site PS-1, 1.4 km upstream of the mountain front. *B,* At PS-4, 1.3 km downstream of the front. *C,* PS-6, 12.9 km downstream of the front. *D,* PS-8, 28.3 km downstream of the front. Photo *A* looks downstream (west); *B-D* look upstream (east). Figure 2 shows locations. Figure by J. Constantz and K.S. Adams.

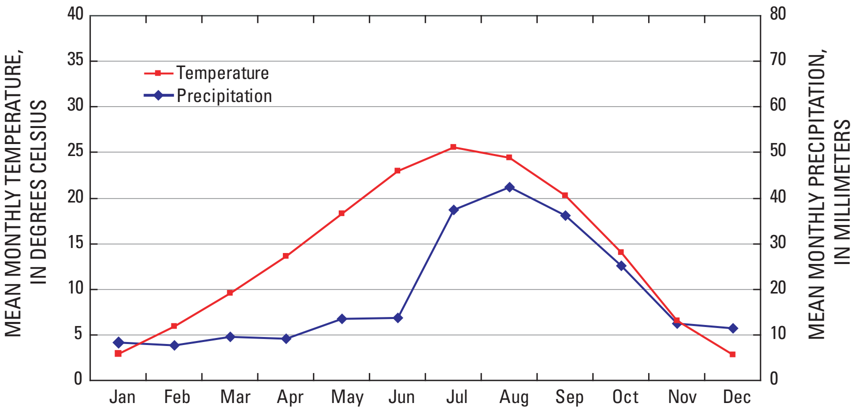

Figure 4. Mean monthly temperature and precipitation at National Weather Service station Bernardo (co-op station number 290915) for 1971 through 2000. Data from http://www.wrcc.dri.edu/Climsum.html, accessed October 30, 2006. See figure 1 for location.

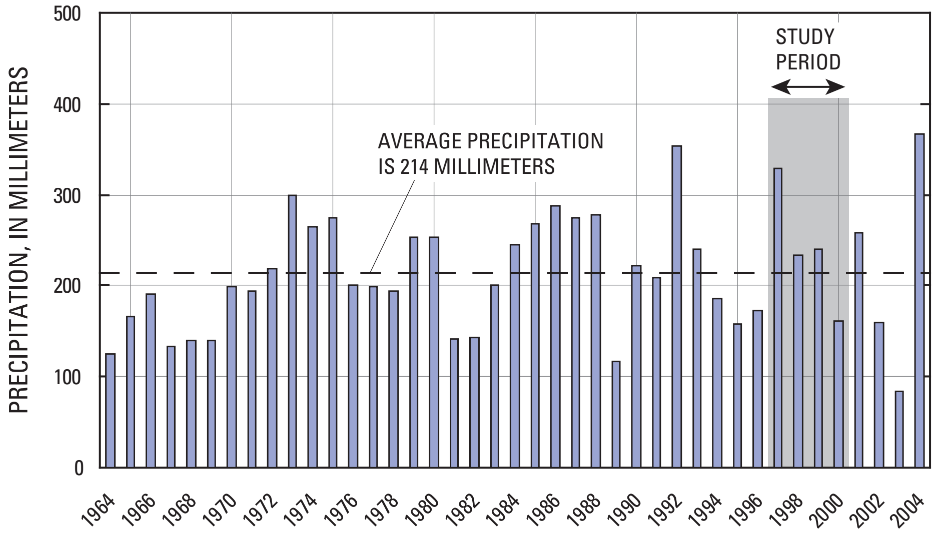

Figure 5. Total annual precipitation at Bernardo (National Weather Service cooperative station 290915) for water years 1964 through 2004. Based on monthly values obtained from http://cdo.ncdc.noaa.gov/ancsum/ACS, accessed October 30, 2006. Values for missing and incomplete months were estimated from precipitation at Los Lunas (station 295150). The Bernardo and Los Lunas stations bracket the confluence of Abo Arroyo with the Rio Grande (fig. 1).

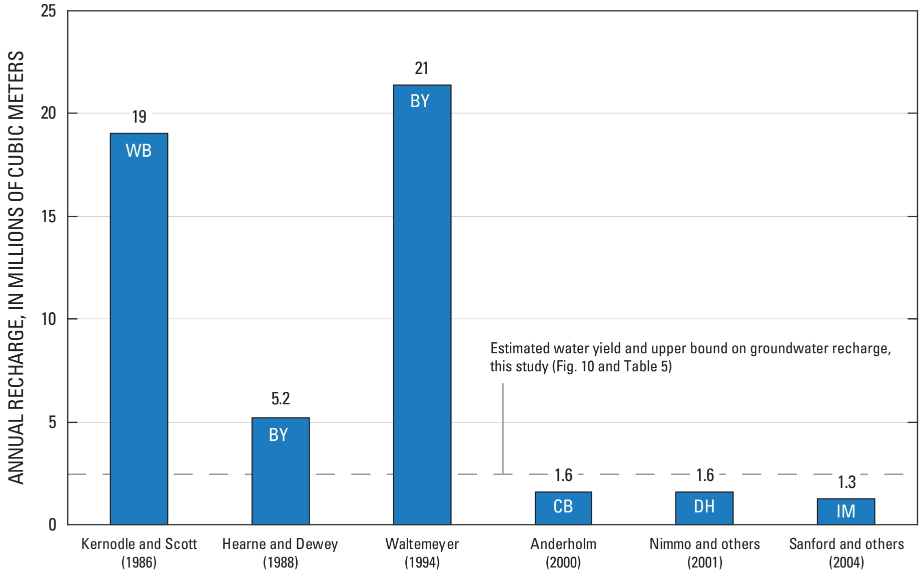

Figure 6. Previous estimates of ground-water recharge from Abo Arroyo to the Middle Rio Grande Basin. Methods included water balance (WB), basin yield (BY), chloride mass balance (CB), Darcy based hydraulic measurements (DH), and inverse modeling (IM) of ground-water heads and chemical composition. Anderholm (2000) developed the chloride mass-balance estimate and compared it to estimates he obtained with the basin-yield relations of Hearne and Dewey (1988) and Waltemeyer (1994); McAda and Barroll (2002) corrected the latter estimate to the value shown here.

beneath middle to upper reaches of the arroyo (fig. 7*A*). Sulfate-to-chloride ratios (fig. 7*B*) carry the chemical signature of the upland catchment, where Paleozoic sediments contain gypsum-bearing units. Ground-water ages become progressively older longitudinally down the channel and laterally away from the channel, with youngest ground water closest to the mountain front (fig. 7*C*).

While recent studies add greatly to the understanding of recharge within the MRGB, the wide range of estimates for Abo Arroyo highlight the uncertainties of surface-water–ground-water exchanges in strongly ephemeral systems. The timing and duration of recharge-producing streamflow and infiltration are largely unknown. The current study addressed this gap. The objectives of the study were to (1) develop thermal techniques for determining the timing and distribution of ephemeral streamflow, (2) measure actual yields of the contributing catchment during a four-year period, (3) establish the relative potential contributions of base flow and storm flow, (4) evaluate the variation of infiltration capacity along the channel, and (5) estimate the proportion of infiltration that becomes recharge, both beneath the channel and on adjacent terrace surfaces. The remainder of this report summarizes the main results.

