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Prepared in cooperation with Bernalillo County Public Works Natural Resource Services

Estimates of Groundwater Recharge Rates and Sources in the East Mountain Area, Eastern Bernalillo County, New Mexico, 2005–12

Scientific Investigations Report 2014–5181

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

Cover, Flume and water-quality monitoring station at Ojito North Spring, a natural spring in Bernalillo County's Ojito de San Antonio Open Space near Cedar Crest, New Mexico. Photograph taken September 12, 2011, by Dianna M. Crilley.

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U.S. Geological Survey

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SALLY JEWELL, Secretary

U.S. Geological Survey
Suzette M. Kimball, Acting Director

U.S. Geological Survey, Reston, Virginia: 2014

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Conversion Factors

Inch/Pound to SI

Multiply	By	To obtain
	Length	
inch (in.)	2.54	centimeter (cm)
inch (in.)	25.4	millimeter (mm)
foot (ft)	0.3048	meter (m)
mile (mi)	1.609	kilometer (km)
	Area	
square foot (ft^2)	0.09290	square meter (m^2)
	Volume	
gallon (gal)	3.785	liter (L)
gallon (gal)	0.003785	cubic meter (m^3)
cubic foot (ft^3)	0.02832	cubic meter (m^3)
	Flow rate	
cubic foot per second (ft^3/s)	0.02832	cubic meter per second (m^3/s)
gallon per day (gal/d)	0.003785	cubic meter per day (m^3/d)
inch per hour (in/h)	0.0254	meter per hour (m/h)
inch per year (in/yr)	25.4	millimeter per year (mm/yr)
	Hydraulic conductivity	
foot per day (ft/d)	0.3048	meter per day (m/d)
	Transmissivity*	
foot squared per day (ft^2/d)	0.09290	meter squared per day (m^2/d)

Temperature in degrees Celsius (°C) may be converted to degrees Fahrenheit (°F) as follows:

°F = (1.8 × °C) + 32

Temperature in degrees Fahrenheit (°F) may be converted to degrees Celsius (°C) as follows:

°C = (°F - 32)/1.8

Vertical coordinate information is referenced to the North American Vertical Datum of 1988 (NAVD 88).

Horizontal coordinate information is referenced to the North American Datum of 1983 (NAD 83).

Elevation, as used in this report, refers to distance above the vertical datum.

Specific conductance is given in microsiemens per centimeter at 25 degrees Celsius (µS/cm at 25 °C).

Concentrations of chemical constituents in water are given in milligrams per liter (mg/L).

* Transmissivity: The standard unit for transmissivity is cubic foot per day per square foot times foot of aquifer thickness [(ft^3/d)/ft^2]ft. In this report, the mathematically reduced from, foot squared per day (ft^2/d), is used for convenience.

Estimates of Groundwater Recharge Rates and Sources in the East Mountain Area, Eastern Bernalillo County, New Mexico, 2005–12

By Steven E. Rice and Dianna M. Crilley

Abstract

The U.S. Geological Survey, in cooperation with the Bernalillo County Public Works Division, has conducted a monitoring program in the East Mountain area of eastern Bernalillo County, New Mexico, since 2000 to better define the hydrogeologic characteristics of the East Mountain area and to provide scientific information that will assist in the sustainable management of water resources. This report presents estimates of groundwater recharge to the aquifers that supply water to a network of springs that discharged within the East Mountain area of eastern Bernalillo County during 2005–12. Chloride concentration, the mass ratio of chloride to bromide, and the stable isotope ratios of hydrogen and oxygen were used to estimate annual groundwater recharge rates and to identify the sources and timing of recharge to the aquifers in the East Mountain area. Groundwater recharge rates were estimated by using a chloride mass-balance (CMB) method applied to data from selected springs located in the study area.

Eleven springs and four downgradient monitoring wells were sampled for this study. On the basis of chloride concentrations and the mass ratio of chloride to bromide, eight of the eleven sampled springs are considered representative of dilute groundwater recharged by meteoric water in the Sandia Mountains. Chloride concentrations at three of the sampled springs were likely affected by nonmeteoric chloride sources.

Results of CMB calculations for the eight springs with chloride to bromide ratios and chloride concentrations within the range of dilute groundwater (not influenced by nonmeteoric chloride sources) indicated that between about 5.5 and 23 percent of annual precipitation recharges the groundwater system. The variation in estimated recharge rates indicated that the mechanisms for recharge and groundwater movement in the East Mountain area are complex and that factors such as climate variability, the extent and interconnection of structural features such as faults and fractures, and potential solution enhancement of the aquifers all play important roles in the rates and timing of recharge.

Stable isotope data from springs and snowpacks sampled in the East Mountain area were compared with local, regional, and global meteoric water lines and were analyzed along with values representing the stable isotope composition of winter precipitation and summer monsoonal rains. Results of the stable isotope analysis from springs in this study suggested that winter precipitation is the primary source of groundwater recharge to the aquifers supplying the springs, but there is a component of more isotopically enriched precipitation being recharged as well, likely from summer monsoonal rains. Specific conductance, groundwater-level hydrographs, snowpack chemistry, and snow-water equivalent data were used to inform the analyses and corroborate the findings of the CMB and stable isotope results.

Introduction

The East Mountain area, which in recent years has become part of the greater Albuquerque metropolitan area, is nearly devoid of surface-water resources. Water supply in the area is obtained from groundwater, and increased groundwater use in the East Mountain area has raised concerns about the sustainability of water resources. Understanding groundwater recharge rates, timing, and sources, when coupled with current and predicted changes in development and climate patterns, will assist water-resource managers in developing sustainable yield estimates for the East Mountain area.

The U.S. Geological Survey (USGS), in cooperation with the Bernalillo County Public Works Natural Resource Services, has been conducting a monitoring program since 2000 to define hydrogeologic characteristics and improve the understanding of groundwater resources in the East Mountain area of eastern Bernalillo County, New Mexico (hereafter referred to as the "East Mountain area" or "study area") (fig. 1). This report examines the chloride concentration, the mass ratio of chloride to bromide (Cl:Br), and the stable isotope ratios of hydrogen ($^{2}H/^{1}H$) and oxygen

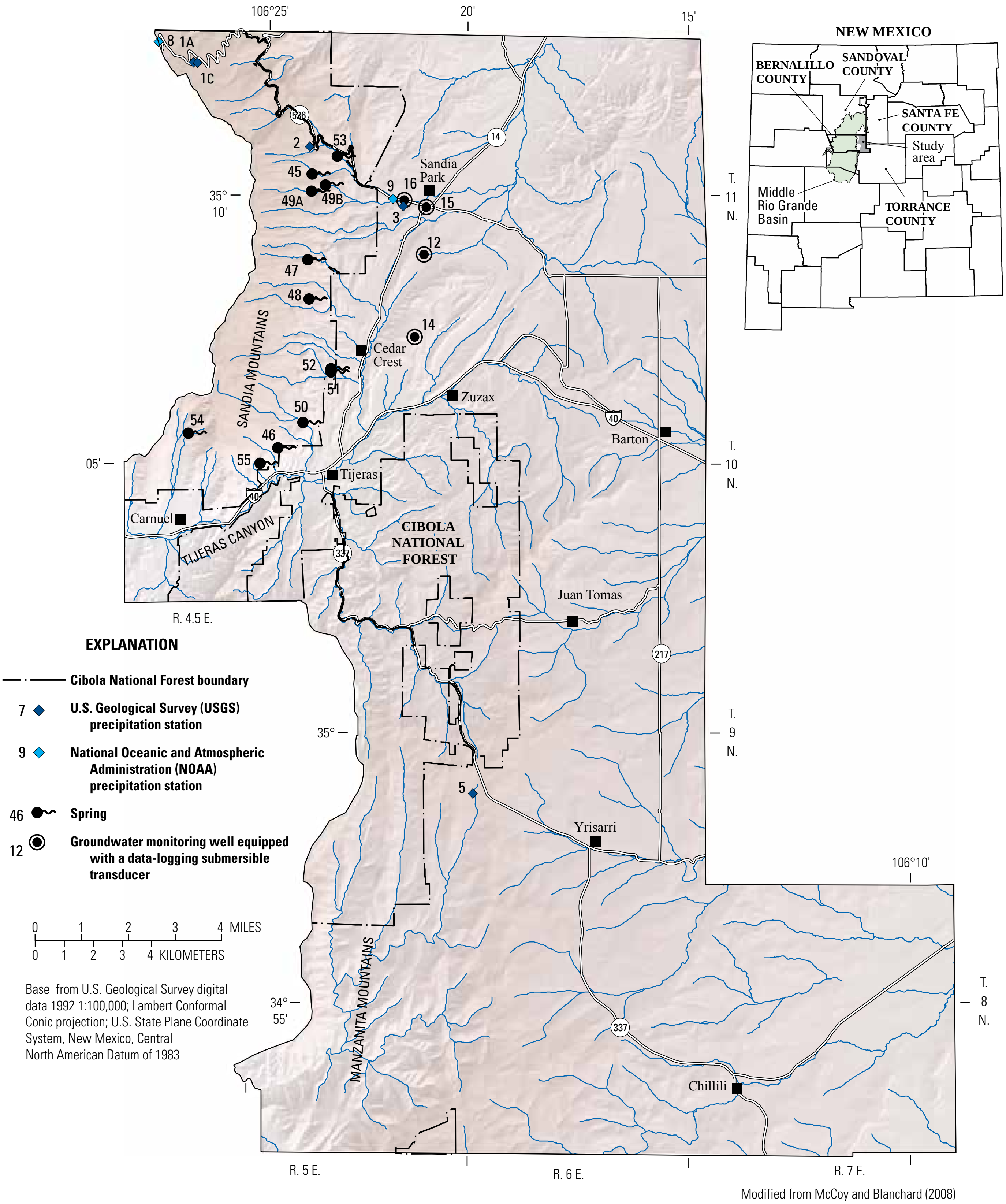

Figure 1. The study area showing the location of data-collection sites in the East Mountain area, eastern Bernalillo County, New Mexico.

($^{18}O/^{16}O$) in samples collected from selected springs in the study area during 2005–12 in an effort to better understand groundwater recharge processes. Groundwater recharge rates in the East Mountain area were estimated by using a chloride mass-balance (CMB) method applied to data from selected springs. The sources and timing of groundwater recharge that contributed to the aquifers in the East Mountain area were examined by using the stable isotope composition of springs sampled in the East Mountain area in comparison with local, regional, and global meteoric water lines and the representative stable isotope composition of winter precipitation and summer monsoonal rain.

Purpose and Scope

The purpose of this report is to present estimates of groundwater recharge rates and to identify the sources and timing of recharge to the aquifers supplying water to selected springs in the East Mountain area of eastern Bernalillo County, N. Mex., during 2005–12. Groundwater recharge rates were estimated on the basis of CMB, and the sources and timing of recharge were identified by using the stable isotope ratios of $^{2}H/^{1}H$ and $^{18}O/^{16}O$ along with the mass ratio of Cl:Br.

Previous Studies

Kelley and Northrop (1975) mapped and presented the geologic framework of the East Mountain area. Additional pertinent geologic mapping and structural investigations in this area were made by Karlstrom and others (1994), Connell and others (1995), Ferguson and others (1996), and Williams and Cole (2007). Titus (1980) provided the first comprehensive investigation into the hydrogeology of the East Mountain area, including water quality and well yield. Jenkins (1982), Kues (1990), White and Kues (1992), Kues and Garcia (1995), Rankin (1996, 2000), Blanchard and Kues (1999), Blanchard (2003, 2004), McGregor (2007, unpublished), and Johnson and Campbell (2008) presented water-level and water-quality data for wells and springs in the area.

Previous investigations of groundwater recharge rates and sources in the East Mountain area and the surrounding region used a variety of methods. Anderholm (1994) used CMB and stable isotope ratios of hydrogen and oxygen to estimate groundwater recharge in the Santa Fe, N. Mex., area. Water-yield regression methods and CMB were used to estimate the amount of groundwater recharge along the western side of the Sandia and Manzanita Mountains draining to the Rio Grande Basin (Anderholm, 2000). McCoy and Blanchard (2008) used chloride concentrations for five springs and the CMB method to estimate groundwater recharge in the East Mountain area. Several other estimates of groundwater recharge have been made in the area by a variety of investigators and are summarized by Bartolino and others (2010).

