MOUNTAIN-FRONT RECHARGE ALONG THE EASTERN SIDE OF THE MIDDLE RIO GRANDE BASIN, CENTRAL NEW MEXICO

U.S. DEPARTMENT OF THE INTERIOR
U.S. GEOLOGICAL SURVEY

Water-Resources Investigations Report 00-4010

Prepared in cooperation with the
CITY OF ALBUQUERQUE PUBLIC WORKS DEPARTMENT

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By Scott K. Anderholm

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2001

U.S. DEPARTMENT OF THE INTERIOR
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U.S. GEOLOGICAL SURVEY
Charles G. Groat, Director

Second printing (revised)

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CONVERSION FACTORS AND VERTICAL DATUM

Multiply	By	To obtain
	Length	
inch	2.54	centimeter
inch	25.4	millimeter
foot	0.3048	meter
mile	1.609	kilometer
	Area	
acre	0.4047	hectare
acre	0.4047	square hectometer
acre	0.004047	square kilometer
square mile	259.0	hectare
square mile	2.590	square kilometer
	Volume	
acre-foot	1,233	cubic meter
acre-foot	0.001233	cubic hectometer
	Flow rate	
acre-foot per year	1,233	cubic meter per year
acre-foot per year	0.001233	cubic hectometer per year
foot per day	0.3048	meter per day
foot per second	0.3048	meter per second
cubic foot per second	0.02832	cubic meter per second

Sea level: In this report, "sea level" refers to the National Geodetic Vertical Datum of 1929—a geodetic datum derived from a general adjustment of the first-order level nets of the United States and Canada, formerly called Sea Level Datum of 1929.

Altitude, as used in this report, refers to distance above sea level.

MOUNTAIN-FRONT RECHARGE ALONG THE EASTERN SIDE OF THE MIDDLE RIO GRANDE BASIN, CENTRAL NEW MEXICO

By Scott K. Anderholm

Abstract

Mountain-front recharge, which generally occurs along the margins of alluvial basins, can be a large part of total recharge to the aquifer system in such basins. Mountain-front recharge occurs as the result of infiltration of flow from streams that have headwaters in the mountainous areas adjacent to alluvial basins and ground-water flow from the aquifers in the mountainous areas to the aquifer in the alluvial basin.

This report presents estimates of mountain-front recharge to the basin-fill aquifer along the eastern side of the Middle Rio Grande Basin in central New Mexico. The basin is a structural feature that contains a large thickness of basin-fill deposits, which compose the main aquifer in the basin. The basin is bounded along the eastern side by mountains composed of crystalline rocks of Precambrian age and sedimentary rocks of Paleozoic age. Precipitation is much larger in the mountains than in the basin; many stream channels debouch from the mountainous area to the basin.

Chloride-balance and water-yield regression methods were used to estimate mountain-front recharge. The chloride-balance method was used to calculate a chloride balance in watersheds in the mountainous areas along the eastern side of the basin (subareas). The source of chloride to these watersheds is bulk precipitation (wet and dry deposition). Chloride leaves these watersheds as mountain-front recharge. The water-yield regression method was used to determine the streamflow from the mountainous watersheds at the mountain front. This streamflow was assumed to be equal to mountain-front recharge because most of this streamflow infiltrates and recharges the basin-fill aquifer.

Total mountain-front recharge along the eastern side of the Middle Rio Grande Basin was estimated to be about 11,000 acre-feet per year using the chloride-balance method and about 36,000 and 38,000 acre-feet per year using two water-yield regression equations. There was a large range in the recharge estimates in a particular subarea using the different methods. Mountain-front recharge ranged from 0.7 to 15 percent of total annual precipitation in the subareas (percent recharge). Some of the smallest values of percent recharge were in the subareas in the southern part of the basin, which generally have low altitudes. The larger percent-recharge values were from subareas with higher altitudes.

With existing information, determining which of the mountain-front recharge estimates is most accurate and the reasons for discrepancies among the different estimates is not possible. The chloride-balance method underestimates recharge if the chloride concentration used in the calculations for precipitation is too small or the chloride concentration in recharge is too large. Water-yield regression methods overestimate recharge if the amount of evapotranspiration of water that infiltrates into the channel bed of arroyos during runoff from summer thunderstorms is large.