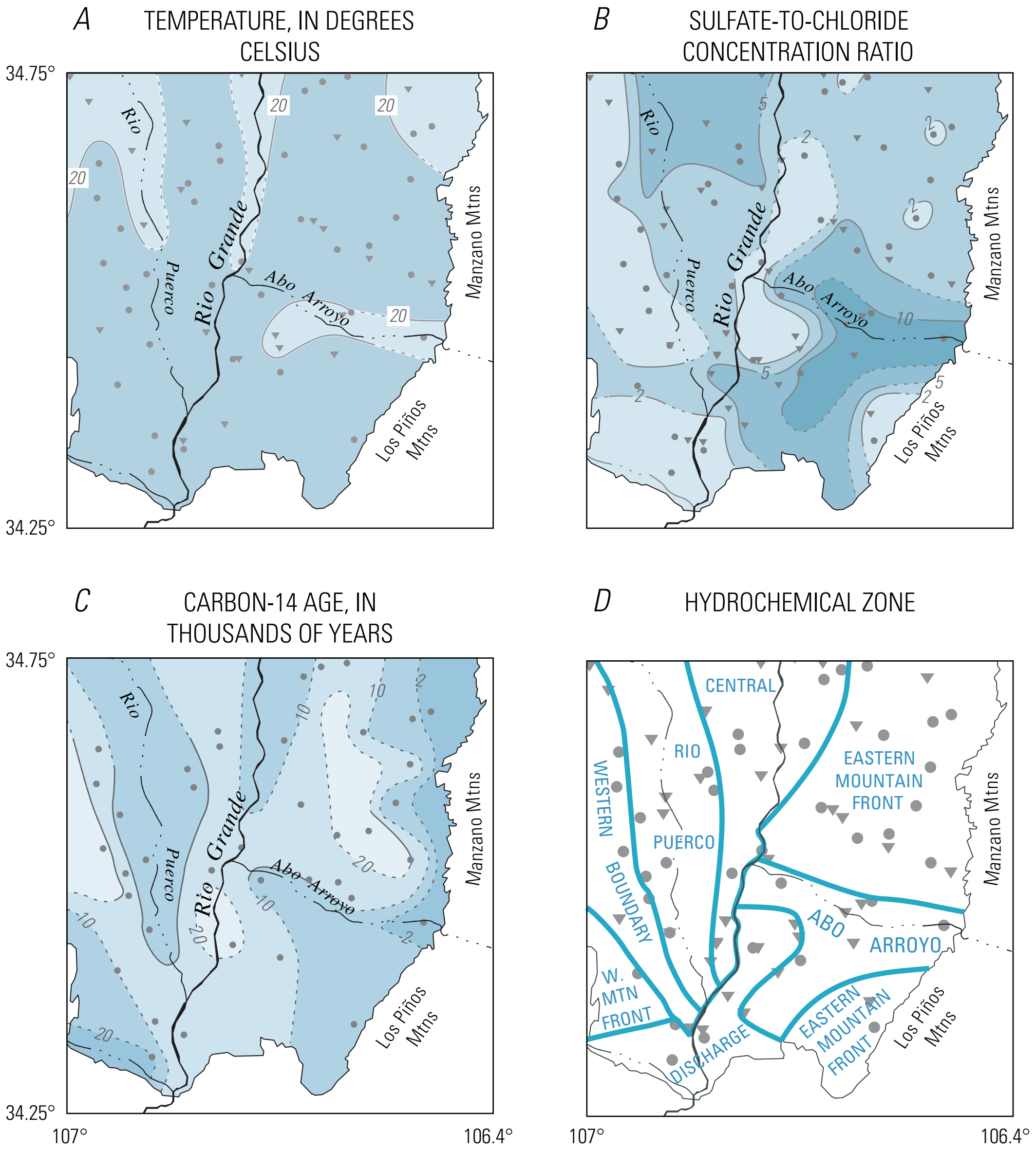

Figure 7. Physical and chemical characteristics of ground water in the vicinity of the Middle Rio Grande Basin affected by recharge from Abo Arroyo. Modified from figures 30, 35, 78, and 100 of Plummer and others (2004). *A*, Temperature. *B*, Sulfate-to-chloride concentration ratio. *C*, Carbon-14 age. *D*, Hydrochemical zone. Triangles and circles, respectively, show locations of archived (USGS National Water Information System) and newly acquired (Plummer and others, 2004) data. Contours dashed where less certain.

Methods

The present study combined long established with newly developed techniques to characterize streamflow, infiltration, and recharge within the Abo Arroyo watershed. This section provides a brief summary of instrumentation and data analysis.

Streamflow

Establishing streamflow characteristics for Abo Arroyo was a priority of the current study. Prior data were limited to annual peak-flow estimates for two tributaries high in the upland catchment—Canada Montoso, a tributary draining less than 15 percent of the upland catchment, and an unnamed tributary draining less than 1 percent of the upland catchment. An automated streamflow-gaging station was established in August 1996 as close as possible to the mountain front following procedures described in Carter and Davidian (1968). The station (USGS 08331660, Abo Arroyo near Blue Springs) monitored streamflow from August 14, 1996 through September 30, 2000 by measuring stream stage at 15-minute intervals. A pressure transducer attached to a nitrogen bubbler measured stage. The measurement point was located in a straight reach of channel two km from the mountain front containing an elevated terrace for housing the pressure transducer, gas controls, and recording equipment. The channel at the gage cut into underlying bedrock, providing stability for the rating curve and a robust anchor for the bubbler outlet. Between the gage and mountain front, the channel receives additional runoff from two tributaries that in aggregate drain almost one percent of the upland catchment. Thus, streamflow at the gage underestimates basin yield by roughly the same proportion. The larger of the two tributaries, Sand Canyon, is a large ravine that has lost most of its contributing area to stream capture by lower-order tributaries feeding Priest Canyon, which joins Abo Arroyo upstream of the gage.

Streambed Temperature

Streambed-temperature anomalies were used to infer ephemeral flow downstream of the gage, as described in Constantz and others (2001) and Stewart (2003). Attempts to detect streamflow with thermocouples (Constantz and Thomas, 1997) failed when flash floods repeatedly disrupted connections to data loggers during the first year of the study. Thereafter, self-contained data loggers (probes) recorded channel temperatures at the locations listed in table 1. Probes resolved temperature to ± 0.16 degrees Celsius (°C) within a nominal range of –5 to 37°C. Temperatures outside this range were truncated (that is, recorded as being at the respective limit). Starting in October 1997, probes were shielded in 15-cm lengths of 1.5-inch diameter schedule-40 polyvinylchloride pipe, which was tethered by aircraft cable to steel pipes driven into the channel below the depth of maximum scour. Starting in February 1998, additional probes were installed outside the channel to serve as controls for distinguishing flow-induced anomalies from anomalies caused by cloud-cast shadows, non-ponding precipitation, and other spurious signals. Initial deployments were on the channel surface to maximize sensitivity to flow. Somewhat serendipitously, sediment movement during larger flows buried several probes to various depths. Inspection of data from buried probes revealed that shallow burial filtered out most non-flow anomalies. Modeling the transport of heat and water for hypothetical test cases indicated that the optimal depth for the thermal detection of flow was approximately 0.2 m (Constantz and others, 2001). During subsequent stages of the study, the redeployment depth of all probes (test and control) was standardized at 0.2 m.

Due to the thick, permeable unsaturated zone downstream of the mountain front, high rates of infiltration accompanied ephemeral flows. Infiltrating water increases the heat capacity and thermal conductivity of channel sediments. The increase in moisture content alone would produce an anomalous temperature response to diurnal, seasonal and other perturbations. The even larger response of streambed temperatures to streamflow events (fig. 8) reflects the rapid advection of heat by infiltrating water (Constantz and others, 2001; Stonestrom and Constantz, 2004). Continuously varying convective and radiative heat exchanges between the dry channel surface and the air and sky cause temperature gradients to be a permanent dynamic of shallow sediments. The temperature of ephemeral flow usually differs from the temperature of the channel sediments prior to flow. Chemical and isotopic data show that storm flow in perennially flowing streams (such as Abo Arroyo near outlet of the upland catchment) is largely released from ground-water storage (Genereux and Hooper, 1998). Ground water has a temperature buffered toward the annual mean. During the summer monsoonal period, storm flow can be many degrees cooler than the ambient surface temperature.

Cessation of flow is less pronounced in temperature records than initiation of flow. Upon cessation, infiltration gives way to the slow process of drainage-limited redistribution. The subsurface flow rate drops sharply, and conduction replaces advection as the dominant heat-transporting process. In contrast to the abrupt change in sediment temperature associated with infiltration, the cessation of flow is marked by a gradual, conduction-dominated recovery to preflowing conditions. Consequently, the response at the end of flow is not symmetric with the response at the beginning. Nevertheless, the cessation of flow is often apparent (fig. 8).

Analysis of thermal records relied on visual inspection. Automated procedures such as the moving standard deviation method (Blasch and others, 2004) proved unreliable for detecting streamflow from Abo Arroyo thermographs due to inconsistent burial depths (Stewart, 2003).

Channel Infiltration

Infiltration measurements in dry arroyo sediments allowed evaluation of potential channel losses during ephem-

Table 1. Locations of stream-gage and channel temperature-measurement sites.

Site	Latitude[1], in degrees	Longitude[1], in degrees	Elevation[2], in meters	Distance to Rio Grande, in kilometers	Distance from mountain front[3], in kilometers
Gage	34.4469	106.4966	1667	31.8	-2.0
PS-1	34.4517	106.5006	1660	30.9	-1.1
PS-2	34.4571	106.5039	1651	29.8	0.0
PS-3	34.4590	106.5106	1646	29.2	0.6
PS-4	34.4622	106.5163	1638	28.5	1.3
PS-5	34.4592	106.5493	1615	25.4	4.4
PS-6	34.4662	106.6297	1560	16.9	12.9
PS-7	34.5075	106.7028	1495	7.9	21.9
PS-8	34.5253	106.7632	1456	1.5	28.3

[1] North American Datum of 1927.

[2] National Geodetic Vertical Datum of 1929.

[3] Channel distance. Negative value is distance upstream; positive value is downstream.

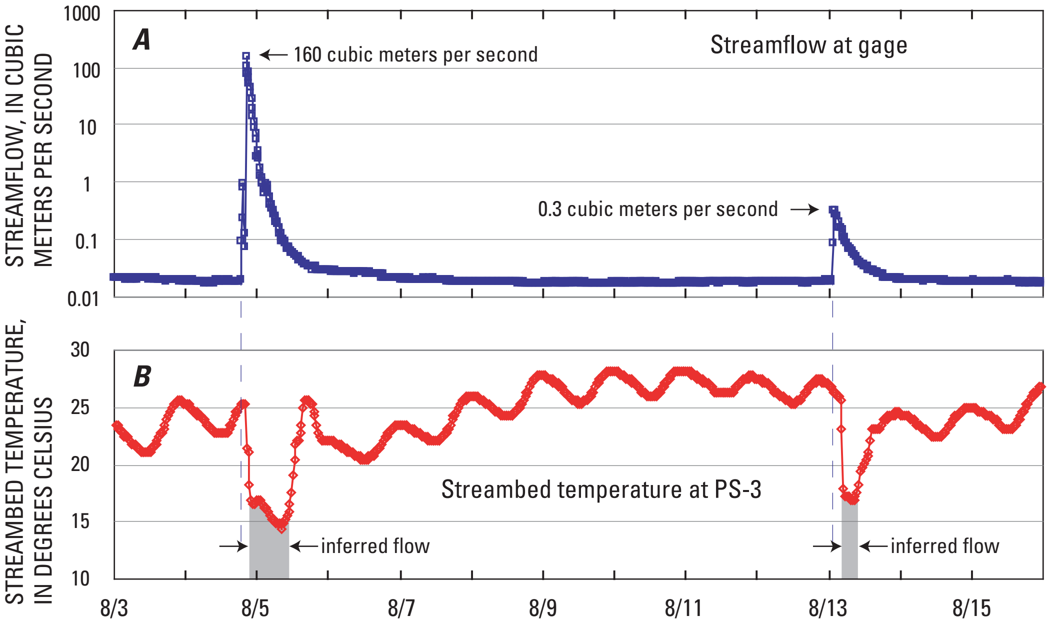

Figure 8. *A*, Streamflow at Abo Arroyo (USGS gage 08331660) and *B*, streambed temperature at probe site PS-3, 2.6 kilometer downstream (and 0.6 kilometer downstream from the mountain front), Aug. 3-16, 1998. The temperature probe was about 0.2 meters below the channel surface when recovered. Shaded areas on the thermograph indicate periods of inferred flow.

eral flow events. Preliminary measurements took place in October 1998 at PS-3, PS-6, and PS-8, 0.6, 13, and 28 km from the mountain front (fig. 2). Measurements at each site were made at three locations in the channel. Additional measurements in June 1999 revisited earlier sites as well as PS-5 and PS-7, 4.4 and 22 km from the mountain front. Measurements followed standard procedures (Bouwer, 1986); however, the rocky nature of the arroyo, especially near the mountain front, prevented hammering conventional steel rings into the ground to obtain a watertight seal.