Description of Study Area

The East Mountain area, as described in this report, encompasses about 260 square miles in eastern Bernalillo County, N. Mex. (fig. 1). The western boundary of the study area is the crest of the Sandia and Manzanita Mountains, whereas the northern, eastern, and southern boundaries are defined as the Bernalillo County line. The study area includes parts of the Sandia, Rio Grande, and Estancia Underground Water Basins, as declared and managed by the New Mexico Office of the State Engineer (http://www.ose.state.nm.us/water_info_groundwater_basin.html). Climate is highly variable across the study area, largely because of variations in elevation, which range from around 6,000 feet (ft) above North American Vertical Datum of 1988 (NAVD 88) in Tijeras Canyon to 10,686 ft above NAVD 88 at the crest of the Sandia Mountains. This range in elevation results in large variations in temperatures, rates of evapotranspiration (ET), precipitation totals, and precipitation that falls as either rain or snow across the study area (McCoy and Blanchard, 2008).

The western edge of the East Mountain area is coincident with a large fault block that has uplifted Precambrian rocks above the Middle Rio Grande Basin to the west and has tipped the overlying Paleozoic and Mesozoic carbonate and clastic units in the study area to the east at approximately 15 degrees (Bartolino and others, 2010). The study area is partially bisected by the northeast-southwest trending Tijeras Fault (fig. 2). Near the intersection of Interstate Highway 40 and New Mexico State Highway 14, the Gutierrez Fault originates as a splay of the Tijeras Fault, down-dropping a central block of complexly folded, faulted, and fractured units forming the Tijeras Graben. Outside of the Tijeras Graben, the Madera Formation of Pennsylvanian age forms much of the surficial geology in the southern part of the study area.

The Madera Formation is primarily a massive limestone and is the primary water-bearing unit in the study area, parts of which have transmissivities much greater than other units in the study area (Bartolino and others, 2010). Groundwater availability and the location and size of springs in the Madera Formation are strongly influenced by structural features, such as faults and fractures, as well as the solution enhancement of the carbonate rock, which can form conduits and voids (Jenkins, 1982). Solution-enhanced features affecting water availability are localized; therefore, many wells completed in the Madera Formation are highly productive, but many dry wells also have been drilled (Titus, 1980). Primarily, springs in the study area either discharge from the Madera Formation or are supplied by groundwater from the Madera Formation. Many more springs are located on the steeper and more heavily faulted and fractured slopes of the Sandia Mountains north of the Tijeras Fault than in the Manzanita Mountains to the south (White and Kues, 1992), where units are more gently dipping (1–2 degrees) and are less heavily faulted and fractured (Kelley and Northrop, 1975). Discharge from springs generally does not travel as surface water very far from the point of origin, either being lost to ET or recharged to the groundwater again through bedrock or alluvial aquifers.

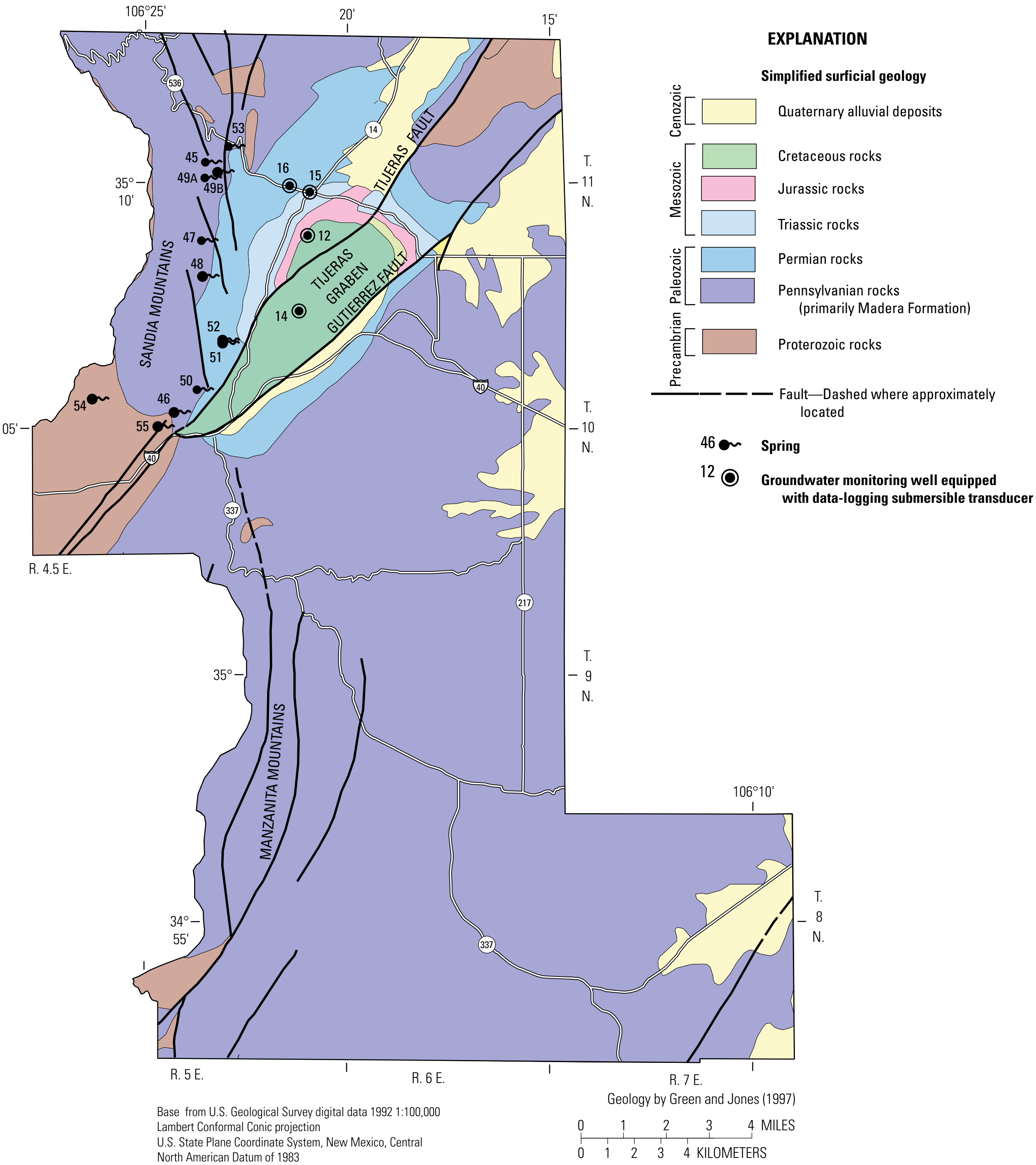

Figure 2. The East Mountain area, eastern Bernalillo County, New Mexico.

Stratigraphically higher carbonate and clastic units of Permian to Cretaceous age are located in the northern part of the study area within and near the Tijeras Graben and can be locally important sources of groundwater (fig. 2). Rocks of Precambrian age outcrop in the northeast corner of the study area as well as in Tijeras Canyon, where they are also an important local source of groundwater supply (Bartolino and others, 2010).

Groundwater recharge to aquifers in the study area can occur as direct infiltration of precipitation (diffuse recharge), infiltration of runoff in channels and arroyos (focused recharge), infiltration from septic tanks, septic disposal fields, or irrigated areas (anthropogenic recharge), or as groundwater inflow from adjacent basins (Bartolino and others, 2010). In areas where surficial geology is heavily faulted, fractured, or solution enhanced, the direct, focused recharge of precipitation can occur.

Methods of Data Collection and Analysis

This section describes the data sources, collection methods and protocols, and analyses used to determine groundwater recharge estimates for the East Mountain area. Data were collected by the USGS for the purposes of this investigation, collected during other USGS investigations applicable to this study, or obtained from other sources such as the National Oceanic and Atmospheric Administration (NOAA).

Spring Data

A network of 11 springs was selected to represent locations indicative of the groundwater recharge occurring in the East Mountain area (sites 45–55, fig. 1). To maintain consistency, site numbers were retained from those used in McCoy and Blanchard (2008). Spring location, elevation, and the type of data collected at these locations during 2005–12 are presented in table 1. Four of the 11 springs had fixed water-quality sampling locations (sites 46, 48, 51, and 52); at the other seven spring locations, water-quality samples were collected as close to the spring discharge point as possible to best represent the source aquifer conditions. Although efforts were made to collect springwater samples from a consistent location, spring discharge points can move over time and throughout the year because of the effects of changing flow rate, geomorphology of the discharge area, and climatic effects such as ET. The location of most spring discharge points varied slightly between sampling events, with the exception of Cienega Spring (sites 49A and 49B). Springwater-quality samples were collected from site 49A (Upper Cienega Spring) between 2005 and September 2007, at which point the spring discharge location became unreliable and dry at times. From the December 2007 through the 2012 site visits, springwater-quality samples were collected approximately 1,000 ft down the drainage from site 49A at site 49B (Cienega Spring), where there was a more reliable spring discharge point that made a better sampling location.

Springwater-quality samples were collected biannually, generally representing the postsnowmelt (spring, April–May) and postmonsoon (fall, September–October) periods of the year. Field water-quality parameters including water temperature, specific conductance, and pH were collected during each sampling visit by following protocols described in Wilde (variously dated). These field-measured values were used to corroborate that springwater-quality values were consistent with previous measurements and represented the same source water as previous sampling events. Springwater-quality samples were collected by using methods described in the USGS National Field Manual for the Collection of Water-Quality Data (U.S. Geological Survey, 2006a). Samples were analyzed for dissolved chloride and bromide at the USGS National Water Quality Laboratory in Denver, Colorado, by using methods described by Fishman and Friedman (1989) and for the stable isotope ratios of hydrogen ($^{2}H/^{1}H$) and oxygen ($^{18}O/^{16}O$)—hereafter abbreviated as $\delta^{2}H$ and $\delta^{18}O$—at the USGS Reston Stable Isotope Laboratory in Reston, Virginia, by using methods described in Révész and Coplen (2008a; 2008b). Springwater-quality samples were analyzed for dissolved chloride during 2005–12, dissolved bromide during 2009–12, and $\delta^{2}H$ and $\delta^{18}O$ during 2008–12. Data quality-assurance samples, such as duplicates and field blanks, were not collected during the analysis period, and therefore quality control on these sample results are limited to laboratory analytical quality procedures. Springwater-quality sample results were, however, checked for consistency within the sample set and against results over time. Water-quality data for the springs sampled as part of this monitoring program are available through the USGS National Water Information System (NWIS) database and can be accessed online at http://waterdata.usgs.gov/nwis with the station identification number listed in table 1 and are summarized in table 2.

Table 1. Site information for data-collection sites in the East Mountain area, eastern Bernalillo County, New Mexico.