INTRODUCTION

Ground-water recharge (recharge) occurs when water is added to the zone of saturation or aquifer (Meinzer, 1923, p. 46). Recharge to an aquifer can occur as the result of infiltration of water through the unsaturated zone or ground-water movement from one aquifer to another. Mountain-front recharge is a term that has been used to describe recharge occurring along the margins of a regional aquifer system that parallels a mountainous area (Water Resources Research Center, 1980, p. 4-1 to 4-3).

In the arid Southwest, mountain-front recharge is an important source of recharge to alluvial-basin aquifers (Kernodle and Scott, 1986; Hearne and Dewey, 1988; and McAda and Wasiolek, 1988). The ultimate source of recharge is precipitation. Precipitation is generally greater and evapotranspiration smaller in the mountainous areas than in adjacent alluvial basins. The larger precipitation and smaller evapotranspiration rates result in increased recharge rates in the mountainous areas or along the alluvial-basin margins. Perennial and intermittent streams also are more common in mountainous areas than in alluvial basins.

Mountain-front recharge can be an important input parameter to ground-water-flow models because it can be a large part of total recharge to an aquifer system and because it is applied to the model boundaries. A change in the rate of mountain-front recharge in a ground-water-flow model can affect how well the model simulates the flow field. Field-based estimates of mountain-front recharge can result in changes in the conceptual model used to formulate the flow model. The volume of mountain-front recharge to the basin-fill aquifer in the Middle Rio Grande Basin in central New Mexico (fig. 1) was estimated in the early 1980's (Kernodle and Scott, 1986). These estimates of recharge have been used in several models of the ground-water flow system of the Middle Rio Grande Basin (Kernodle and Scott, 1986; Kernodle and others, 1987; and Kernodle and others, 1995). On a regional scale, however, little work has been done to evaluate the volume of mountain-front recharge to the Middle Rio Grande Basin since the 1980's. In 1997 the U.S. Geological Survey, in cooperation with the City of Albuquerque, began an investigation designed to estimate mountain-front recharge to the basin-fill aquifer along the eastern side of the Middle Rio Grande Basin.

Purpose and Scope

This report presents estimates of mountain-front recharge to the basin-fill aquifer along the eastern side of the Middle Rio Grande Basin. The eastern side of the basin is divided into nine subareas, and recharge estimates are made for each subarea using chloride-balance and water-yield regression methods. The recharge estimation methods are evaluated and the estimates for each subarea are compared. Existing data are used to make the recharge estimates.

Previous Investigations

Many investigations of ground-water hydrology and geochemistry have been conducted in the Middle Rio Grande Basin. Some of the more comprehensive investigations include Spiegel (1955), Bjorklund and Maxwell (1961), Titus (1963), Kernodle and Scott (1986), Anderholm (1988), Hawley and Haase (1992), Thorn and others (1993), and Kernodle and others (1995).

Few estimates of recharge to basin-fill deposits in the Middle Rio Grande Basin have been published. In most published reports, recharge is discussed but the volume of recharge is not estimated. Theis (1938, p. 291) estimated ground-water inflow from mountainous and mesa areas to the Rio Grande Valley to be about 748 acre-feet per year per linear river mile for the middle Rio Grande Valley. Theis and Taylor (1939, p. 270) estimated ground-water inflow from mountainous and mesa areas to the Rio Grande Valley to be about 820 acre-feet per year per linear river mile for the area from about Los Lunas to Belen (fig. 1). These estimates were made assuming inflow from both sides of the river. Determining what part of this inflow is due to mountain-front recharge along the eastern side of the Middle Rio Grande Basin is not possible given the information in the reports. Kernodle and Scott (1986, p. 12) estimated the volume of mountain-front recharge along the eastern side of the Middle Rio Grande Basin (a distance of about 80 miles) to be about 72,000 acre-feet per year.