In October 1998, single-use infiltrometers were fabricated from pairs of sheet metal strips that were formed into concentric rings and emplaced into the channel bed (fig. 9). Concrete poured into the annular space between the rings created a seal with channel sediments. Drums trucked into the arroyo supplied the infiltrometers with water. A float valve maintained a constant head of about 0.05 m while infiltration rates were measured. Infiltration runs lasted 0.5 to 2 hours, with infiltration rates usually stabilizing after 10 to 30 minutes. The circular infiltrometers had an area of 0.3 m^2. Sheet metal forms were supplanted in June 1999 with reusable wooden frames that created square infiltration basins having an inside area of approximately 0.8 m^2. The wooden forms were sturdier than the sheet metal forms and had a larger annular opening for concrete, improving the seal between the infiltrometer and the sediments. In addition to providing a better seal, the larger area of the square infiltrometers reduced effects of lateral divergence beneath the infiltrometer.

Unsaturated-Zone Solutes

Atmospherically derived solutes also served as tracers of infiltration and recharge. Unsaturated-zone chloride and bromide profiles from beneath the channel and from transects adjacent to the channel were collected in late spring and summer of 1996 and 1997, prior to the start of monsoonal storms. Channel profiles were sampled 1.2 km upstream from the mountain front and 0.3, 0.4, 2.4, 4.1, and 28.2 km downstream from the mountain front. Transect profiles were sampled on terrace surfaces adjacent to Abo Arroyo 1.4 km upstream from the mountain front and 0.4 and 4.4 km downstream from the mountain front.

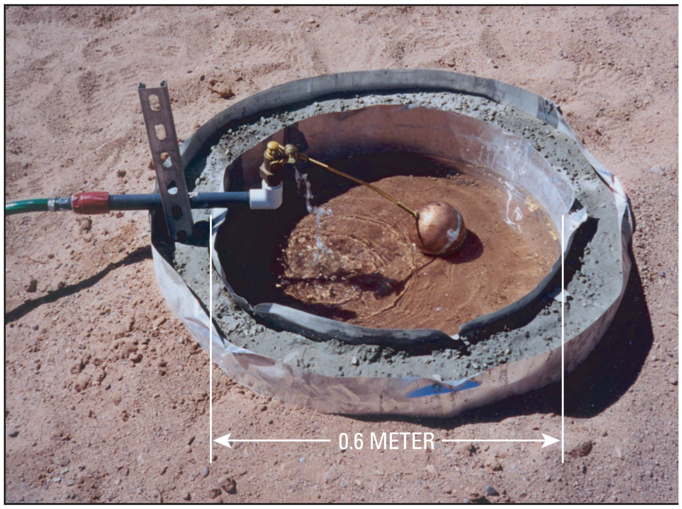

Figure 9. Single-use infiltration ring showing concrete seal and flow-regulating valve that maintains constant depth of ponding during measurements.

Continuous cores were obtained with a hydraulically driven sampler to depths of 5–6 m on terrace transects and as deep as possible within the channel. After drying samples to determine water content, soluble salts were extracted by using methods described in Stone (1984). Chloride and bromide concentrations were determined by using single-column ion chromatography with silica-bonded ion exchangers. Analytical uncertainty was about five percent. Pore water concentrations of chloride ranged from 3 to 5,100 milligrams per liter (mg/L). Pore water concentrations of bromide ranged from less than 0.02 to 62 mg/L.

A chloride mass-balance approach was used to infer recharge rates in areas of active recharge (Edmunds and others, 1988; Allison and others, 1994) and accumulation times in areas of negligible recharge (Tyler and others, 1996). A value of 0.29 grams of chloride per cubic meter of precipitation was used to calculate atmospheric chloride deposition on the basis of atmospheric deposition collected near Santa Fe, N. Mex. (Anderholm, 1994).

Profiles of unsaturated-zone pore water beneath the channel and in transects adjacent to the channel were analyzed to evaluate the proportion of infiltrating water that becomes deep percolation and ground-water recharge from evapoconcentration of shallow pore water. Concentrations of conservative solutes beneath the depth of evapotranspirative extraction indicate the fraction of infiltrating water percolating toward the water table. This approach assumes steady-state conditions exist between the time-averaged mass flux of solute at the land surface and at the sampling depth (Edmunds and others, 1988). Alternatively, where steady conditions do not exist, the mass of accumulating solute from the imbalance between infiltration and deep drainage indicates the time since recharging conditions last prevailed (Tyler and others, 1996).

Results and Discussion

Streamflow Characteristics

Streamflow in Abo Arroyo reflects the interaction of monsoon-dominated precipitation with the relatively large proportion of exposed bedrock comprising the upland watershed. Streamflow responds quickly to storms. Base flow (perennial flow between storms) is minimal in volume and extent. Only at the gage does base flow persist. Except for possible snowpack, the storage capacity of the upland catchment would seem limited by the relatively impermeable bedrock. Even so, only a small fraction of precipitation becomes streamflow.

Annual streamflow increases non-linearly with annual precipitation (fig. 10). Orographically weighted average precipitation in the upland catchment about 368 mm per year (Anderholm, 2000), 1.7 times higher than the average at Bernardo (214 mm, water years 1964–2004). Adjusting measured precipitation amounts at Bernardo (altitude 1443 m above sea level) by a factor of 1.7 yields the estimated precipitation for the upland catchment (1660–3048 m above sea level) for each year of the study. Multiplying these values by the area of the upland catchment (650 km^2) approximates the yearly volumes of precipitation contributing to streamflow at the gage. The total streamflow in WY 2000, the driest year, represented about 1 percent of the estimated precipitation volume. The total streamflow in WY 1997, the wettest year, represented about 9 percent of the precipitation volume. Streamflow volumes in water years 1998 and 1999 each represented about 3 percent of estimated precipitation. As annual precipitation increases, runoff volumes rise disproportionately (Langbein, 1949). The upward curvature of the relation between annual streamflow and precipitation (fig. 10) reflects the decreasing relative importance of evapotranspiration, sublimation, and depression-storage losses as precipitation increases in the watershed.

Total annual streamflow during the study period ranged from 0.8 to 15.3 million cubic meters (Mm^3), a factor of 19. In contrast, precipitation at the Bernardo weather station during the same time varied between 161 and 329 mm, a factor of 2, (fig. 10). Annual streamflow was largest during WY-1997, when annual precipitation at Bernardo (329 mm) was 154 percent of the 41-year average. Water year 1997 was the third wettest year on record. Annual streamflow was smallest in WY 2000, when annual precipitation at Bernardo (161 mm) was 75 percent of the 41-year average. The total annual streamflow corresponding to the long-term average annual precipitation, which approximates the average annual basin yield, is about 2.0 Mm^3. This is less than one tenth of the largest previous estimated basin yield (fig. 6).

Records of daily mean and peak instantaneous streamflows illustrate the ephemeral, flashy nature of Abo Arroyo discharge. Daily mean streamflows (the average of all 15-minute instantaneous streamflows on a given day) varied from zero to 37.7 m^3/s during the four-year study period (fig. 11). The four-year median value of 0.012 m^3/s was less than 1/3000 of the maximum. Annual median values varied from 0.006 m^3/s in WY 2000 to 0.025 m^3/s in WY 1998 (table 2). Daily mean streamflow was 37.7 m^3/s on June 6, 1997 during a monsoonal flow that lasted eight hours at the gage. Maximum instantaneous streamflow on that day was 195.5 m^3/s.

The highest instantaneous streamflow during the study period, 227 m^3/s, occurred on July 31, 1997, during the second of two flash floods arriving roughly eleven hours apart. Each event lasted about four hours. Daily mean streamflow was 32.6 m^3/s on that day.

Flow at the gage is bimodal, with brief storm flows interrupting long periods of minimal base flow. Ninety-five percent of daily average values (average flows on 1386 days) were less than 0.058 m^3/s (inset, fig. 11).

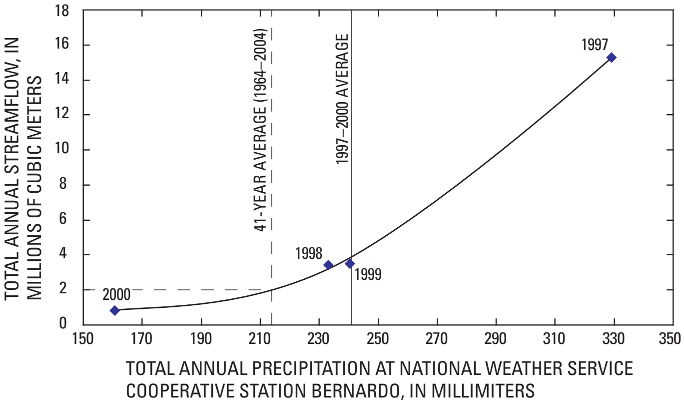

Figure 10. Relationship between annual streamflow at the Abo Arroyo gage (USGS 08331660) and annual precipitation at Bernardo (National Weather Service cooperative station 290915) for water years 1997–2000.