[Site locations shown in figure 1. NAD 83, North American Datum of 1983; ft-blsd, feet below land surface datum; ft, feet; NAVD 88, North American Vertical Datum of 1988; °, degrees; ', minutes; ", seconds; NA, not applicable; USGS, U.S. Geological Survey; swe, snow-water equivalent; swq, snow-water quality; P, precipitation; NOAA, National Oceanic and Atmospheric Administration; cgw, continuous groundwater level; cqw, continuous water quality; bqw, biannual water quality; NA, not applicable]

Site number[1]	Station identification number	Station type	Station name	Latitude (NAD 83)	Longitude (NAD 83)	Well depth (ft-blsd)	Open interval (ft-blsd)	Elevation (ft above NAVD 88)	Operating agency	Types of data used in this report
1A	351228106261130	Precipitation	Upper Sandia A	35°12'28"	106°26'11"	NA	NA	10,030	USGS	swe
1C	351229106260830	Precipitation	Upper Sandia C	35°12'29"	106°26'08"	NA	NA	10,091	USGS	swe, swq
2	351054106233330	Precipitation	Middle Sandia	35°10'54"	106°23'33"	NA	NA	8,020	USGS	P
3	350948106212630	Precipitation	Lower Sandia	35°09'48"	106°21'26"	NA	NA	7,030	USGS	swq
5	345853106195130	Precipitation	Middle Manzanita	34°58'53"	106°19'51"	NA	NA	7,460	USGS	P
8	298011	Precipitation	Sandia Crest	35°13'	106°27'	NA	NA	10,686	NOAA	P
9	298015	Precipitation	Sandia Park	35°13'	106°22'	NA	NA	7,019	NOAA	P
12	350853106205701	Monitoring well	Piñon Ridge	35°08'53"	106°20'57"	220	120–215	6,960	USGS	cgw, cqw
14	350721106211001	Monitoring well	Sierra Vista	35°07'21"	106°21'10"	340	120–335	6,970	USGS	cgw, cqw
15	350946106205401	Monitoring well	Sandia Park 1	35°09'46"	106°20'54"	110	95–105	6,870	USGS	cgw, cqw
16	350954106212401	Monitoring well	Sandia Park 2	35°09'54"	106°21'24"	180	155–175	6,940	USGS	cgw, cqw
45	351022106231401	Spring	Wolf Spring	35°10'22"	106°23'14"	NA	NA	7,640	NA	bqw
46	350518106235701	Spring	Carlito Spring	35°05'18"	106°23'57"	NA	NA	6,810	NA	bqw
47	350850106232001	Spring	Cañoncito Spring	35°08'50"	106°23'20"	NA	NA	7,561	NA	bqw
48	350807106231701	Spring	Cole Spring	35°08'07"	106°23'17"	NA	NA	7,430	NA	bqw
49A	351008106231601	Spring	Upper Cienega Spring	35°10'08"	106°23'16"	NA	NA	7,680	NA	bqw
49B	351012106230401	Spring	Cienega Spring	35°10'12"	106°23'04"	NA	NA	7,540	NA	bqw
50	350543106233901	Spring	Hondo Spring	35°05'43"	106°23'39"	NA	NA	6,920	NA	bqw
51	350613106230601	Spring	Ojito Spring (South)	35°06'13"	106°23'06"	NA	NA	6,760	NA	bqw
52	350617106231101	Spring	Ojito Spring (North)	35°06'17"	106°23'11"	NA	NA	6,800	NA	bqw
53	351043106225101	Spring	unnamed spring near Bills Spring	35°10'43"	106°22'51"	NA	NA	7,420	NA	bqw
54	350554106262201	Spring	Three Gun Spring	35°05'54"	106°26'22"	NA	NA	7,360	NA	bqw
55	350501106240101	Spring	Lower Carlito Spring	35°05'01"	106°24'01"	NA	NA	6,384	NA	bqw

[1]Site numbers are consistent with those used in McCoy and Blanchard (2008).

Table 2. Summary of selected water-quality data for selected springs in the East Mountain area, Bernalillo County, New Mexico, 2005–12.

[Site locations shown in figure 1. mg/L, milligrams per liter; µS/cm, microsiemens per centimeter; –, not measured]

Site number	Station name	Date	Dissolved chloride (mg/L)	Dissolved bromide (mg/L)	Specific conductance (µS/cm)	Delta oxygen-18 (per mil)	Delta deuterium (per mil)
45	Wolf Spring	03-10-05	15	–	570	–	–
		04-06-05	19	–	750	–	–
		04-27-05	32.6	–	795	–	–
		05-18-05	31.4	–	800	–	–
		06-29-05	14.4	–	790	–	–
		09-01-05	–	–	800	–	–
		12-29-05	39	–	750	–	–
		02-28-06	40.4	–	483	–	–
		04-04-06	41.5	–	720	–	–
		08-31-06	40.5	–	720	–	–
		09-26-07	36.6	–	720	–	–
		12-04-07	4.33	–	456	–	–
		04-04-08	38.4	–	722	–	–
		04-26-10	24.6	0.031	736	-11.72	-83.3
		10-29-10	24.6	–	–	–	–
		06-12-12	–	–	469	-11.62	-82.2
46	Carlito Spring	03-08-05	1.63	–	290	–	–
		04-12-05	1.73	–	200	–	–
		04-29-05	1.9	–	450	–	–
		05-24-05	1.92	–	460	–	–
		06-29-05	1.94	–	470	–	–
		09-01-05	1.65	–	470	–	–
		12-30-05	1.69	–	480	–	–
		03-14-06	1.76	–	470	–	–
		04-12-06	1.63	–	470	–	–
		06-21-06	1.63	–	480	–	–
		08-28-06	1.65	–	470	–	–
		09-28-07	1.61	–	460	–	–
		12-11-07	1.69	–	479	–	–
		04-07-08	1.7	–	375	–	–
		04-15-08	–	–	–	-12.61	-87.66
		11-03-08	1.6	–	471	-12.66	-89
		05-20-09	1.62	–	409	-12.61	-89.15
		10-27-09	1.64	0.03	471	-12.59	-89.3
		04-27-10	1.7	0.031	467	-12.59	-88.5
		10-29-10	1.63	0.022	465	-12.62	-88.4
		05-16-11	1.55	0.028	468	-12.58	-89.4
		11-15-11	1.92	–	469	-12.63	-89.3
		06-12-12	1.66	–	466	-12.65	-89.4
		10-12-12	1.88	0.032	411	-12.58	-89.4
47	Cañoncito Spring	04-05-05	1.68	–	550	–	–
		04-29-05	1.67	–	550	–	–
		05-20-05	1.73	–	550	–	–
		06-30-05	1.63	–	540	–	–
		08-31-05	1.62	–	550	–	–
		12-28-05	1.51	–	550	–	–
		03-01-06	1.48	–	540	–	–
		04-05-06	1.59	–	540	–	–
		08-26-06	1.45	–	540	–	–
		09-28-07	1.32	–	530	–	–
		12-04-07	1.45	–	534	–	–

Table 2. Summary of selected water-quality data for selected springs in the East Mountain area, Bernalillo County, New Mexico, 2005–12.—Continued

[Site locations shown in figure 1. mg/L, milligrams per liter; µS/cm, microsiemens per centimeter; –, not measured]

Site number	Station name	Date	Dissolved chloride (mg/L)	Dissolved bromide (mg/L)	Specific conductance (µS/cm)	Delta oxygen-18 (per mil)	Delta deuterium (per mil)
47	Cañoncito Spring—Continued	04-05-05	1.68	–	550	–	–
		04-06-08	1.46	–	393	–	–
		11-03-08	1.39	–	539	-12.31	-86.3
		05-21-09	1.39	–	509	-12.31	-85.75
		10-26-09	1.4	0.028	546	-12.3	-86.3
		04-27-10	1.76	0.023	545	-12.14	-84.7
		10-29-10	1.35	0.026	533	-12.3	-86.5
		05-08-11	1.35	0.025	501	-12.34	-86.2
		11-11-11	1.34	–	438	-12.25	-86.7
		06-13-12	1.48	–	446	-12.27	-86.8
48	Cole Spring	04-05-05	1.97	–	600	–	–
		04-27-05	2.07	–	610	–	–
		05-20-05	2.29	–	630	–	–
		06-30-05	2.29	–	630	–	–
		09-01-05	2.21	–	630	–	–
		12-28-05	2.07	–	630	–	–
		03-01-06	1.97	–	610	–	–
		04-05-06	2.09	–	610	–	–
		08-29-06	1.94	–	600	–	–
		09-25-07	1.88	–	590	–	–
		12-04-07	1.93	–	604	–	–
		04-06-08	1.95	–	425	–	–
		11-03-08	1.83	–	598	-12.43	-86.6
		05-21-09	1.82	–	498	-12.38	-87.06
		10-26-09	1.76	0.036	597	-12.47	-87.1
		04-27-10	1.83	0.033	584	-12.48	-86.9
		10-29-10	1.86	0.029	607	-12.4	-87.3
		05-08-11	1.77	0.029	598	-12.36	-87.2
		11-11-11	1.72	–	589	-12.38	-88
		06-13-12	1.83	–	549	-12.4	-87.5
49A	Upper Cienega Spring	04-06-05	–	–	590	–	–
		04-21-05	2.43	–	570	–	–
		04-27-05	3.46	–	570	–	–
		05-18-05	7.2	–	580	–	–
		06-29-05	15.8	–	590	–	–
		09-01-05	20.7	–	600	–	–
		12-29-05	19.6	–	590	–	–
		02-28-06	18.6	–	429	–	–
		04-04-06	18.4	–	580	–	–
		06-21-06	16.9	–	560	–	–
		08-31-06	5.1	–	570	–	–
		09-14-07	16	–	580	–	–
49B	Cienega Spring	12-04-07	15.8	–	466	–	–
		04-04-08	15.7	–	560	–	–
		11-03-08	17.9	–	573	-12.41	-85.6
		05-20-09	15.7	–	583	-12.11	-85.91
		10-26-09	16.5	0.026	584	-12.21	-86.3
		04-27-10	3.76	0.015	526	-12.06	-84.9
		07-02-10	–	–	–	-12.22	-84.4
		07-28-10	–	–	–	-12.23	-87.4

Table 2. Summary of selected water-quality data for selected springs in the East Mountain area, Bernalillo County, New Mexico, 2005–12.—Continued

[Site locations shown in figure 1. mg/L, milligrams per liter; µS/cm, microsiemens per centimeter; –, not measured]

Site number	Station name	Date	Dissolved chloride (mg/L)	Dissolved bromide (mg/L)	Specific conductance (µS/cm)	Delta oxygen-18 (per mil)	Delta deuterium (per mil)
49B	Cienega Spring—Continued	08-10-10	–	–	–	-12.27	-85.9
		08-23-10	–	–	–	-12.25	-86.6
		09-08-10	–	–	–	-12.24	-85.8
		10-29-10	18.3	0.028	582	-12.26	-85.9
		05-12-11	18.5	0.013	485	-12.19	-85.9
		06-12-12	16.9	–	575	-12.33	-87.2
50	Hondo Spring	11-03-08	2.07	–	575	-12.38	-87.9
		05-21-09	2.03	–	519	-12.37	-87.18
		10-27-09	2.02	0.044	565	-12.49	-87.9
		04-26-10	2.07	0.038	570	-12.43	-87.4
		10-29-10	2.03	0.034	560	-12.34	-88.2
		05-12-11	2.11	0.03	456	-12.21	-87.7
		10-21-11	2.48	–	573	-12.29	-87.3
		06-12-12	2.07	–	556	-12.4	-87.6
51	Ojito Spring (South)	04-16-08	–	–	–	-12.24	-84.53
		11-03-08	5.58	–	481	-12.26	-85.8
		05-20-09	5.53	–	458	-12.23	-86.56
		10-27-09	5.46	0.035	461	-12.19	-86.3
		04-26-10	5.61	0.034	456	-12.18	-86.5
		10-29-10	5.42	0.036	466	-12.3	-86.6
		05-12-11	5.48	0.032	450	-12.19	-86.6
52	Ojito Spring (North)	04-16-08	–	–	–	-12.21	-84.75
		11-03-08	5.67	–	464	-12.2	-86.5
		05-20-09	5.38	–	462	-12.15	-87.12
		10-27-09	5.4	0.032	477	-12.18	-86.3
		04-26-10	5.55	0.024	451	-12.18	-85.9
		10-29-10	5.42	0.029	461	-12.22	-86.8
		05-12-11	5.22	0.029	438	-12.19	-87
		10-21-11	5.48	–	427	-12.26	-87
		06-13-12	5.46	–	430	-12.21	-87
53	unnamed spring near Bills Spring	10-26-09	94.2	0.072	1,030	-11.77	-82.5
		04-26-10	86.9	0.031	798	-12.03	-84.1
		10-29-10	102	0.062	1,040	-11.79	-84
		05-12-11	92	0.058	942	-11.84	-83.8
		10-21-11	92.7	–	895	-11.68	-83.1
		06-12-12	101	–	956	-11.55	-82.8
54	Three Gun Spring	10-29-10	5.08	0.072	493	-11.75	-83.7
55	Lower Carlito Spring	10-12-12	2.37	0.044	472	-12.4	-88.3

Precipitation Data

Precipitation data were collected from sites maintained by either the USGS or NOAA (sites 1A, 1C, 2, 3, 5, 8, and 9; fig. 1, table 1). The elevation of precipitation-data-collection stations ranged from 7,019 ft above NAVD 88 (site 9) to 10,686 ft above NAVD 88 (site 8), representing the range in elevations of the groundwater recharge areas for the springs investigated in this study. Precipitation data from the USGS stations (sites 2 and 5) were obtained by using a tipping-bucket rain gage (model TE525WS, Texas Electronics, Dallas, Texas), in conjunction with a pulse-counting data logger (HOBO Micro Station, Onset Computer Corporation), and seasonally by utilizing a snowfall adapter (model CS705, Campbell Scientific). The snowfall adapter consisted of a reservoir of antifreeze and a thin layer of mineral oil so that snowfall could be captured and measured as it fell even if ambient temperatures were below freezing, thus reducing potential losses from ET, wind, and (or) sublimation. Tipping-bucket rain gages were serviced quarterly and calibrated annually according to USGS quality-assurance protocols for precipitation data (U.S. Geological Survey, 2006b).