Thomas (1995) estimated infiltration and evaporation rates in the channel of Tijeras Arroyo, a stream with headwaters in the mountainous area adjacent to the Middle Rio Grande Basin (fig. 1). Thomas found that infiltration rates at the mountain front ranged from 2.28 to 30 feet per day and that daily evaporation rates were insignificant compared to daily infiltration rates. Estimating annual infiltration rates from these data is not possible because flow in Tijeras Arroyo at the mountain front is not perennial.

Geographic Setting

The Middle Rio Grande Basin is a structural basin in central New Mexico containing a large thickness of basin-fill deposits of Tertiary age. These deposits, which are the main aquifer in the basin, consist of clay, silt, sand, and gravel. Along the eastern and western sides of the Middle Rio Grande Basin,

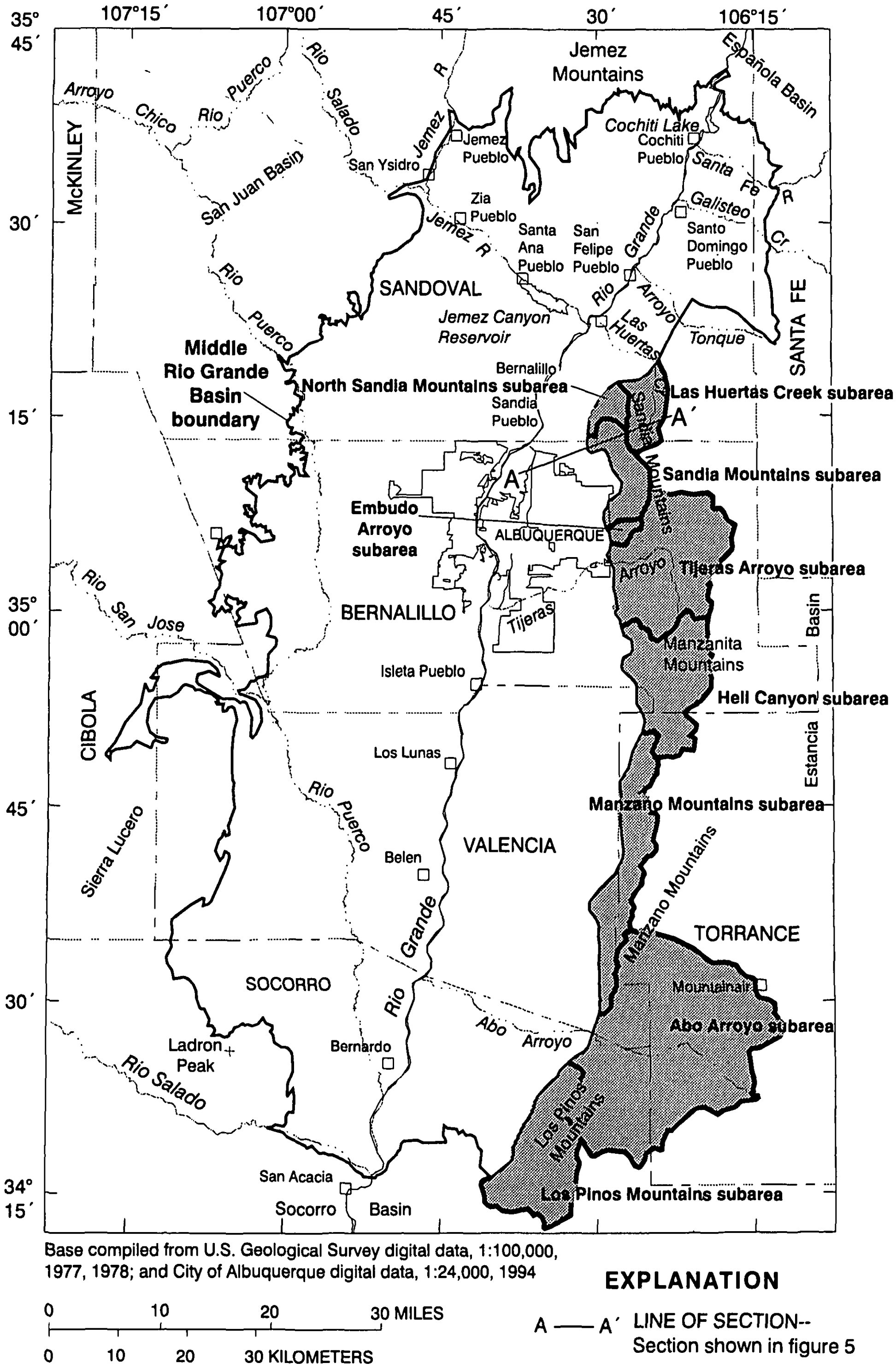

Figure 1. Location of Middle Rio Grande Basin and subareas along the eastern side of the basin, central New Mexico.

large faults separate the basin-fill deposits from bedrock. The basin is bounded on the east by the Sandia, Manzanita, Manzano, and Los Pinos Mountains; on the north by the Española Basin and Jemez Mountains; on the west by the San Juan structural basin, Sierra Lucero, and Ladron Peak; and on the south by the Socorro Basin (fig. 1).

The eastern side of the Middle Rio Grande Basin has a large degree of topographic relief relative to that in the overall basin. The mountains along the eastern side of the basin are steep. Near Albuquerque, in a distance of about 2 miles, the altitude from the basin margin to the crest of the Sandia Mountains increases about 4,000 feet. A gently sloping piedmont extends from the foot of the mountains to the Rio Grande. There has been little dissection of the piedmont by streams that debouch onto the piedmont from the mountainous area along the eastern side of the basin.

The Rio Grande, which is generally the lowest point in the basin, runs north to south and is the main surface-water drainage in the basin (fig. 1). The larger tributaries to the Rio Grande in the Middle Rio Grande Basin generally have headwaters in areas adjacent to the basin.

Abo Arroyo, Tijeras Arroyo, and Las Huertas Creek are some of the larger tributaries to the Rio Grande that have headwaters in the mountainous area adjacent to the eastern side of the Middle Rio Grande Basin (fig. 1). These streams have relatively large drainage areas compared with the other watersheds along the eastern side of the Middle Rio Grande Basin. Several times a year, these streams discharge to the Rio Grande for 1 day or less as the result of runoff from intense summer thunderstorms.