Base flow is critical for sustaining the riparian ecosystem near the mountain front. In terms of duration, base flow dominates the four-year record. In terms of volume, however, storm flow accounts for nearly all water passing though the gage. Ranked average daily streamflows show a sharp inflection at the 95-percentile level (inset, fig. 11). Defining the corresponding flow rate, 0.058 m^3/s, as the threshold between base flow and storm flow, 80 percent of the total flow in WY 2000, the driest year, was storm flow (table 2). The channel was dry for periods up to 29 days at the gage in that year (fig. 11). In WY 1997, the wettest year, storm flow accounted for 98 percent of total flow at the gage, even though the channel flowed throughout the year. While brief even in aggregate, monsoonal storm flows dominate the discharge from the upland catchment. Basin recharge from streambed infiltration is almost entirely from storms associated with summer monsoons.

Temperature-Based Indications of Flow

The channel at the mountain front was seasonally persistent, as documented by site visits (fig. 12). Streambed temperatures exhibited three distinct patterns—two when flowing and one when dry. During water years 1998 and 1999, which had typical precipitation, diurnal temperature amplitudes dropped sharply for 10–14 weeks following the onset of monsoonal storms. The pattern was already in effect at the beginning of the thermograph record, following monsoonal storms in 1997. Diurnal amplitudes generally remained below 2–3°C; daily averages remained relatively constant and close to the average annual temperature (in the range of 15–20°C). The channel was flowing when visited during these periods. In WY 1997 and 1998, starting in October or November, these relatively constant periods were followed by 7–8-month periods of intermediate diurnal amplitudes (typically 5–10°C) that tracked the seasonally varying temperature. The channel was also flowing when visited during these periods. The intermediate periods

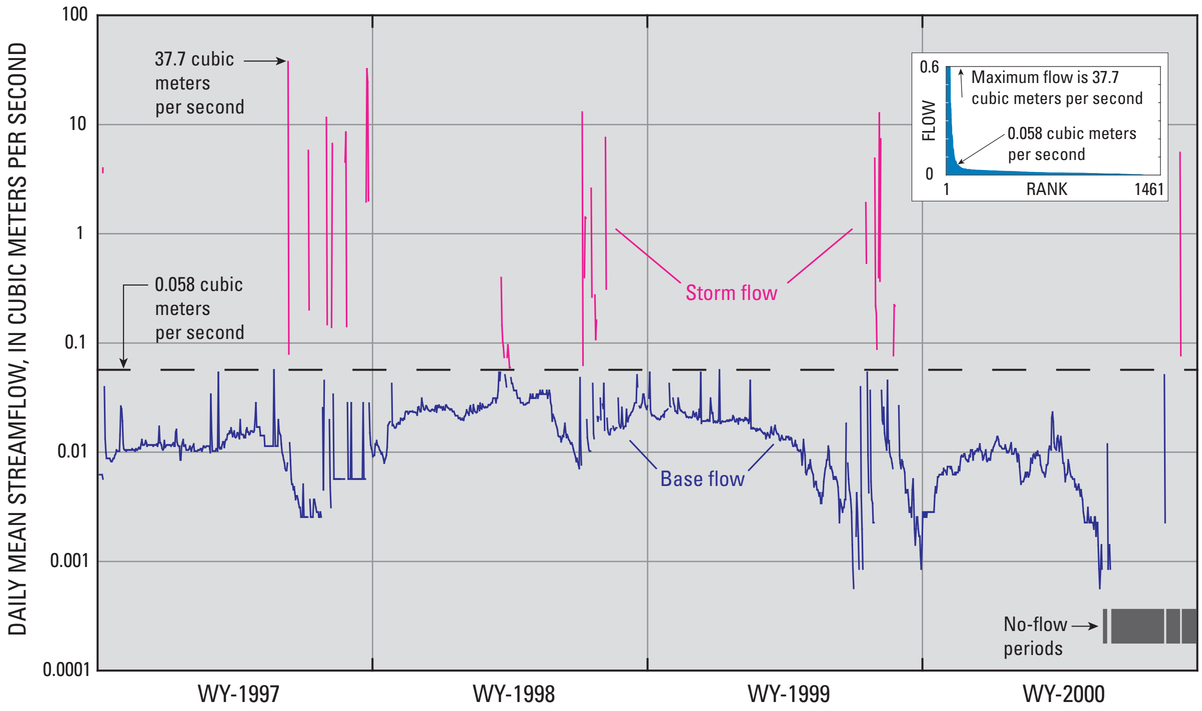

Figure 11. Daily mean streamflow at Abo Arroyo (USGS gage 08331660) during water years 1997-2000. Inset shows ranked values on a linear scale truncated at 0.6 cubic meters per second to display low flows. The dashed line on the main plot is the level below which 95 percent of daily mean streamflows occurred. This threshold operationally divides storm-generated runoff from base flow. Of the 75 values greater than the threshold, 88 percent (66) occurred within one day, all but one within three days, and none more than four days of a storm-induced runoff event. The total number of daily values is 1461.

Table 2. Stream flow at Abo Arroyo (USGS gage 08331660) for water years 1997-2000. Summary daily statistics and total storm-flow versus base-flow volumes.

[Derived from daily means data obtained at http://waterdata.usgs.gov/nwis; accessed September 25, 2006]

Water year[1]	Median daily average flow, in cubic meters per second	Maximum daily average flow, in cubic meters per second	Minimum daily average flow, in cubic meters per second	Total volume[2], in millions of cubic meters	Storm-flow volume[2], in millions of cubic meters	Base-flow volume[2], in millions of cubic meters	Storm-flow proportion of total volume, in percent
1997	0.011	37.7	0.003	15.3	14.9	0.3	98
1998	0.025	13.0	0.007	3.4	2.8	0.7	80
1999	0.015	12.7	0.000[3]	3.5	3.1	0.4	88
2000	0.006	5.6	0.000[4]	0.8	0.7	0.2	80
Four-year study period							
1997–2000	0.012	37.7	0.000[5]	23.1	21.4	1.6	93

[1] Water year is October 1 through September 30 and denoted by calendar year in which it ends.

[2] Values rounded for reporting purposes. Calculations used unrounded numbers, causing apparent discrepancies in least significant digit.

[3] Channel was dry for periods of 1–2 days (4 days total during water year).

[4] Channel was dry for periods of 4–29 days (112 days total during water year).

[5] Channel was dry for a total of 116 days during the four-year study period.

were followed by abrupt transitions to high diurnal amplitudes, often exceeding 15°C, which also tracked the seasonal temperature. The channel was dry when visited during these periods (fig. 12).

The response of sediment temperatures to diurnal forcing from the atmosphere reflects not only the presence or absence of flowing water, but also the direction of water exchange between the stream and underlying sediments. Gaining streams show smaller diurnal temperature variations than losing streams because ground water is buffered from fluctuations at the land surface (Constantz and Stonestrom, 2003). Thus, periods of relatively constant temperatures suggest gaining conditions. The mountain-front thermograph shows seasonal cycles of monsoonally driven gaining conditions followed (in water years 1997 and 1998) by losing conditions followed (in all water years) by dry conditions. The period of channel loss in WY 1999 was too short to resolve as drought set in at the end of the study.

Figure 13 illustrates streamflow at the gage together with temperatures in the channel and adjacent to the channel for August 1999, which was an active monsoonal period. This period included eleven flows with peaks that ranged from less than 1 m^3/s to 155 m^3/s. Shading on the streambed thermographs indicates periods of inferred flow. Despite variations among records reflecting differences in burial depths, the utility of streambed thermographs for inferring ephemeral flow downstream of the gage is readily apparent.

Analysis of thermographs provides information about the timing and duration of ephemeral flows within the basin. The majority of flows extending into the basin occurred in July through September. Comparison of thermographs with