Snow water equivalent (SWE), the amount of water contained within the snowpack, was measured monthly from two sites during the winter season: (1) site 1A during 2001–12 and (2) site 1C during 2010–12 (table 1). Snow depth and SWE were measured at 1-ft intervals along a fixed 100-ft transect by using a snow tube sampler following U.S. Department of Agriculture protocols for snow-survey sampling (U.S. Department of Agriculture, 1984). Snow-survey data (snow depth and SWE) from site 1A were consistently biased low and unrepresentative of the average snow depth and SWE for that area because of a poor site location. As a result, data collected from site 1A during 2001–12 were omitted from the analyses in this report.

Samples for snowpack chemistry were collected on December 28, 2011, from site 1C (Upper Sandia) and site 3 (Lower Sandia) by using methods outlined by Ingersoll and others (2005). Snowpack water-quality samples were analyzed for dissolved chloride and specific conductance at the USGS National Water Quality Laboratory in Denver, Colo., and for $\delta^{2}H$ and $\delta^{18}O$ at the USGS Reston Stable Isotope Laboratory in Reston, Va.

Precipitation data collected as part of this monitoring program, including continuous precipitation data, snow depth, SWE, and snowpack chemistry data, are available from the NWIS database (http://waterdata.usgs.gov/nwis).

Groundwater Data

A network of four groundwater-monitoring wells (sites 12, 14–16; fig. 2, table 1) was selected to represent unconfined groundwater conditions in a geologically complex area where intense faulting and fracturing influence groundwater flow (McGregor, 2007, unpublished). The four wells were drilled in 1998 as part of the East Mountain area monitoring program and are completed in different geologic formations as follows: (1) site 12 (Piñon Ridge), Cretaceous-age Dakota Sandstone; (2) site 14 (Sierra Vista), Cretaceous-age Mesaverde Group; (3) site 15 (Sandia Park 1), Triassic-age Chinle Group; and (4) site 16 (Sandia Park 2), Permian-age Abo and Yeso Formations. Information on well depth and the open (screened) interval is presented in table 1. Additional geologic and water-quality information for these four monitoring wells can be found in the Bernalillo County Regional Groundwater Monitoring Report (McGregor, 2007, unpublished).

Continuous water-level data were recorded in the four monitoring wells during 2005–10 by using submersible pressure transducers with internal data-logging capacity; water-level data from the monitoring wells during the period 2005–8 are discussed in McCoy and Blanchard (2008). In January 2010, the instrumentation in the four groundwater monitoring wells was upgraded to include the continuous monitoring of the water-quality parameters specific conductance and water temperature. Continuous water-level and water-quality data were collected hourly, with instrumentation serviced and checked quarterly for sensor function, fouling, and calibration in accordance with USGS protocols for continuous water-quality monitors (Wagner and others, 2006). Data records of water level and water quality from the four wells were subject to the USGS records review process and are available from the NWIS database.

Groundwater Recharge Estimation By Using Chloride Mass Balance

The CMB method has been used by investigators in semiarid environments to determine the rates of groundwater recharge to the groundwater system (Anderholm, 1994, 2000; Phillips, 1994; Heilweil and others, 2007). The CMB method used to estimate groundwater recharge in this study can be expressed as the following equation:

$$R = \mathrm{P}\frac{C_P}{C_S} \qquad (1)$$

where

- R is the annual recharge amount, in inches;
- P is the average annual precipitation (rain and snow), in inches;
- C_P is the average chloride concentration of bulk precipitation in the study area, in milligrams per liter; and
- C_S is the chloride concentration of water from the spring, in milligrams per liter.

The C_P is defined in this report as the aggregate of chloride from precipitation and chloride from atmospheric deposition between precipitation events. Successful use of the CMB method relies on meeting a number of assumptions, and uncertainty exists where these assumptions are not fully realized. The assumptions are modified from Dettinger (1989) to best represent conditions in the East Mountain area and are presented and evaluated below.

(1) *All precipitation that falls on the land surface is either recharged or lost to evaporation and (or) transpiration.*
There are no surface-water diversions or appreciable surface-water runoff from the East Mountain area except that of spring discharge, and potential losses to ET exceed annual precipitation totals.

(2) *Average annual precipitation and chloride concentration in bulk precipitation have not changed with respect to time.*
Groundwater ages reported by Blanchard (2004) for nine wells and a spring in the East Mountain area are between 14 and 26 years old. This study assumes that regional precipitation patterns and average chloride concentration in precipitation have not changed appreciably over this period.

(3) *The rate of groundwater recharge over time has not been substantially altered by human activities such as changes in land use and land cover.*
The East Mountain area includes rural communities within and adjacent to the Cibola National Forest and wilderness areas. Although development of the East Mountain area has increased in recent years (Bartolino and others, 2010), the area of groundwater recharge for the springs analyzed by using the CMB method is still largely unaltered except for a few small housing developments and areas that are traversed by roadways. Land cover in the area has remained relatively consistent for many years, as the area is largely administered as Cibola National Forest and National Forest wilderness (U.S. Forest Service, 2014).

(4) *Precipitation within the study area is the only source of chloride.*
Precipitation is the source of chloride in groundwater recharge because the recharge areas upgradient from the springs are largely absent of human sources of chloride, such as septic systems and road deicing salts. Additionally, the primarily Paleozoic carbonate and clastic rock aquifers contain little evaporate deposits that could introduce chloride into the groundwater through water-rock interaction (dissolution) (Titus, 1980).

(5) *Chloride behaves conservatively and predictably within the system.*
Chloride is an ideal natural tracer because of its chemically conservative behavior, high solubility, low reactivity, and low concentration in most rocks and minerals; the weathering of most rocks—with the exception of evaporate deposits—is not an additional source of chloride to groundwater (Feth, 1981).

Estimates of Groundwater Recharge Rates and Sources

Estimation of Groundwater Recharge Rates Based on Chloride Mass Balance

The CMB method of estimating groundwater recharge is useful in arid and semiarid areas where recharge rates are often low in comparison to total precipitation, making other methods of recharge estimation, such as the water balance method, less reliable (Scanlon and others, 2002). Because of aquifer mixing, chloride concentrations in groundwater are often representative of a more areally averaged recharge compared to chloride concentrations of individual precipitation events or localized vadose zone pore-water samples; however, aquifer mixing is not always complete, and variations in chloride concentration can exist in areas with preferential groundwater pathways and (or) large recharge events that rapidly transport unmixed water through the aquifer.

Sources of Chloride

In most cases chloride in groundwater is sourced from meteoric (rain and snow) recharge, such as bulk precipitation; however, chloride also can be introduced into the groundwater system from the interaction of recharge with nonmeteoric chloride sources, such as the dissolution of chloride-bearing geologic materials, dusts from surficial deposits, or matter from human sources, such as septic systems and road deicing salts (Davis and others, 1998; Mullaney and others, 2009). In the study area, chloride-bearing geologic units are not prevalent, but dusts from upwind areas may contribute to the chloride concentration of bulk precipitation. Human sources of chloride exist within the study area; however, these sources are localized and can generally be delineated where they may affect natural groundwater by using the geochemical method of chloride-to-bromide mass ratios.

Sources Indicated By Chloride-to-Bromide Mass Ratios

Dilute groundwater that is not influenced by nonmeteoric chloride sources generally has a predictable range of values of the Cl:Br ratio by mass (Mullaney and others, 2009). The Cl:Br ratio can be altered by the addition or removal of both chloride and bromide through a variety of scenarios including the use of road deicing salt, septic systems, evaporative concentration prior to groundwater recharge, or preferential uptake of ions via plant transpiration (Heilweil and others, 2007). Mullaney and others (2009) reported chloride concentrations less than

20 mg/L and Cl:Br ratios less than 300 as the approximate range for dilute groundwater and defined binary mixing curves to help define the sources of elevated chloride concentrations and Cl:Br ratios (fig. 3). A theoretical upper Cl:Br ratio limit of 400 for waters not affected by human sources was identified by Jagucki and Darner (2001). Where chloride concentrations exceed 20 mg/L and Cl:Br ratios exceed 400, there is increasing indication that the groundwater has been influenced by a nonmeteoric chloride source.

The Cl:Br ratios of water from springs in the study area ranged widely from approximately 46 to 2,800. Eight of the 11 springs analyzed had median Cl:Br ratios within the range of dilute groundwater, suggesting little to no human or other nonmeteoric sources of chloride and supporting their use in the CMB calculation of groundwater recharge in the East Mountain area (fig. 3). Sites 46–48, 50–52, and 54–55 had median Cl:Br ratios below 300 and median chloride concentrations below 20 mg/L (table 3). Site 49B (Cienega Spring), site 45 (Wolf Spring), and site 53 (unnamed spring near Bills Spring) had Cl:Br ratios and (or) chloride concentrations indicating nonmeteoric sources of chloride. Site 49B had 3 samples in which the Cl:Br ratio exceeded 300 and 1 sample in which the Cl:Br ratio was below 251, with all 4 samples having chloride concentrations below 20 mg/L. The binary mixing curves in figure 3 indicated that site 49B may be affected by road deicing salt or animal waste. Because of the location of site 49B (no roads upgradient), it would be more likely that the source of the elevated chloride concentrations and Cl:Br ratios was from animal waste rather than road deicing salt. The remaining two springs, site 45 (Wolf Spring) and site 53 (unnamed spring near Bills Spring), both had Cl:Br ratios and chloride concentrations exceeding the range of dilute groundwater. Site 45 had only one sample collected for chloride and bromide analysis that plotted on the binary mixing curve associated with impacts from sewage or animal waste. The spring at site 45 is not downgradient of any development, so elevated Cl:Br ratio and chloride concentration could also be a result of ion concentration caused by evaporation and (or) transpiration effects prerecharge or postdischarge. Site 53 had Cl:Br ratios over 1,000 and consistently elevated chloride concentrations. The spring at site 53 is located in a steep ravine below New Mexico State Highway 536, a road which leads up to the crest of the Sandia Mountains. During the winter, this road is treated with road deicing salts, and surface runoff from this road during snowmelt and rain events likely influences the quality of springwater being discharged at site 53.