Many stream channels or arroyos with headwaters in the mountainous area on the eastern side of the Middle Rio Grande Basin do not extend westward from the mountains to the Rio Grande. Bjorklund and Maxwell (1961, p. 49) indicated that many of the channels that drain the western slopes of the Sandia and Manzano Mountains decrease in width and depth relatively rapidly downstream from the mountainous areas because infiltration reduces flow in the channels.

Climate

The climate of the Middle Rio Grande Basin is arid to semiarid and of the mountainous areas adjacent to the basin is subhumid to humid (Tuan and others, 1969, p. 157-68). Skies are generally clear, humidity is generally low, evaporation is high, and temperatures range widely from night to day.

Precipitation generally increases with increasing altitude. Normalized mean annual precipitation from 1931 to 1960 (U.S. Department of Commerce, no date) indicates that precipitation ranges from about 6 inches between Los Lunas and Belen (in the Middle Rio Grande Basin) to greater than 30 inches in the Sandia and Manzano Mountains (adjacent to the Middle Rio Grande Basin) (fig. 2). Mean annual precipitation in the mountainous area along the eastern side of the basin generally is greater than 16 inches, whereas precipitation in the basin generally is less than 10 inches.

Most precipitation falls during July, August, September, and October (fig. 3) as a result of intense rainstorms; the percentage of annual precipitation that occurs during these months decreases with altitude. About 58 percent of annual precipitation falls from July through October at the Albuquerque weather station (altitude 5,200 feet), 51 percent at the Sandia Park weather station (altitude 6,900 feet), and 45 percent at the Sandia Crest weather station (altitude 10,600 feet). The percentage of annual precipitation falling during the winter months (December through March) increases with altitude. About 35 percent of annual precipitation falls during the winter months at Sandia Crest. November is the driest month in Albuquerque, April is the driest month in Sandia Park, and May is the driest month at Sandia Crest. Precipitation in the mountainous areas during November through March is generally in the form of snow. During most years, snow melts during April and May in the higher mountainous areas.