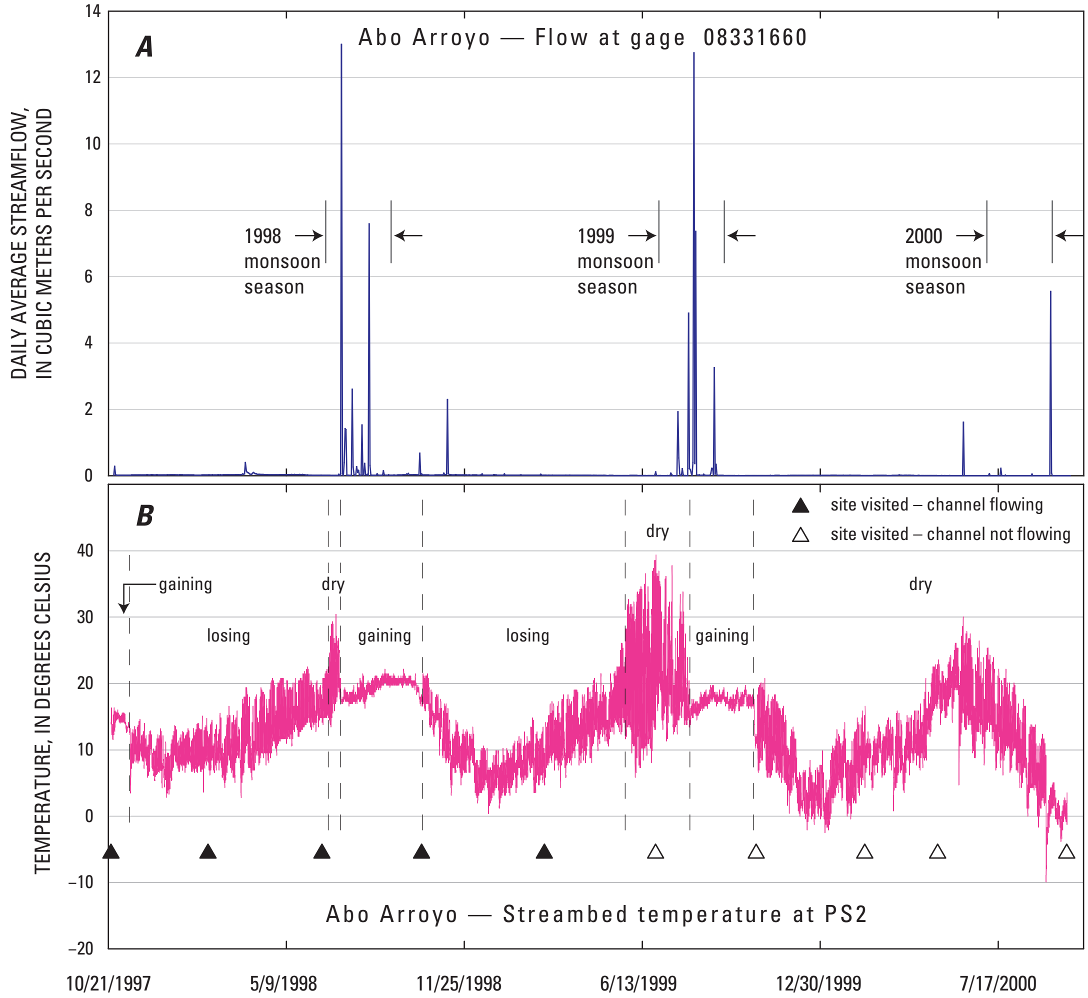

Figure 12. Relation between streamflow and mountain-front channel temperatures for the period of record at the mountain-front temperature logger (probe site PS-2, two kilometers downstream from the gage). *A*, Monsoonally driven streamflow at the Abo Arroyo gage (USGS 08331660). *B*, Mountain-front streambed thermograph and interpretation of temperature patterns as seasonally driven transitions from a monsoonally induced gaining state (ground water entering the reach) to a post-monsoonal losing state (stream water leaving the reach) to a dry state. The preceding water year (1997) had 154 percent of normal precipitation; water years 1998-2000 ranged from 112 to 75 percent of normal. Filled and hollow triangles indicate channel state during site visits.

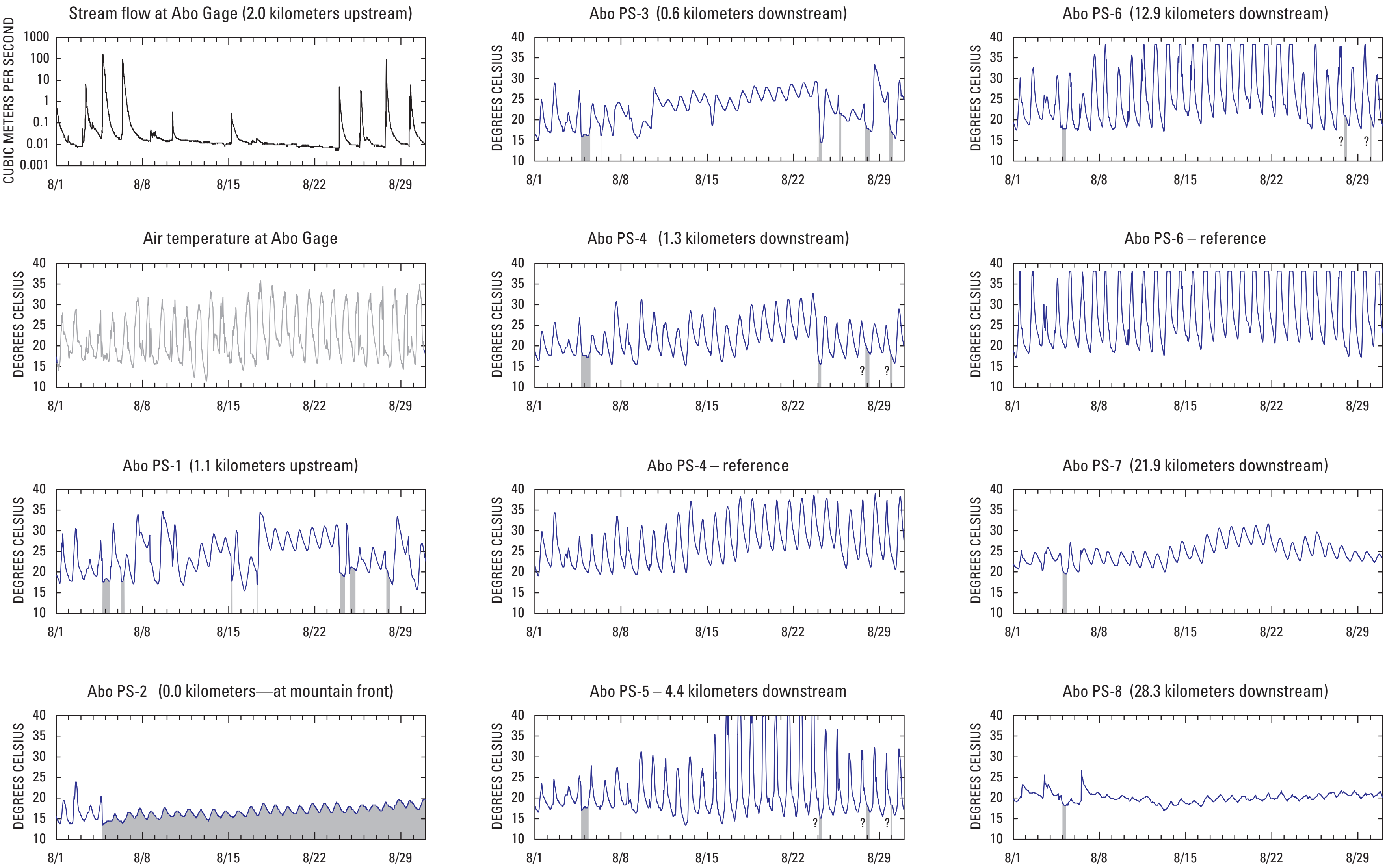

Figure 13. Streamflow at gage (measured) and downstream (shaded areas, as inferred from channel and reference temperatures), Abo Arroyo, New Mex. August 1999.

streamflow at the gage provided information on the general relationship of catchment flow and ephemeral flow downstream of the gage. Infiltration losses during ephemeral flows are high, with only the largest flows reaching the Rio Grande. Flows were classified according to how far into the basin they extended (table 3). Class I flows extended all the way the Rio Grande floodplain. Class II flows extended at least a kilometer into the basin, as detected by PS-4 (1.3 km from the mountain front), but did not reach the Rio Grande. Class III flows infiltrated into the coarse sediments near the mountain-front, upstream of PS-4. Storm hydrographs exhibited a high degree of self-similarity, with roughly similar shapes regardless of magnitude (fig. 8). The duration of classified flows varied from 3.0 to 6.5 hours, with a median duration of 5.0 hours (table 3).

Stewart (2003) presents the complete set of thermographs for Abo Arroyo. The record includes a number of gaps and is of a shorter duration than the streamflow record. Therefore, the relationship between flow in the MRGB inferred from available thermal data and flow at the gage was applied to the entire streamflow record to provide statistics for the four-year study period. Inspection of the thermographs indicated that runoff events with peak flow rates greater than about 150 m^3/s extended all the way to the Rio Grande floodplain. Similarly, those with peak flow rates exceeding a value of about 12 m^3/s extended past PS-4. In general, those with peak flows smaller than 12 m^3/s did not reach PS-4 (table 3).

Applying these thresholds to the stream flow record, there were five class I flows during the four-year period (two each in WY 1997 and 1998, one in WY 1999, and none in WY 2000), or on average about one per year. There were 17 class II flows during the four-year period, or about four per year. Nearly all of the class I and class II flows (18 in total) occurred in the months of July, August, and September. Four class II flows occurred in June and October (two in each month). Including snowmelt-generated events, there were 84 class III flows during the four-year period, or about 21 per year.

Snowmelt events were type III, with one exception. In December 1997, an unusually large amount of snow fell throughout the area, accumulating on the higher mountains. National Weather Service cooperative weather stations at Bernardo (altitude 1443 m), Los Lunas (1475 m), and Mountainair (1987 m) recorded greater than 0.20, 0.28, and 0.53 m of snowfall for the month, with the heaviest snowfall at Bernardo falling on December 20. At higher altitudes (2,600-2,900 m), three SNOTEL stations within a radius of 173 kilometers from PS-2 (stations 06p01s, 05p04s, and 07s04s, with azimuths from north relative to PS-2 of 3, 24, and 225°) recorded regional snowstorms on December 1-3, 6-8, 10, and 20-27 (USDA-NRCS, 2006). The cooperative weather station at the

Table 3. Classification of ephemeral flows by thermally determined downstream distance.