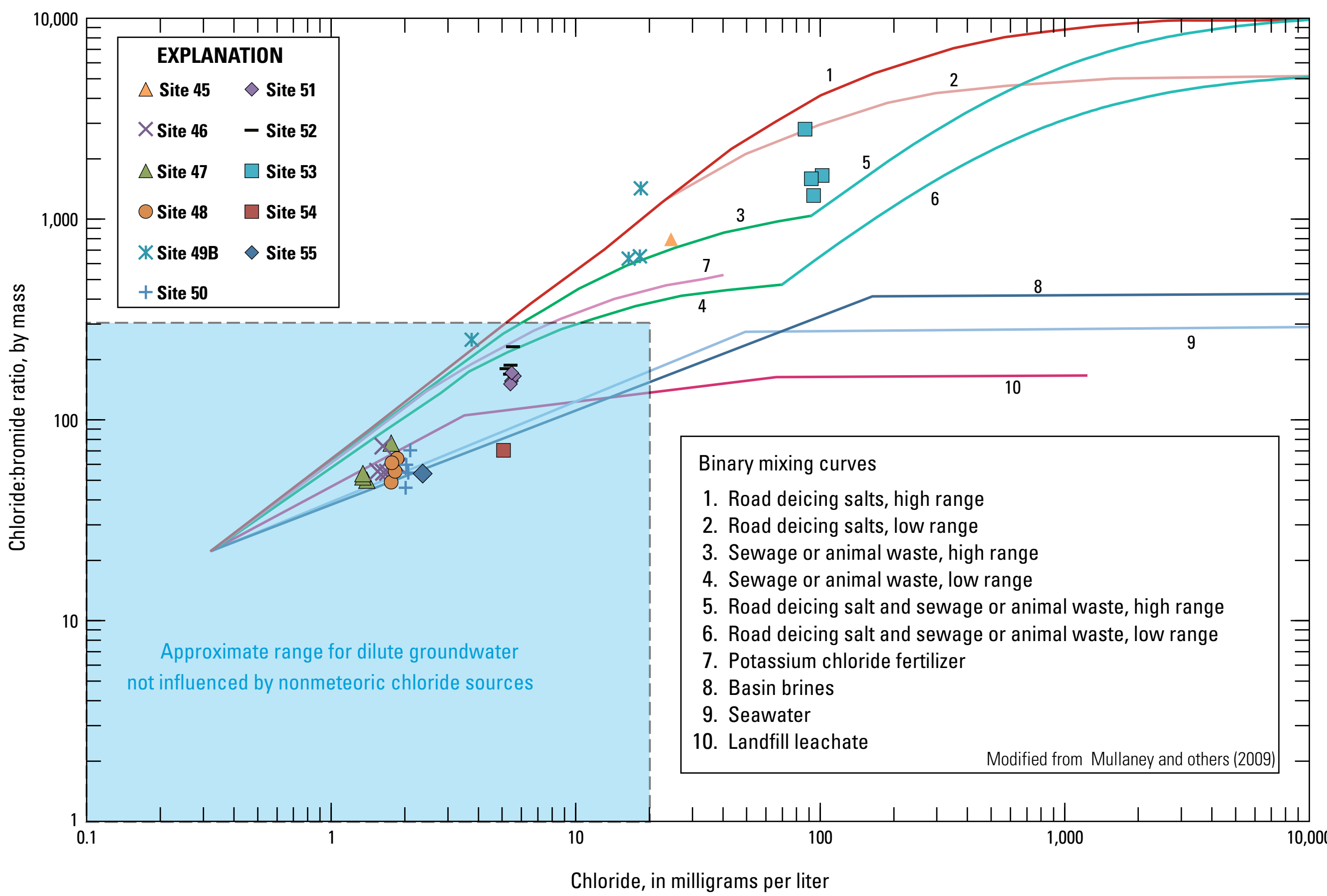

Figure 3. Binary mixing curves representing sources of chloride and the relation of dissolved-chloride concentrations to chloride:bromide mass ratios for samples from select springs in the East Mountain area, Bernalillo County, New Mexico, 2010–12.

Table 3. Summary of the computational inputs and results of the chloride mass-balance estimation of groundwater recharge for selected springs in the East Mountain area, Bernalillo County, New Mexico, 2005–12.

[Site locations shown in figure 1. mg/L, milligrams per liter; Mdn, median; n, number of samples; Avg, average; Min, minimum; Max, maximum; N/A, not applicable. Values of chloride:bromide mass ratios in **bold** indicate dilute groundwater not influenced by nonmeteoric chloride sources]

Site number	Station name	Chloride: bromide mass ratio		Annual precipitation (P) (inches)	Chloride concentration of bulk precipitation (CP) (mg/L)	Chloride concentration of springs (CS) (mg/L)				Annual recharge (R) based on chloride mass balance (inches)				Annual recharge (R), as percentage of precipitation
		Mdn[1]	(n)	Avg	Avg	Mdn[1]	(n)	Min	Max	Mdn[1]	(n)	Min	Max	Range
45	Wolf Spring	794	(1)	22.0	0.3	32.0	(14)	4.33	41.5	0.2	(14)	0.2	1.5	0.9–6.8
46	Carlito Spring	**55**	**(5)**	22.0	0.3	1.66	(23)	1.55	1.94	4.0	(23)	3.4	4.3	15–20
47	Cañoncito Spring	**53**	**(4)**	22.0	0.3	1.47	(20)	1.32	1.76	4.5	(20)	3.8	5.0	17–23
48	Cole Spring	**58**	**(4)**	22.0	0.3	1.94	(20)	1.72	2.29	3.4	(20)	2.9	3.8	13–17
49A	Upper Cienega Spring	N/A	(0)	22.0	0.3	16.0	(11)	2.43	20.7	0.4	(11)	0.3	2.7	1.4–12
49B	Cienega Spring	644	(4)	22.0	0.3	16.5	(9)	3.76	18.5	0.4	(9)	0.4	1.8	1.8–8.2
50	Hondo Spring	**57**	**(4)**	22.0	0.3	2.07	(8)	2.02	2.48	3.2	(8)	2.7	3.3	12–15
51	Ojito Spring (South)	**161**	**(4)**	22.0	0.3	5.51	(6)	5.42	5.61	1.2	(6)	1.2	1.2	5.5
52	Ojito Spring (North)	**183**	**(4)**	22.0	0.3	5.44	(8)	5.22	5.67	1.2	(8)	1.2	1.3	5.5–5.9
53	unnamed spring near Bills Spring	1,616	(4)	22.0	0.3	93.4	(6)	86.9	102	0.1	(6)	0.1	0.1	0.5
54	Three Gun Spring	**71**	**(1)**	22.0	0.3	5.08	(1)	5.08	5.08	1.3	(1)	1.3	1.3	5.9
55	Lower Carlito Spring	**54**	**(1)**	22.0	0.3	2.37	(1)	2.37	2.37	2.8	(1)	2.8	2.8	13

[1]Where only one sample was collected from a site, the result for that sample is reported as the median, minimum, and maximum.

Estimation of Mean Chloride in Bulk Precipitation

In this study, the chloride concentration of bulk precipitation used in the CMB calculation was assumed to be 0.30 mg/L, a value which was determined by Anderholm (1994) for the Santa Fe, N. Mex., area and has since been used in other investigations of groundwater recharge in the region (Anderholm, 2000; McCoy and Blanchard, 2008). Chloride concentrations in the snowpack samples collected in December 2011 from site 1C and site 3 were 0.29 mg/L and less than 0.06 mg/L, respectively, with the actual concentration from site 3 below the reporting level of the analytical laboratory.

McCoy and Blanchard (2008) calculated mean annual precipitation for the study area by using data from surrounding precipitation-data-collection stations to create the following linear regression equation relating elevation and precipitation:

$$P = 0.0024\left(E\right) + 0.6923 \qquad (2)$$

where

P is the precipitation amount, in inches; and
E is the elevation, in feet above NAVD 88.

Applying this equation to the range of elevations within the recharge areas of the springs (about 7,500 to 10,500 ft above NAVD 88) results in calculated mean annual precipitation values ranging from 18.7 to 25.9 inches per year (in/yr). The mean value of this range, 22 in/yr, was selected for the CMB calculation. The recharge areas of the springs are assumed to be located between the approximate elevations of the lowest sampled spring and the crest of the Sandia Mountains.

Estimation of Mean Chloride in Groundwater

Chloride concentrations in samples from springs in the study area varied widely between 1.32 mg/L (site 47, September 28, 2007) and 102 mg/L (site 53, October 29, 2010) (table 2); however, the variability of chloride concentrations at individual spring sites generally was low. Additionally, no seasonal pattern was identified in chloride concentrations after the monsoon or snowmelt periods. Chloride concentration data from five spring sites (45–49A/B) are plotted in figure 4. Overall, no distinct trends over time were observed for the period of record, with the exception of site 49A/B, which indicated possible chloride dilution in response to the high snowfall years of 2005 and 2010 and a large monsoon event in 2006.

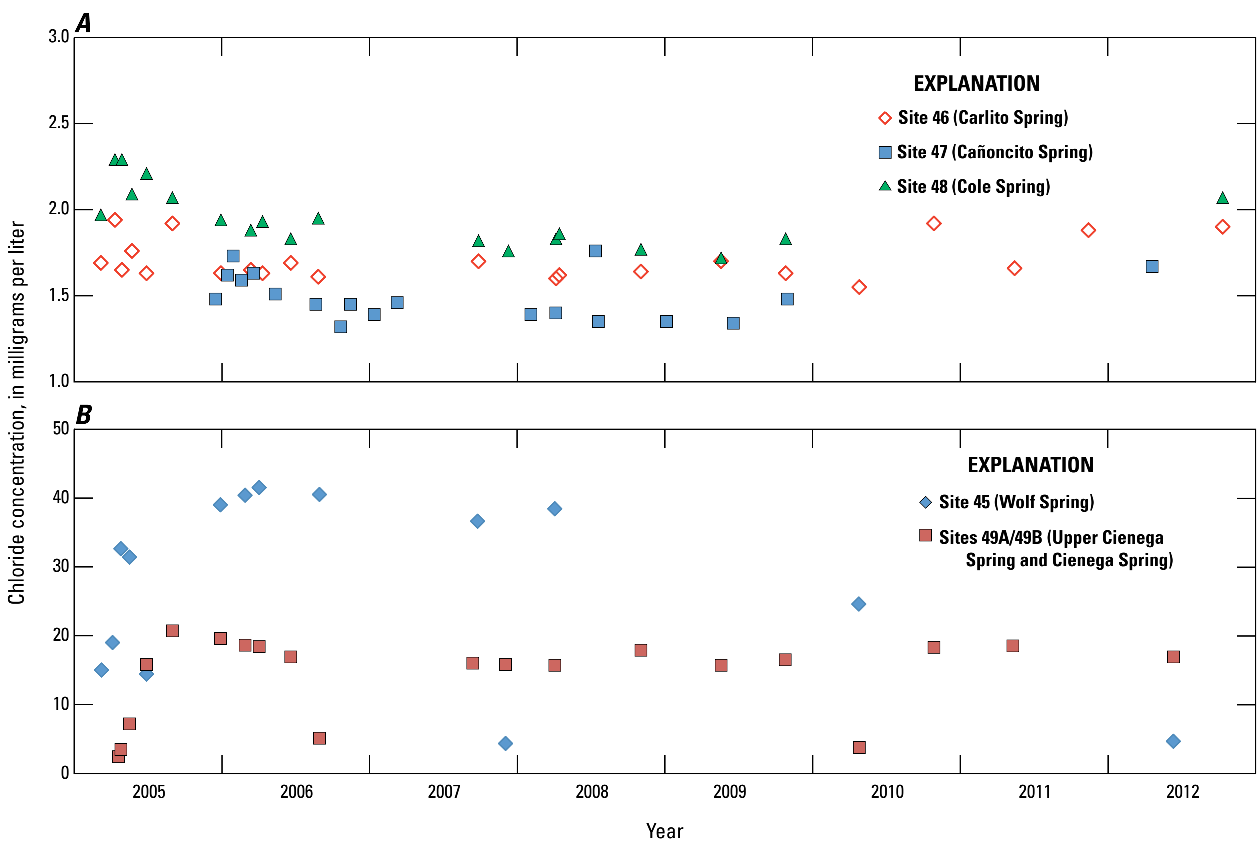

Figure 4. Dissolved-chloride concentrations for samples from select springs in eastern Bernalillo County, New Mexico, 2005–12.

Average specific conductance values for each spring ranged from approximately 450 to 940 microsiemens per centimeter (µS/cm). Sites 45 and 53, which exhibited elevated Cl:Br ratios and chloride concentrations, also had the greatest specific conductance values and the largest variation within the record. Excluding these two sites, the remaining springs had average specific conductance values between 450 and 590 µS/cm and were relatively constant throughout the record, with standard deviations between 2.3 and 8.5 percent of the average values. A significant relation between specific conductance and chloride concentration was not identified by linear regression analysis (Helsel and Hirsch, 2002); thus, specific conductance does not appear to be a viable proxy for chloride concentration for future analyses in the study area.