Annual precipitation at a particular site in the area can vary considerably (fig. 4). From one year to the next, annual precipitation can vary by more than 5 inches at the Albuquerque weather station and as much as 16 inches at the Sandia Crest weather station. These large variations in annual precipitation can have major effects on the availability of moisture and runoff from the mountainous areas, especially on the smaller watersheds.

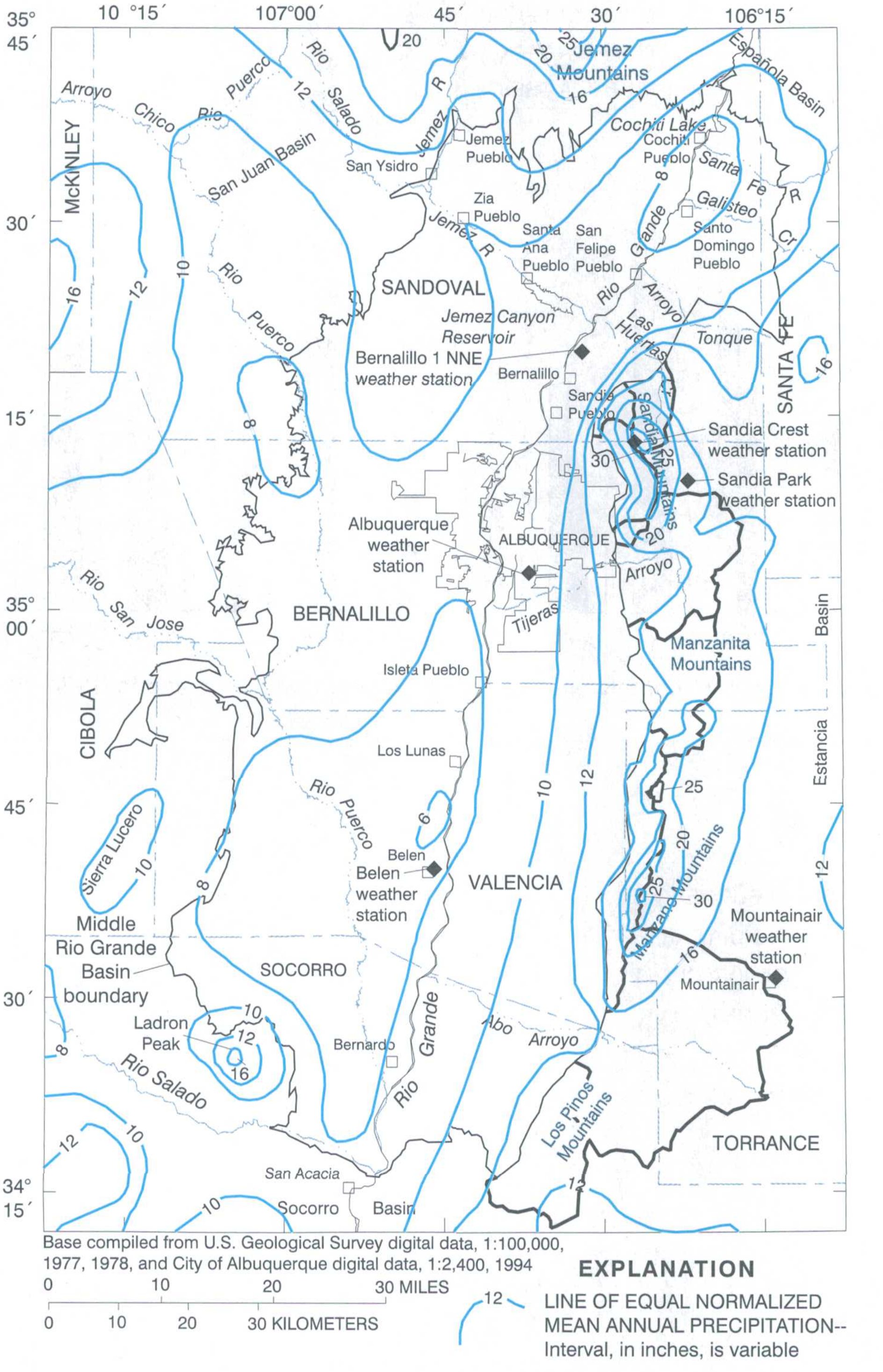

Figure 2. Normalized mean annual precipitation in the Middle Rio Grande Basin and vicinity, central New Mexico, 1931-60 (from U.S. Department of Commerce, no date).