Class[1]	Time of peak flow[2]	Peak flow value, in cubic meters per second	Event flow volume, in millions of cubic meters	Event flow duration[3], in hours
I	1998/07/04 16:30	181.7	22.17	5.0
I	1999/08/04 18:45	154.9	25.41	5.7
II	1999/08/06 09:15	91.2	16.12	6.5
II	1999/08/27 19:15	86.5	3.28	3.0
II	1998/07/16 21:15	43.9	3.77	4.0
II	1998/07/08 17:45	37.6	2.28	5.3
II	1998/07/27 16:15	37.6	1.66	3.2
III	1998/07/07 18:15	11.1	0.49	3.8
III	1998/07/30 17:15	8.3	0.47	4.0
III	1998/07/21 22:00	6.6	0.66	5.8
III	1999/08/03 09:30	6.3	0.65	5.5
II	1999/08/23 23:45	4.7	0.47	5.0
III	1999/08/25 17:45	3.3	0.34	4.7

[1] Class I flows extended to the Rio Grande floodplain. Class II flows extended past probe site PS-4, 1.3 kilometers from the mountain front. Class III flows dissipated prior to reaching PS-4.

[2] Mountain standard time.

[3] Cutoff for event duration was 2.5 percent of the respective peak flow value.

Albuquerque airport, which records detailed hourly weather conditions, recorded snow on December 3 and 10–11, followed by alternating periods of snow and light rain December 20–25.

The Abo gage recorded only minor increases in stream flow above base-flow levels (fig. 11). In contrast, streambed thermographs indicated extended periods of snowmelt-fed infiltration throughout the channel, starting on December 20 (fig. 14). At PS-3, 0.6 km from the mountain front, infiltration continued until January 3, 1998. At PS-8, 28 km from the mountain front, the infiltration period was shorter, lasting only 1–2 days. Nearly constant, slightly positive streambed temperatures indicated the presence of liquid water in sufficiently close proximity to melting snow and ice to regulate the temperature. Once proximal snow and ice had melted, removing the source of infiltrating water as well as the regulation of temperature by the latent heat of fusion, streambed temperatures again followed air temperatures (fig. 14).

These results show that snowmelt can lead to extended periods of infiltration. The rate of melt-water generation, as indicated by the stream gage, in this case was low. The rate of infiltration was presumably similarly limited by the rate of melt-water generation (supply controlled). While not observed during the four-year study period, the potential exists for considerably larger flows generated by rain from a slowly moving frontal system melting heavy snowpack.

Stream-Channel Infiltration

Infiltration measurements along the dry arroyo allowed evaluation of potential seepage variations during ephemeral-flow events. The first measurements, with the 0.3 m^2 infiltrometer (see methods) were in June 1998 after the channel had been dry for eight months. Subsequent measurements, with the 0.8 m^2 infiltrometer, were in October 1998 and June 1999. The channel had been dry for two and five months, respectively, prior to the latter measurements.

The first set of measurements suggested that potential infiltration rates decreased down channel toward the Rio Grande (fig. 15). Point-to-point variability was large, especially near the mountain front (28 km from the Rio Grande). This was consistent with expectations, as sediment size decreased while sorting increased down channel. However, the smallest value was obtained near the mountain front, in a fine-invaded low-flow channel. Leakage was often difficult to eliminate, especially with the sheet-metal forms in the coarsest sediments. The larger wooden forms of the square infiltrometers created better concrete seals. Subsequent measurements with the large infiltrometers suggested less dependence on location (square symbols, fig. 15).

Quasi-steady rates from the large infiltrometers averaged 5.5×10^{-5} m/s with a standard error of 1.2×10^{-5} m/s (fig. 15). Early time infiltration rates ranged from 0.3 to 2 mm/s. The product of the infiltration rate and the wetted area of the channel gives a lower bound on instantaneous loss rate during early flow. The channel at PS-4, 1.3 km downstream of the mountain front, is about 90 m wide (fig. 2). Assuming an infiltration rate of one mm/s, the corresponding loss rate at PS-4 would be about 0.3 Mm^3 per kilometer of channel per hour. This rate can account for the observed flow loss in most cases, and underestimates losses due to seepage into channel banks and due to higher hydraulic-pressure gradients during streamflow than during infiltrometer measurements. Thermographs show that infiltration losses consume most flows in transit. Computational methods for estimating seepage losses from a transient pulse of water moving down an initially dry, permeable channel are currently under development (Niswonger and others, 2006). Flood-pulse velocities in such situations can be an order of magnitude slower than predicted by standard equations for the propagation of kinematic waves.

Environmental Tracers

Profiles of pore-water chloride and bromide indicate focused recharge beneath the active channel of Abo Arroyo and no recharge currently on the adjacent terrace. Figure 16 shows water content and solute profiles near PS-1. Bromide concentrations mimic those of chloride, supporting assumptions of conservative behavior and meteoric origin. Chloride and bromide concentrations beneath the channel are uniformly low, indicating continued removal of infiltrating solutes by deep percolation and recharge. In contrast, profiles beneath the adjacent terrace surfaces show large accumulations of chloride and bromide between depths of 0.1–0.5 m—the approximate bottom of the root zone—and 5 m. Solute profiles near PS-1 (fig. 16) were intermediate between those near PS-3, closer to the mountain front, and PS-5, farther from the mountain front. Channel profiles varied little throughout the reach.

Anderholm (1994) determined the amount of chloride in wet fall and dryfall near Santa Fe in the Española Basin, an upland catchment draining into the northeast portion of the MRGB. Assuming the same effective concentration in precipitation at Abo Arroyo as that measured near Santa Fe (0.3 grams of chloride per cubic meter of precipitation) and an average precipitation rate of 0.3 m/yr at the mountain front, the meteoric deposition rate is 0.09 gram of chloride per square meter of land surface per year. Assuming the chloride deposition rate has remained relatively constant, the time required to accumulate a given mass of chloride is the profile inventory divided by the deposition rate (both expressed per area of land surface).

Figure 17 and table 4 summarize the chloride inventories for transects near PS-1, PS-3, and PS-5. Figure 17 shows the inventories in integral form (cumulative mass of solute per cumulative volume of water, starting at land surface). The slope of each curve indicates the pore-water concentration. Curves representing the channel profiles are approximately linear with low slopes, indicating low concentrations, consistent with steady movement of chloride through the profile by recharging water. Curves representing profiles away from the channel and mountain front are non-linear, with higher slopes near the land surface, at the origin of each plot. These

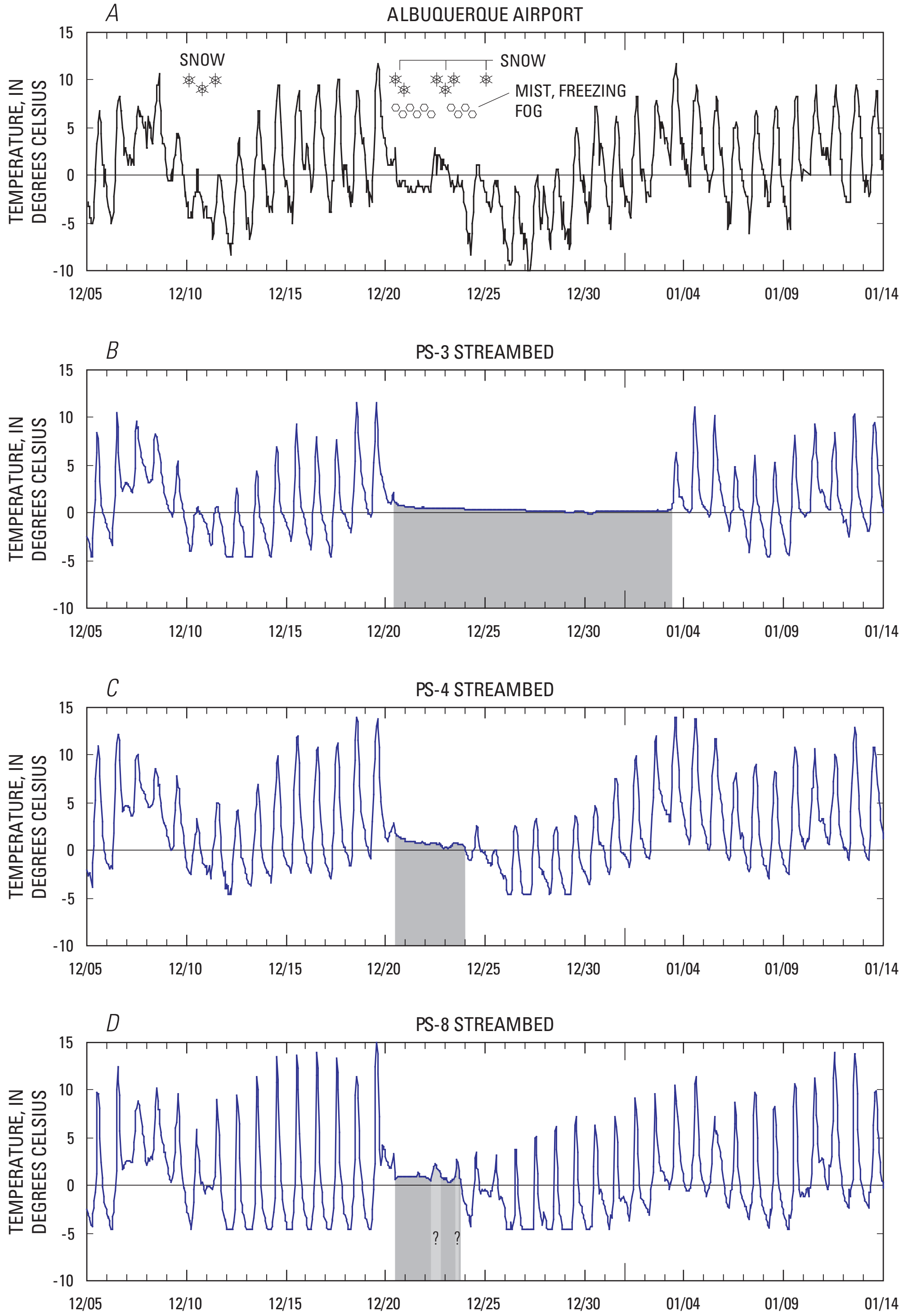

Figure 14. Weather conditions and channel-surface temperatures for Abo Arroyo downstream from the mountain front for period marked by snow accumulation, followed by extended period of snowmelt infiltration. *A*, Air temperature and logged weather conditions at Albuquerque airport (National Weather Service cooperative station 290234, about 63 kilometers north of PS-4, elevation 1617 meters; data from http://cdo.ncdc.noaa.gov/ulcd/ULCD, accessed Nov. 3, 2006). *B–D*, Streambed thermographs at PS-3, PS-4, and PS-8, respectively, 0.6, 1.3, and 28.3 kilometers downstream from the mountain front. Shading indicates intervals of inferred snowmelt infiltration. Graphs show data from December 5, 1997 to January 14, 1998.