Continuous specific conductance values recorded at groundwater monitoring well sites 12, 14, and 15 varied between 1,000 and 1,500 µS/cm, whereas at site 16 the average specific conductance was 720 µS/cm (fig. 5). The specific conductance values measured in the groundwater monitoring wells were greater than those measured for the springs. Groundwater monitoring well sites are located

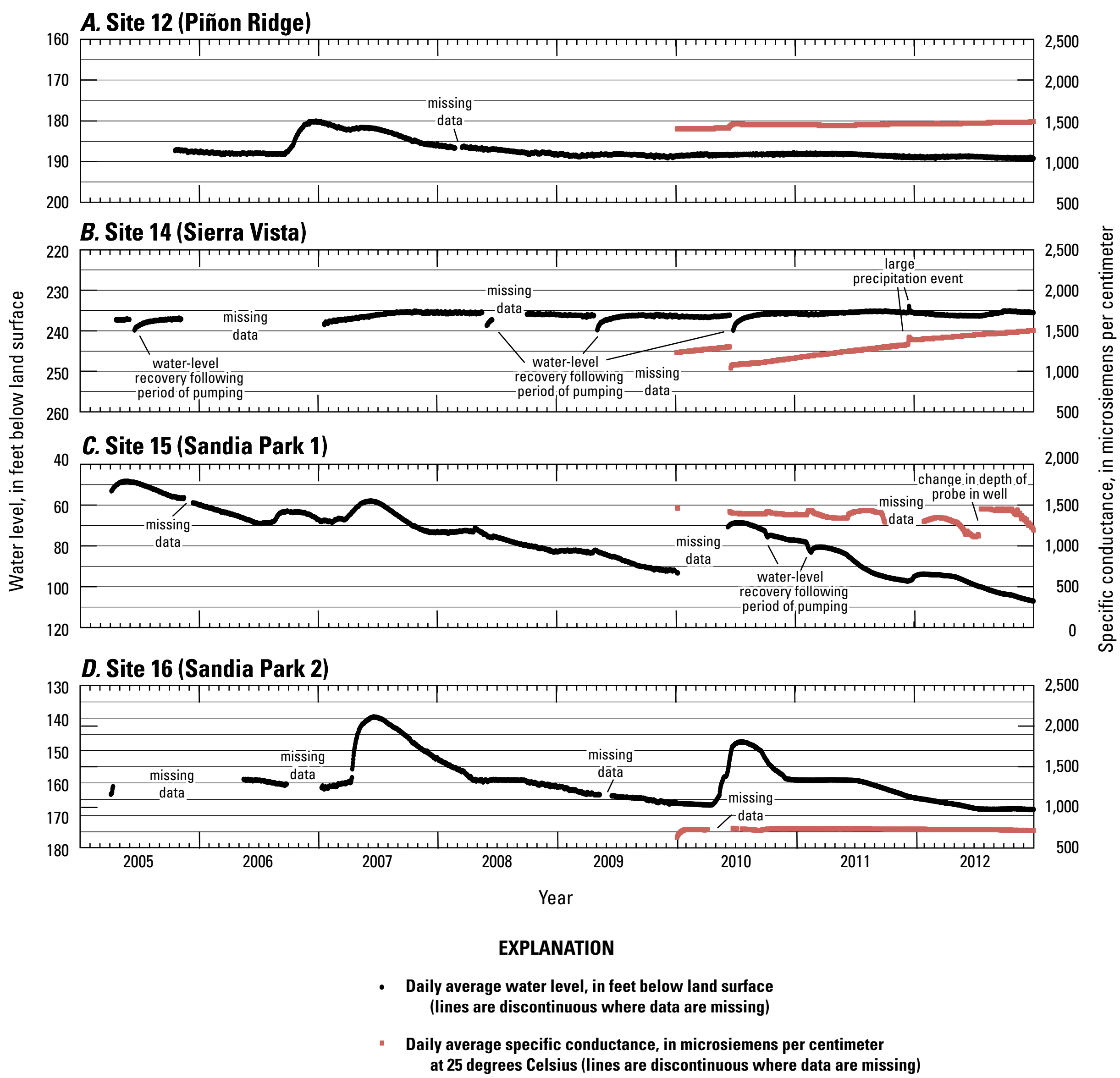

Figure 5. Continuous water-level data, in feet below land surface, and specific conductance data for selected groundwater monitoring wells in the East Mountain area, Bernalillo County, New Mexico, 2008–12. Line gaps indicate missing data. *A*, Site 12 (Piñon Ridge). *B*, Site 14 (Sierra Vista). *C*, Site 15 (Sandia Park 1). *D*, Site 16 (Sandia Park 2).

downgradient from the springs and from the higher elevation recharge areas, which can result in increased groundwater residence time and increased specific conductance values at the wells as compared to the springs. Specific conductance values in groundwater monitoring wells may also be greater than those in springs because of recharge to groundwater monitoring wells from septic tanks and septic disposal fields, and (or) the groundwater monitoring wells may be completed in a geologic unit other than the water-bearing Madera Formation, which is considered the primary source of water to the springs. Similar to the springs, specific conductance values in the monitoring wells do not show much variation over the period of record.

Groundwater Recharge Rates Based on Chloride Mass Balance

Chloride concentrations and calculated CMB groundwater recharge rate estimates for each sampling event during 2005–12 are presented for each spring site in figure 6. Groundwater recharge rate estimates calculated for each sampling event for the eight springs with Cl:Br ratios and chloride concentrations within the range of dilute groundwater (not influenced by nonmeteoric chloride sources; sites 46–48, 50–52, and 54–55) ranged from 1.2 to 5.0 in/yr and varied substantially between sites. Sample median, minimum, and maximum concentrations of chloride and annual groundwater

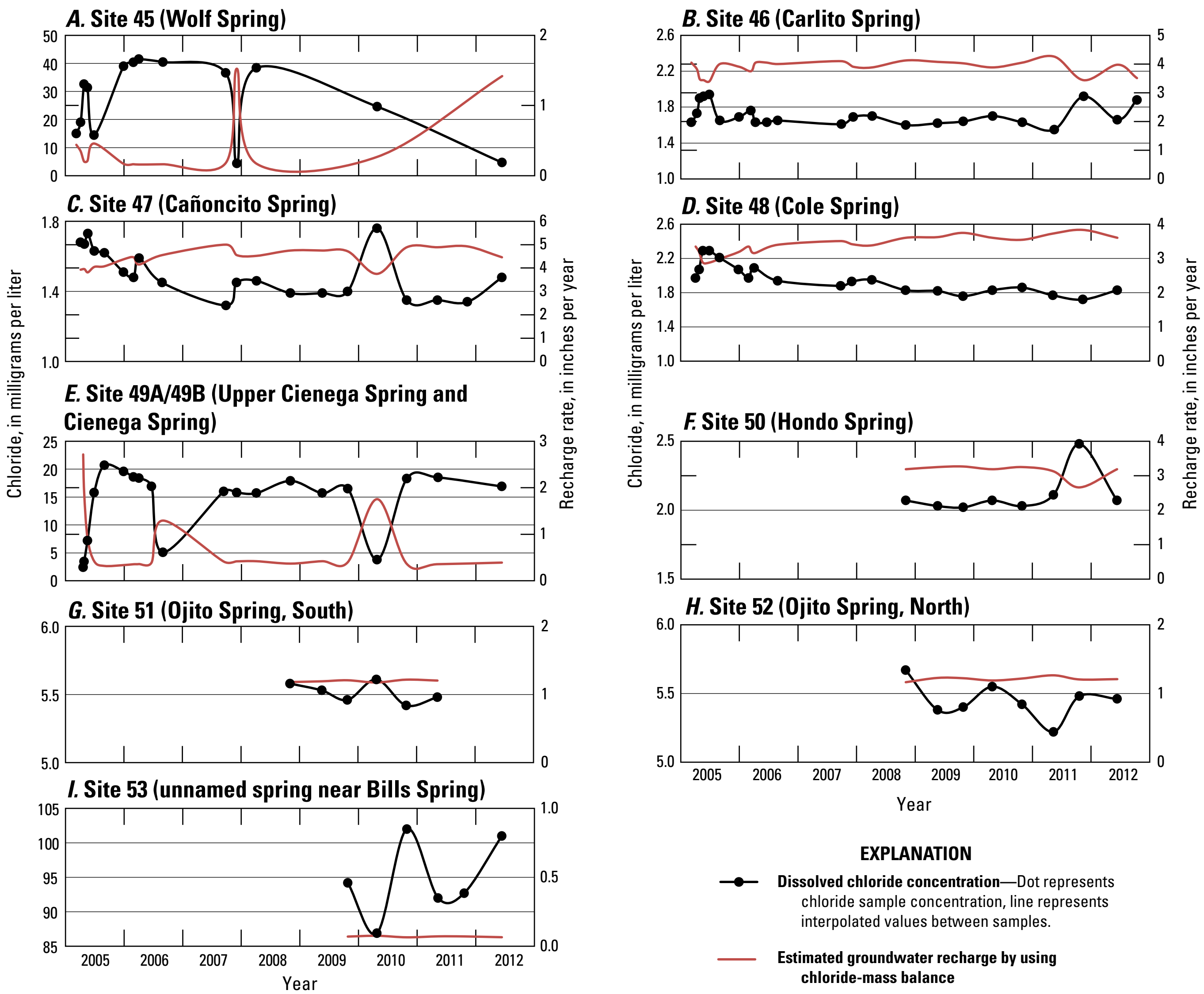

Figure 6. Chloride concentration and estimated groundwater recharge rate for select springs in the East Mountain area, eastern Bernalillo County, New Mexico, 2005–12.

recharge estimates—in inches and as a percentage of annual precipitation—were calculated for each spring site on the basis of CMB and are presented in table 3.

Annual groundwater recharge estimates for the eight springs with Cl:Br ratios and chloride concentrations within the range of dilute groundwater (sites 46–48, 50–52, and 54–55) varied from 5.5 to 23 percent of mean annual precipitation (table 3). Results of the CMB calculation by Anderholm (2000) for the western slope of the entire East Mountain area (including parts of Bernalillo, Sandoval, Santa Fe, and Torrance Counties, N. Mex.) that drains to the Rio Grande Basin estimated that between 0.7 and 9 percent of the mean annual precipitation resulted in groundwater recharge. The CMB calculation by McCoy and Blanchard (2008) estimated groundwater recharge between 0.7 and 23 percent of the mean annual precipitation for a more limited network of five springs in the East Mountain area of Bernalillo County. Although presented in figure 6 and table 3, the CMB results from sites 45, 49A/B, and 53 in this study were not considered representative of actual recharge rates because of the likely influence from sources of nonmeteoric chloride.

Seasonal Response in Recharge Rates

By correlating the results of the CMB groundwater recharge estimates in figure 6 to the groundwater-monitoring-well hydrographs in figure 5, the increase in calculated recharge in some cases corresponded to water-level increases in response to above-average snowfall or monsoon seasons; however, the responses by the springs and the groundwater monitoring wells were not consistent. These responses indicate a range of sensitivity to the effects of short-term climate variability and groundwater recharge timing. Snow-depth and SWE data for site 1C indicated a large amount of potential groundwater recharge during early 2010 (fig. 7). The melting of this snowpack and subsequent groundwater recharge were reflected in the response of the hydrograph of site 16 and likely occurred at site 15, although this part of the record is missing because of a data-logger malfunction; however, a commensurate rise in groundwater recharge is not seen in the CMB results. Hydrographs from sites 12 and 14 did not show a response to this recharge event, but the hydrograph from site 12 showed an apparent recharge pulse in response to the 2006 monsoon season. Site 14 is located within the Tijeras Graben, and site 12 is adjacent to it. Groundwater movement along and through the complex structural features associated with the graben may diminish or enhance the effects of short-term recharge events.