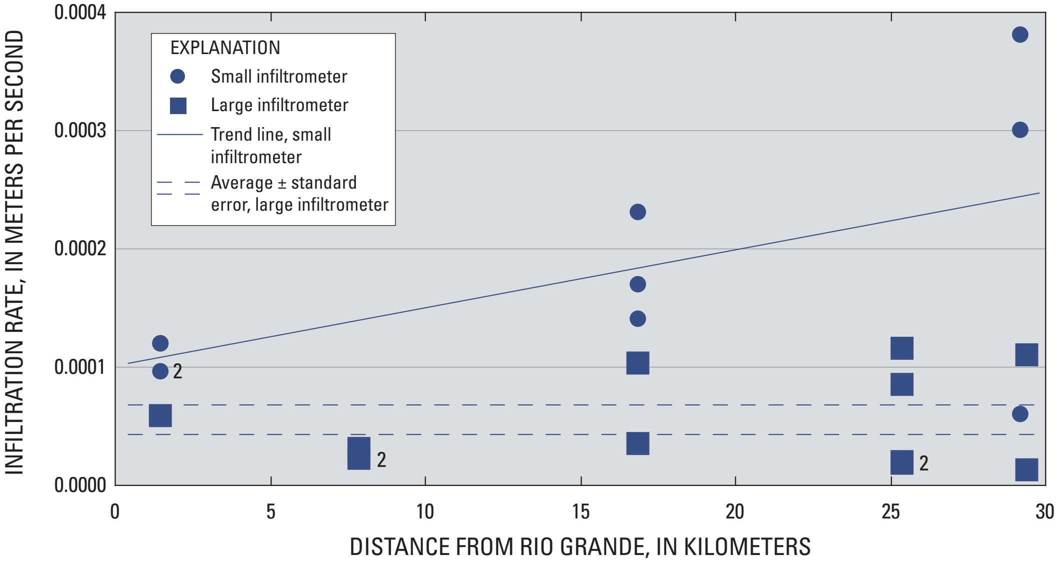

Figure 15. Late-time (quasi-steady) infiltration rates in the dry streambed of Abo Arroyo at five locations between the mountain front and the Rio Grande. Preliminary measurements with the small infiltrometer were in June 1998. Subsequent measurements with the large infiltrometer were in October of 1998 and June of 1999. Numbers next to data symbols indicate number of overlapping points.

high slopes correspond to the sub-root bulges of figure 16 and indicate net accumulation of incoming solutes under current climatic conditions.

Chloride inventories beneath the terrace are large, reaching 1.3 kg/m^2 in the top 8.5 m of unsaturated zone 0.5 km from the channel near PS-5, 4.4 km from the mountain front (table 4). This amount of chloride represents 15 thousand years of accumulation at current rates of deposition. Chloride inventories in terrace profiles near PS-3, close to the mountain front, represent six to seven hundred years of accumulation in the sampled interval (uppermost 4–5 m). Integral solute profiles are straighter closer to the mountain front (fig. 17). These locations were evidently flushed more recently, perhaps by snowmelt from the adjacent mountains during a cooler climatic period.

All transect profiles indicate negligible recharge through terrace surfaces and focused recharge beneath the channel. Conventional chloride mass-balance calculations assume steady state conditions, which do not apply to the terraces at present. Such calculations, however, provide an upper limit on recharging fluxes. This upper bound for terrace profiles varied from 0.04 mm/year (near PS-5) to 0.9 mm/year (near PS-3). Current recharge rates are lower, and may be negative. Studies in arid and semiarid basins suggest that under current climatic conditions there may be small amounts upward flow across the water table in much of the MRGB (Scanlon and others, 2006). Even a positive recharge rate of 1 mm/yr for the entire Abo recharge zone (fig. 7) would provide less than 0.3 Mm^3 per year of total recharge. Direct recharge through extra-arroyo surfaces is clearly minimal.

The concentration of chloride in pore-water becomes higher than that of infiltrating streamflow due to evaporative losses of water during dry periods between flows. The ratio of concentrations in infiltrating water and in pore water below the depth of evaporative removal indicates the fraction of infiltration that percolates toward the water table, eventually becoming recharge. Base flow provides a robust upper bound on the concentration of chloride in infiltrating streamflow. A lower bound is harder to identify, but can reasonably be approximated by the concentration of chloride in pure mountain-front recharge as determined by Plummer and others (2003).

Calculations based on these end-member estimates of chloride concentration indicate that much of the water that infiltrates into the channel eventually becomes recharge (table 5). Pore water from the shallower intervals (1.8–3.5 m) indicates that recharge is between 14 and 100 percent of channel infiltration. Pore water from the two deepest intervals (4.3–4.9 and 4.3–6.7 m) indicates that 43 to 100 percent of infiltration becomes recharge. While the uncertainty is large, as a first approximation it appears that roughly half of infiltrating water recharges the underlying aquifer based on meteoric chloride. From the relation between annual streamflow and precipitation (fig. 10), the long-term estimate of average annual streamflow is 2.0 Mm^3 , on the basis of 41 years of precipitation. During the four-year study period, flows reached the Rio Grande only during wetter than average years. If all streamflow becomes infiltration before reaching the Rio Grande, the long-term average annual recharge rate is about 1.0 Mm^3. This is in agreement with recent estimates and as much as twenty times less than prior estimates (fig. 6).

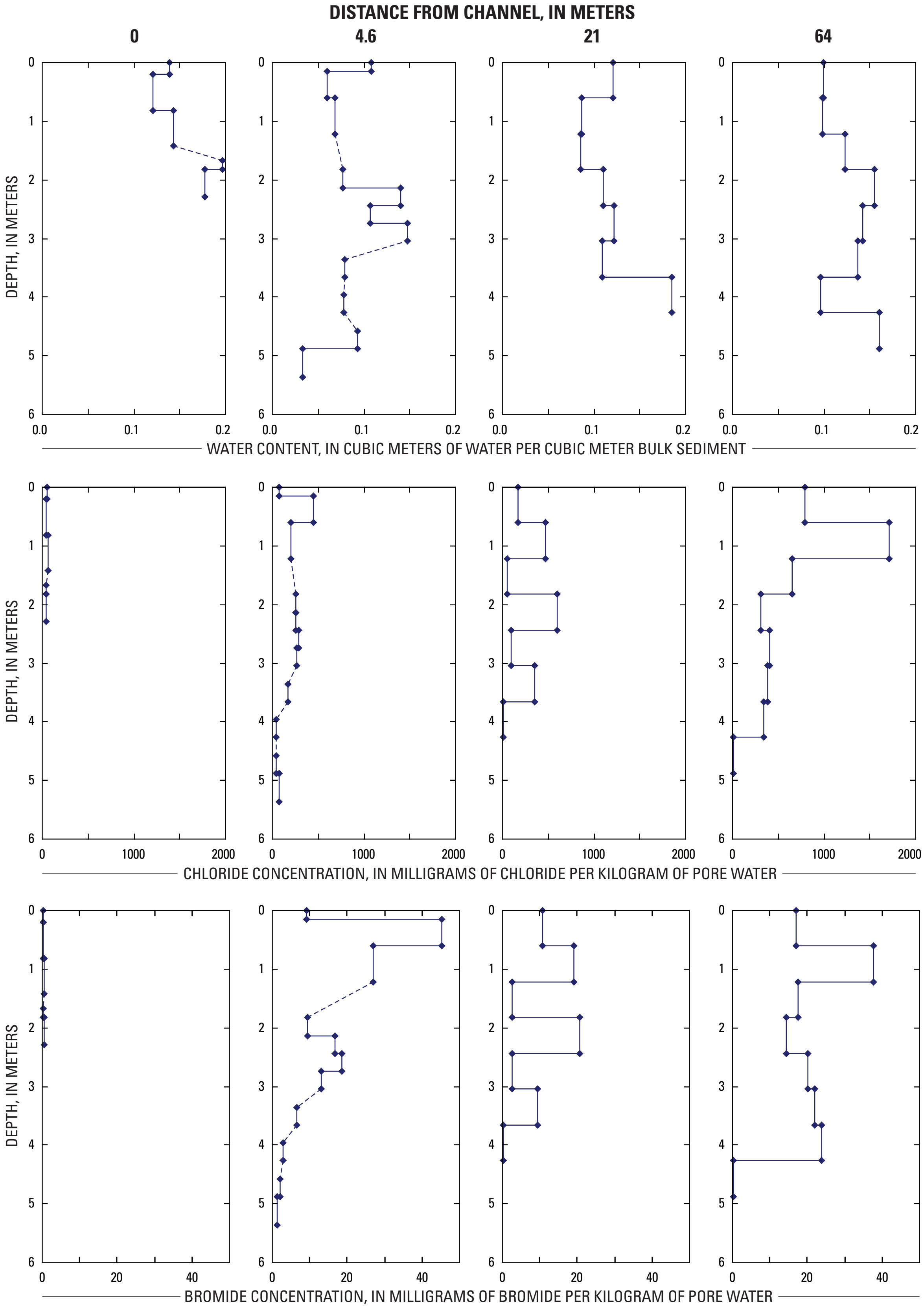

Figure 16. Unsaturated-zone profiles of water content and pore-water concentrations of chloride and bromide along a transect perpendicular to Abo Arroyo, 1.4 kilometers upstream from the mountain front (between gage and PS-1; table 1).