Uncertainty in Groundwater Recharge Rates

Uncertainties in estimated groundwater recharge can occur when using the CMB method if groundwater is partially evaporated before recharge or after discharge or if chloride is added to the groundwater from geologic or human sources, resulting in artificially increased Cl:Br ratios and chloride concentrations and an underestimation of the amount of recharge. Conversely, the retention of chloride in the solid phase (undissolved in groundwater or retained in the vadose zone) can lead to decreased Cl:Br ratios and chloride concentrations that would lead to overestimation of groundwater recharge. The analysis of Cl:Br ratios and chloride concentration helped to identify locations potentially affected by nonmeteoric chloride concentrations so that recharge estimates for these locations would be representative of natural groundwater recharge in the study area. The locations of most of the springs in the East Mountain area are advantageous for groundwater recharge rate calculations

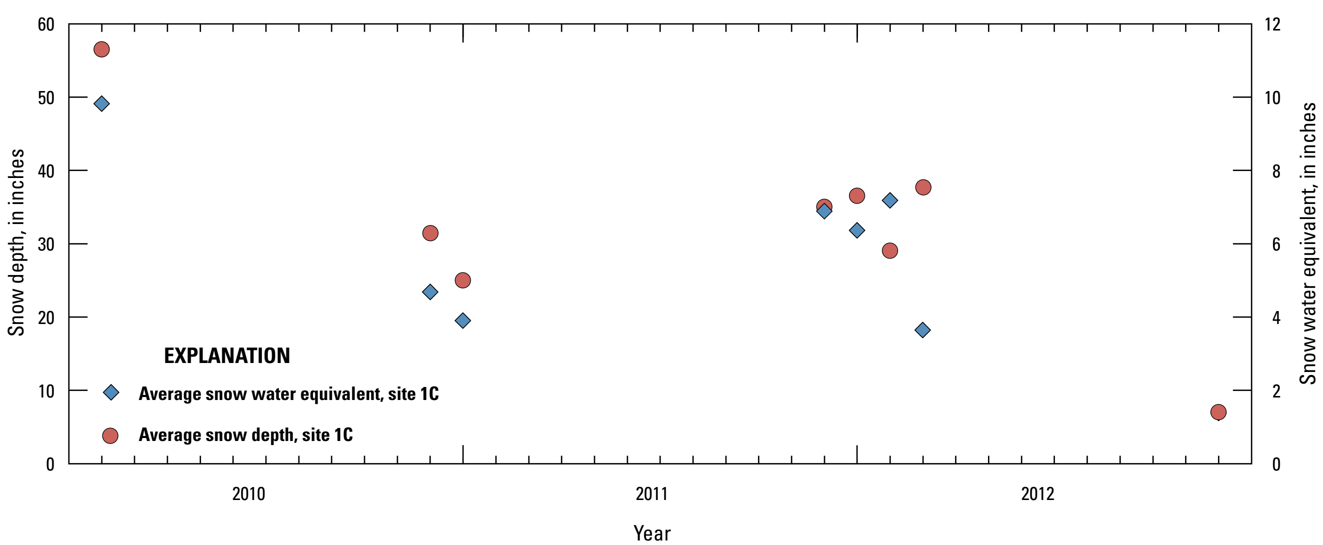

Figure 7. Mean snow depth and mean snow water equivalent measured at site 1C located in the Sandia Mountains at elevation 10,091 feet above the North American Vertical Datum of 1988, 2010–12.

because they are upgradient from human sources of chloride. Additionally, a previous investigation (Blanchard, 2004) indicated there was relatively young groundwater in the area, which reduces the influence of aquifer-rock dissolution on chloride concentrations in groundwater.

Uncertainty in calculated groundwater recharge rates also may be introduced by the assumptions of mean chloride concentration in precipitation and mean annual precipitation, especially with large inter-annual and intra-annual variability in the spatial and temporal distribution of precipitation across the study area. The magnitude of any uncertainty in groundwater recharge estimates from uncertainty in chloride concentrations or precipitation would be proportional to the magnitude of uncertainty in the values used in the calculations.

Estimation of Groundwater Recharge Sources Based on Stable Isotope Analysis

The stable isotopes of ^{2}H and ^{18}O are ubiquitous in the oceans, atmosphere, precipitation, surface water, and groundwater. They behave conservatively and predictably in low-temperature (less than 40 degrees Celsius) environments and do not decay over time (Kendall and McDonnell, 1998), making them useful in hydrologic investigations. The predictable signatures and behaviors of these isotopes make them particularly valuable in areas of distinct seasonal precipitation pattern and large variation in annual temperature, both of which are found in the East Mountain area.

Stable Isotopes as Tracers for Groundwater Recharge Source

The stable isotopes of hydrogen and oxygen fractionate by meteorological processes in a predictable manner (Craig, 1961). Many variables can affect how this fractionation occurs, but it is largely a function of temperature, with colder temperatures resulting in more depletion of the heavier isotopes (^{2}H and ^{18}O) than in the Standard Mean Ocean Water (SMOW) of Craig (1961). Other factors affecting stable isotope composition of precipitation include season, elevation, latitude, storm track, and precipitation amount (Plummer and others, 2004). Stable isotope composition also can be altered by evaporative losses between the precipitation event and groundwater recharge, but once in the subsurface, the proportions of ^{2}H and ^{18}O are relatively stable compared to their lighter, more abundant counterparts (^{1}H and ^{16}O) because transpiration by plants is not selective to the lighter or heavier isotopes (Gat, 1996). All of these factors can help constrain the source and behavior of the water that recharges the aquifers in the study area.

Stable isotopic composition of waters is expressed in a change (enrichment or depletion) from a known baseline standard, the SMOW of Craig (1961), because the oceans are the source of nearly all meteoric precipitation (Clark and Fritz, 1997). Isotopic fractionation occurs in relation to temperature, with higher temperatures providing the energy to evaporate a larger proportion of the heavier isotopes of hydrogen and oxygen. Isotopic compositions are therefore presented as a deviation (delta, δ) in parts per thousand (per mil) from SMOW. To better understand how δ^2H and δ^{18}O relate to one another and patterns of precipitation, values are plotted against known linear relations of stable isotope composition including the Global Meteoric Water Line (GMWL; Craig, 1961), as well as the Local Meteoric Water Lines (LMWL) created from local datasets.

Groundwater Recharge Sources Based on Stable Isotope Analysis

In the study area, a largely bimodal precipitation pattern exists, with the bulk of annual precipitation resulting from either winter storms or summer monsoonal rains. Precipitation totals from these two annual events vary widely from year to year, as well as within the study area, with winter storms providing a larger component of annual precipitation as elevations increase (McCoy and Blanchard, 2008). Stable isotope compositions of groundwater generally represent a mix of these two precipitation periods and can be used to identify the primary seasonal contributors to groundwater recharge, with winter precipitation largely having a more depleted signature than summer monsoonal precipitation, which is more enriched.

A plot of the stable isotope compositions of spring discharge (fig. 8) locates values above the GMWL, indicating that precipitation largely has a more arid vapor source than represented by the GMWL, similar to other midcontinent areas, and that the lower slope of a linear best-fit regression (coefficient of determination [R^2] of 0.81; Helsel and Hirsch, 2002) compared to the GMWL is characteristic of an area with relatively low humidity (Clark and Fritz, 1997; Scholl and others, 2004). Although it is likely that some evaporation occurs prior to groundwater recharge, it does not appear to occur at a magnitude that substantially alters the overall trend of stable isotope compositions. Limiting the effects of evaporation on groundwater recharge can occur in different manners, such as the melting of snowpack during the spring when ET is reduced or by rapid infiltration of precipitation into the subsurface through faults, fractures, solution conduits, or other preferential pathways.

The mean δ^2H and δ^{18}O compositions of springs sampled during this study were -87 and -12.3 per mil, respectively. A volume-weighted mean annual composition of δ^2H and δ^{18}O in precipitation, calculated from seven precipitation stations in the region (Johnson and Campbell, 2008), was -79.0 and -10.8 per mil, respectively. The seven regional precipitation stations were located at an average elevation of approximately 6,940 ft above NAVD 88, an elevation that is somewhat lower than the average elevation of spring discharge points (7,266 ft above NAVD 88) in the study area. Although the

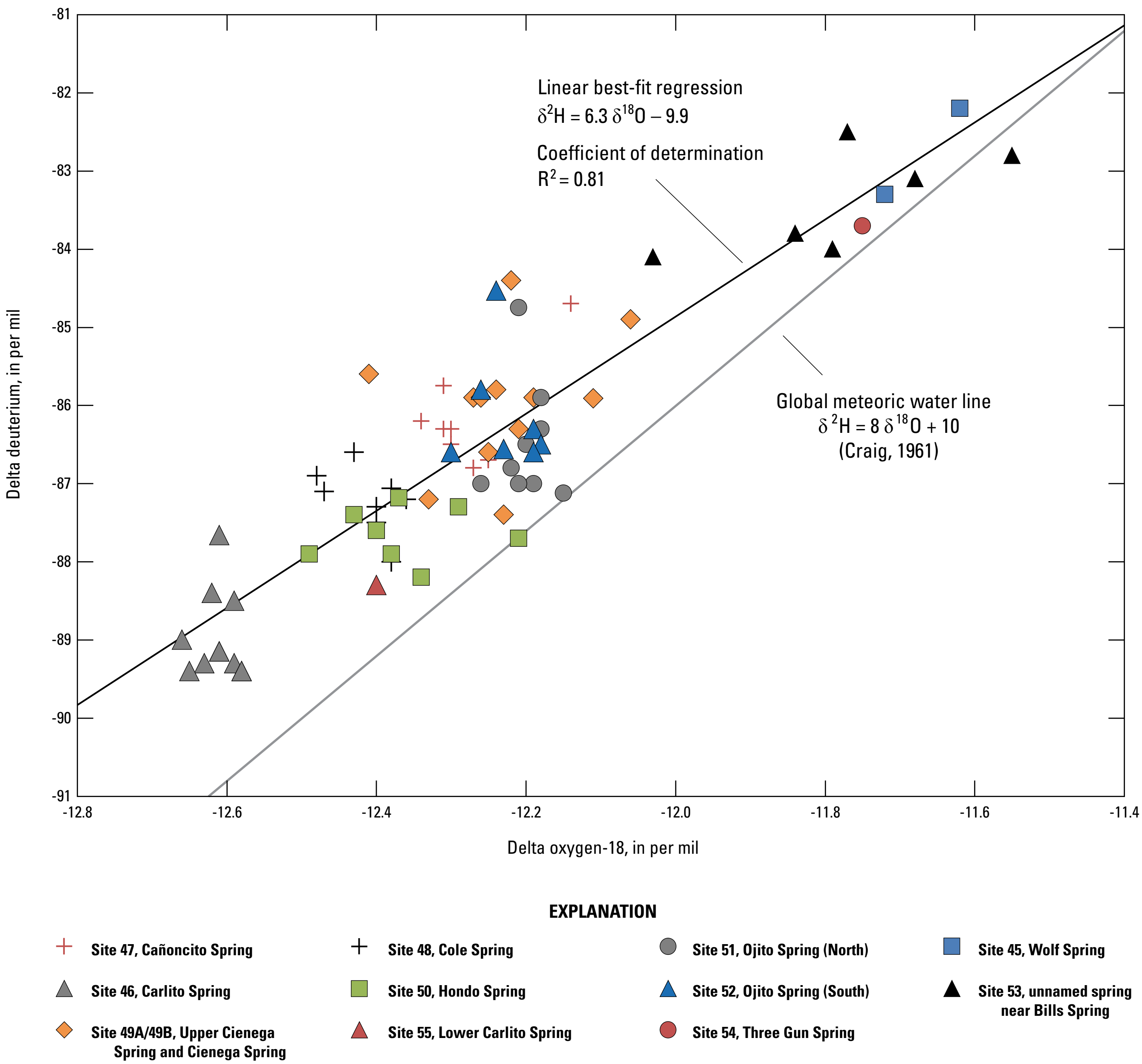

Figure 8. Deuterium and oxygen-18 data for springs in the East Mountain area, Bernalillo County, New Mexico, 2008–12.

average elevations for the seven regional precipitation stations and spring discharge points are similar, the precipitation compositions are subject to the elevation and temperature effects of the sample location, whereas the groundwater recharge at the springs occurs at an elevation higher than the discharge point. Snowpack chemistry samples from the two study area precipitation stations, Lower Sandia (7,030 ft above NAVD 88, site 3) and Upper Sandia (10,091 ft above NAVD 88, site 1C) had stable isotopic compositions of δ^2H, -107; δ^{18}O, -15.4; and δ^2H, -163; δ^{18}O, -22.2 per mil, respectively. These samples represent the most ^{2}H- and ^{18}O-depleted stable isotope values collected during the study. Although precipitation compositions from Johnson and Campbell (2008) and the snowpack chemistry samples from this study largely indicated stable isotope depletion with increasing elevation, no significant relation was found between stable isotope composition and spring elevation by using linear regression methods (Helsel and Hirsch, 2002), indicating that high elevation precipitation is a primary source of groundwater recharge regardless of the spring discharge elevation.