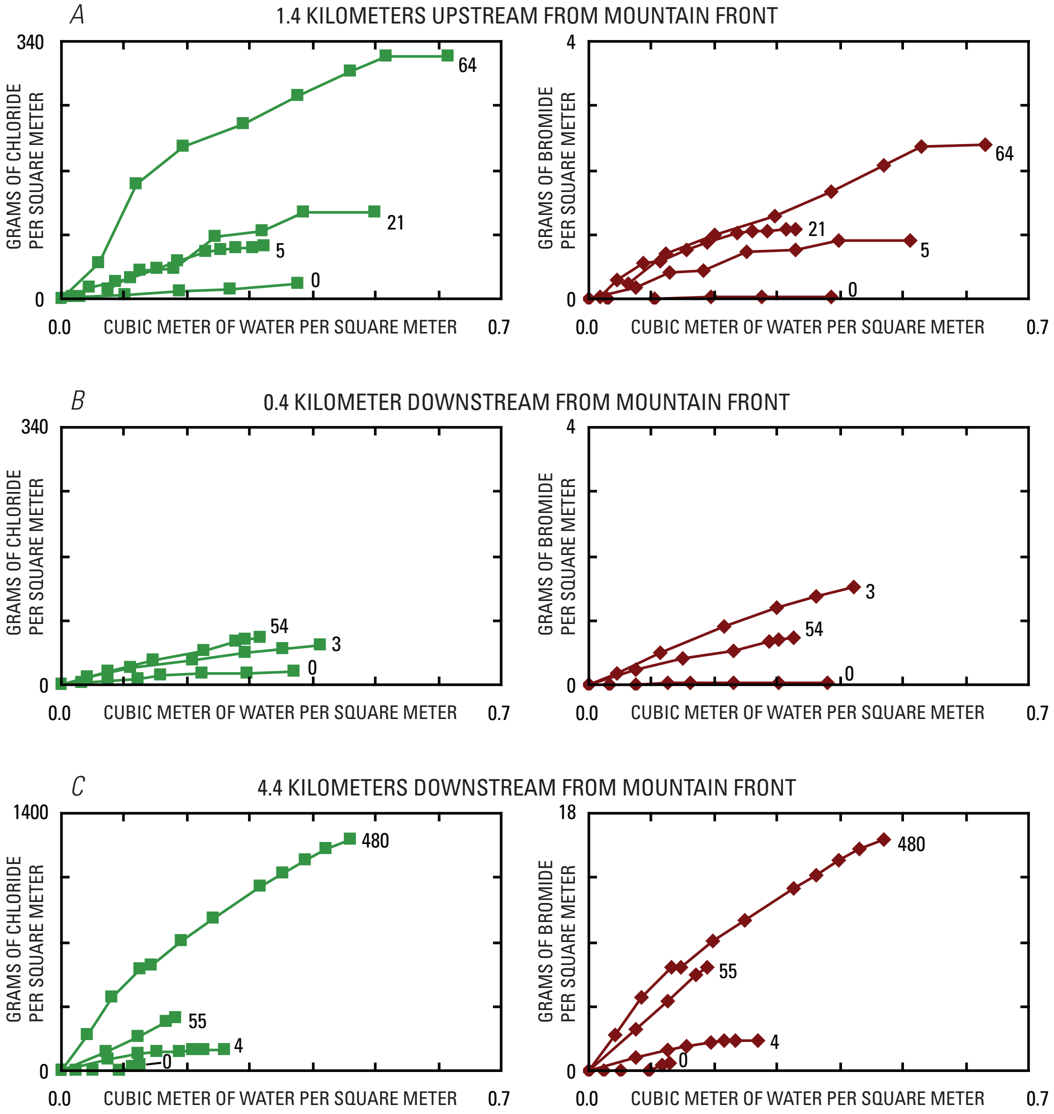

Figure 17. Relationship between cumulative chloride (bromide) and cumulative water along transects starting from Abo Arroyo onto the adjacent terrace. Plotted quantities are per square meter of land surface. Integration is from land surface downward into the unsaturated zone. Numbers next to the plotted data series indicate distance from the corresponding profile to the channel, in meters. *A,* Transect located 1.4 kilometers upstream from the mountain front, near PS-1. *B,* Transect located 0.4 kilometer downstream from the mountain front, near PS-3. *C,* Transect located 4.4 kilometers downstream of the mountain front, near PS-5.

Table 4. Chloride inventories and accumulation times from unsaturated-zone profiles sampled on transects normal to Abo Arroyo, New Mexico.

Distance from channel[1], in meters	Sampled depth, in meters	Chloride inventory[2], in grams	Accumulation time[3], in years
Near PS-1, 1.4 kilometers upstream from mountain front			
5	5.4	69	770
21	4.3	114	1300
64	4.9	320	3600
Near PS-3, 0.4 kilometers downstream from mountain front			
3	4.9	53	590
54	4.3	62	690
Near PS-5, 4.4 kilometers downstream from mountain front			
4	6.1	118	1300
55	3.0	297	3300
480	8.5	1319	15000

[1] Measured from closest channel bank.

[2] Mass of chloride in pore water, per square meter of land surface, between land surface and bottom of sampled profile.

[3] Assuming a deposition rate of 0.09 gram of chloride per square meter per year.

Table 5. Chloride concentrations in streambed pore water and inferred bounds on deep percolation, Abo Arroyo, New Mexico.

Distance from mountain front[1], in kilometers	Top of interval, in meters	Bottom of interval, in meters	Chloride concentration, in grams per kilogram of pore water	Lower bound on percolation[2], as a percentage of infiltration	Upper bound on percolation[3], as a percentage of infiltration
-1.2	1.8	3.5	33	20	100
0.3	1.8	3.5	17	39	100
0.4	4.3	4.9	15	43	100
2.4	1.8	2.4	46	14	100
4.1	1.8	2.4	41	16	100
28.2	4.3	6.7	10	63	100

[1] Distance upstream is negative; downstream is positive.

[2] Based on infiltration having the end-member composition of eastern mountain-front recharge (Plummer and others, 2003).

[3] Based on infiltration having the composition of base flow at the Abo gage (see text). Values greater than 100% reported as 100%.

Conclusions

This chapter presents an overview of a four-year study of streamflow, infiltration, and associated ground-water recharge at Abo Arroyo in south-central New Mexico. The study provided the foundation for using heat as a tracer of streamflow in strongly ephemeral systems.

A stream gage installed for the duration of the study collected high frequency measurements in the upland catchment near a gap in the mountain front through which the arroyo enters the Middle Rio Grande Basin (MRGB). Total annual streamflow at the Abo Arroyo gage ranged from 15.3 million cubic meters (Mm^3) in water year (WY) 1997, the first and wettest year of the study, to 0.8 Mm^3 in the last and driest year (WY-2000). A wide range of precipitation conditions prevailed during the course of the study, with annual precipitation ranging between 75 and 154 percent of average. Total annual streamflow increased nonlinearly with total annual precipitation, indicating that storage and evapotranspiration losses in the upland catchment become increasingly important with increasing aridity.

Summer monsoonal runoff dominated streamflow volume during all four years. Base flow at the gage accounted for only 20 percentage total runoff during the driest year and 2 percent during the wettest year. Daily mean streamflow varied from zero (dry channel) to 37.7 m^3/s. Nearly all flows that reached the basin represented discrete pulses of runoff from brief monsoonal storms. The maximum peak streamflow was 227 m^3/s during the study period. The duration of runoff pulses at the gage varied little, with an average duration of about five hours.

Streambed temperatures at eight locations in the MRGB indicated the timing and extent of streamflow. Much of the study involved development and improvement of the thermal detection technique. Shallow burial of temperature probes (at 0.2 m) and deployment of controls facilitated the determination of flow.

Streambed temperatures indicated that most runoff entering the basin becomes infiltration prior to reaching the Rio Grande. Only the largest flows reached the Rio Grande, during the monsoon season. A classification of flows based on the thermal detection of travel distance indicated that five flows reached the Rio Grande during the four-year study period. Flows were minimal during non-monsoonal months. Streambed temperatures in December 1997 indicated a period of snowmelt-fed infiltration that extended throughout the reach. Snowmelt infiltration lasted two weeks near the mountain front; however, data at the gage indicated that flow rates were small.

Chloride mass-balance calculations provided estimates of the proportion of infiltration that becomes deep percolation and eventual recharge. Chloride in unsaturated-zone pore water beneath the channel suggests that approximately half of infiltrating streamflow becomes recharge, although the range of estimates is large (14–100 percent). Analysis of unsaturated-zone chloride and bromide profiles from transects adjacent to Abo Arroyo showed that direct recharge through terrace surfaces is negligible under current climatic conditions. Analysis of streamflow and streambed temperature records, combined with recharge information from environmental tracers, indicates that the long-term average recharge in the study reach is about 1.0 million cubic meters per year.

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