The isotopic compositions of study area springwater samples were plotted against calculated meteoric water lines for Santa Fe, N. Mex. (Anderholm, 1994), which is approximately 40 miles northeast of the Sandia Crest station, and for the Placitas, N. Mex., area (Johnson and Campbell, 2008), which is approximately 6 miles northeast of the Sandia Crest station (fig. 9). The isotopic composition of springwater samples in this study correlate more closely to the LMWL for Santa Fe than for the Placitas area, likely because the Santa Fe study meteoric collection site (approximately 7,400 ft above NAVD 88) is more similar in average elevation to the groundwater recharge elevations of the springs and receives a larger component of winter precipitation recharge, even though the Placitas area is closer to the study area. All of the springwater samples were more depleted in ^{2}H and ^{18}O than the mean annual precipitation composition for the Placitas study area of Johnson and Campbell (2008) (shown as a red circle on fig. 9) and more enriched than the compositions of the snowpack chemistry samples collected during this study, indicating that although the springs appear to be recharged by primarily more isotopically depleted precipitation, there is contribution of more enriched precipitation as well.

There is little difference in isotopic composition of study area springwater depending on the sampling season (fig. 9). There is also little variation in isotopic composition within the two sampling seasons, with percentage of standard deviation being less than 2 percent of the average compositions for postsnowmelt samples and less than 3 percent for postmonsoon samples. This lack of variation indicates that although there is evidence for rapid infiltration and groundwater recharge to parts of the aquifer on seasonal or even storm-event timescales, there is an element of longer term storage and mixing within the aquifer, leading to the relatively stable isotopic compositions over time at the spring discharge points. There were no apparent trends in isotopic composition over the analysis period for individual spring sites on the basis of visual inspection of the data.

Hydrographs from some of the wells investigated in this report respond to seasonal climate variability more markedly than others, but overall the most pronounced short-term groundwater recharge pulses appeared to be related to the melting of winter snowpack at higher elevations (fig. 5). This finding agrees with the isotopic findings from the springs in the study area, which indicated that winter precipitation usually is the primary groundwater recharge mechanism, and

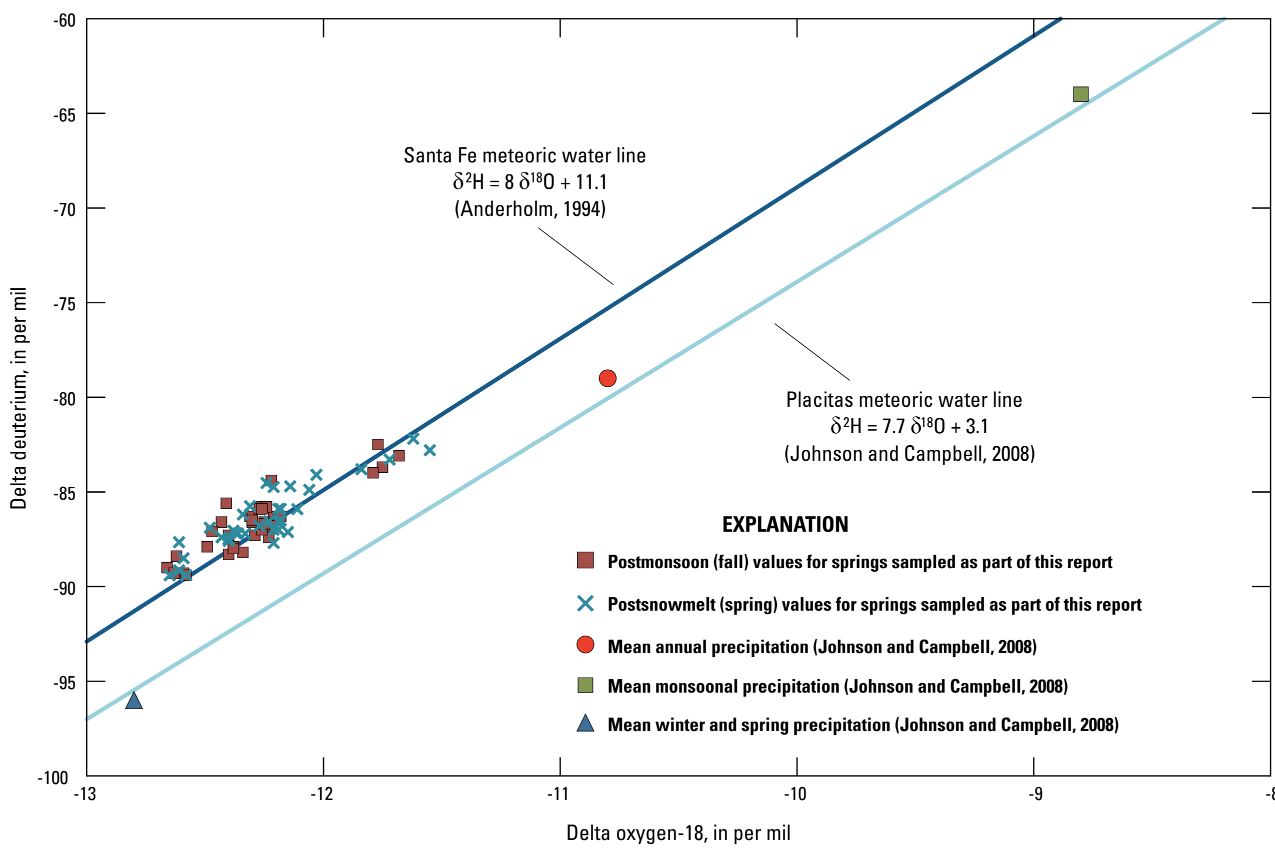

Figure 9. Stable isotope results for springwater samples collected during 2008–12 from eastern Bernalillo County, New Mexico, in comparison with the local meteoric water lines reported for Santa Fe, N. Mex., and Placitas, N. Mex., and the mean annual and seasonal precipitation reported for Placitas, N. Mex.

which also agreed with the findings of Anderholm (1994) for the Santa Fe area and Johnson and Campbell (2008) for the Placitas area.

When the stable isotope values were compared to the CMB groundwater recharge estimates by using linear regression techniques (Helsel and Hirsch, 2002), no relation was identified between stable isotopic composition of groundwater and estimated recharge rate via the CMB calculation, nor was a relation found between stable isotope composition and the variability of estimated recharge over time. Stable isotope values at springs during the snowmelt season did not appear to vary greatly in response to variations in snowpack and SWE at site 1C. These results support the assumption that although preferential flow paths may exist between groundwater recharge locations and some springs, there is likely a component of older, well-mixed groundwater being supplied by a less structurally or solutionally enhanced aquifer matrix that is stabilizing these geochemical parameters.

Stable isotope results for δ^2H and $\delta^{18}O$ support the conceptual understanding that groundwater recharge in the study area is primarily sourced from the melting of winter snowpack in the Sandia Mountains. Infiltration of precipitation from summer monsoonal rains is a secondary source of groundwater recharge on the basis of stable isotope results. Although variable, the muted or nonexistent water-level responses to monsoon rainfall events in the four wells investigated in this study (fig. 5) agreed with findings from the spring stable isotope analysis that rainfall during the monsoon season has a reduced role in groundwater recharge to springs in the East Mountain area. Parts of the study area with less structural deformation and (or) solution enhancement of the aquifers may receive a smaller percentage of annual precipitation to groundwater recharge, whereas areas that are heavily fractured or faulted may receive a larger percentage of precipitation as recharge.

Summary

In the East Mountain area of eastern Bernalillo County, New Mexico, increased water use has raised concerns about the sustainability of water resources in the area, prompting a desire to better understand the mechanisms of groundwater recharge to support water resource management scenarios of future demand and availability. This study estimated groundwater recharge rates by using a chloride mass-balance (CMB) method applied to data from selected springs located in the study area and by using the mass ratio of chloride to bromide (Cl:Br) and the stable isotope ratios of hydrogen (δ^2H) and oxygen ($\delta^{18}O$) to identify the sources and timing of recharge water contributed to aquifers in the East Mountain area. Additionally, specific conductance, groundwater-level hydrographs, snowpack chemistry, and snow-water equivalent data were used to inform the analyses and corroborate the findings of the CMB and stable isotope investigations.

During 2005–12, water-quality samples were collected biannually from a network of 11 springs in the East Mountain area and analyzed for dissolved chloride, dissolved bromide, specific conductance, and the stable isotope ratios of δ^2H and $\delta^{18}O$. The chloride concentrations of 8 of the 11 springs—along with an average annual precipitation rate of 22 inches and an average bulk precipitation chloride concentration of 0.30 milligrams per liter (mg/L)—were used to estimate groundwater recharge rates in the East Mountain area.

An analysis of chloride concentrations and Cl:Br ratios supported the selection of 8 of the 11 springs as examples of dilute (not influenced by nonmeteoric chloride sources) groundwater for use in CMB calculations. Three of the 11 springs examined were excluded from CMB calculations because of likely interaction of recharge waters with nonmeteoric chloride sources. CMB estimates of groundwater recharge to the other eight springs in the study area ranged from 5.5 to 23 percent of the annual precipitation. The range of estimated groundwater recharge rates indicated that groundwater recharge in the East Mountain area is complex and spatially variable depending on the local geology and extent of faulting, fracturing, and solution enhancement of the aquifers. Variable responses to seasonal groundwater recharge events in the four wells investigated in this study support the assumption of hydrologic complexity. Measurements of specific conductance showed little variation over time at individual springs and wells and do not appear to be a viable proxy for chloride concentration for future analyses in the study area.

The stable isotope compositions of 11 springs and 2 snowpack samples were analyzed in conjunction with the CMB estimates to provide information on the timing and sources of groundwater recharge. Annual precipitation largely occurs in a bimodal manner in the East Mountain area as either winter precipitation or summer monsoonal rains, each having a distinct isotopic range. The stable isotope ratios of δ^2H and $\delta^{18}O$ in samples from springs and snowpack were compared with local, regional, and global meteoric water lines and analyzed along with values representing the stable isotope composition of winter precipitation and monsoonal rainfall in the region. Results of the isotopic analysis suggested that winter precipitation is the leading source of groundwater recharge to the aquifers supplying springs in the East Mountain area, with a lesser contribution of more enriched recharge that is likely from monsoonal rainfall. Although variable, the muted or nonexistent water-level responses to monsoon rainfall events in the four wells investigated in this study agreed with findings from the springwater stable isotope analysis that rainfall during the monsoon season has a reduced role in groundwater recharge to springs in the East Mountain area.

The higher elevation areas of the study area are likely the principal groundwater recharge zone because of higher annual precipitation and a larger proportion of precipitation falling as snow compared to lower elevation parts of the study area. Groundwater recharge estimation results from the springs in the East Mountain area, however, may not be indicative of recharge rates or timing across the entire study area because of the possibility that the springs are formed on preferential pathways that may allow for more rapid recharge and focused transmission to the discharge point at the spring. Parts of the study area with less structural deformation and (or) solution enhancement of the aquifers may receive a smaller percentage of annual precipitation to groundwater recharge, whereas areas that are heavily fractured or faulted may receive a larger percentage of precipitation as recharge.

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