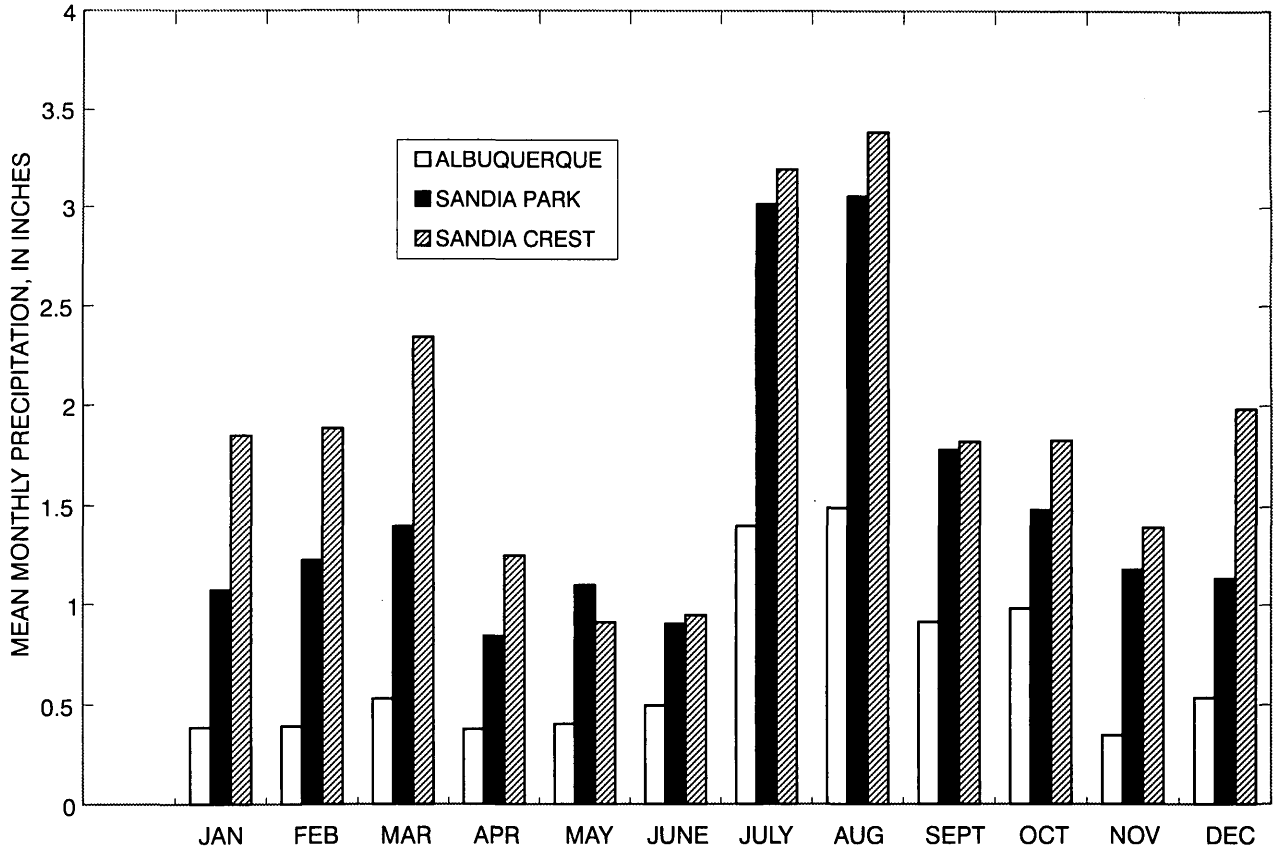

Figure 3. Mean monthly precipitation at selected weather stations, 1954-78.

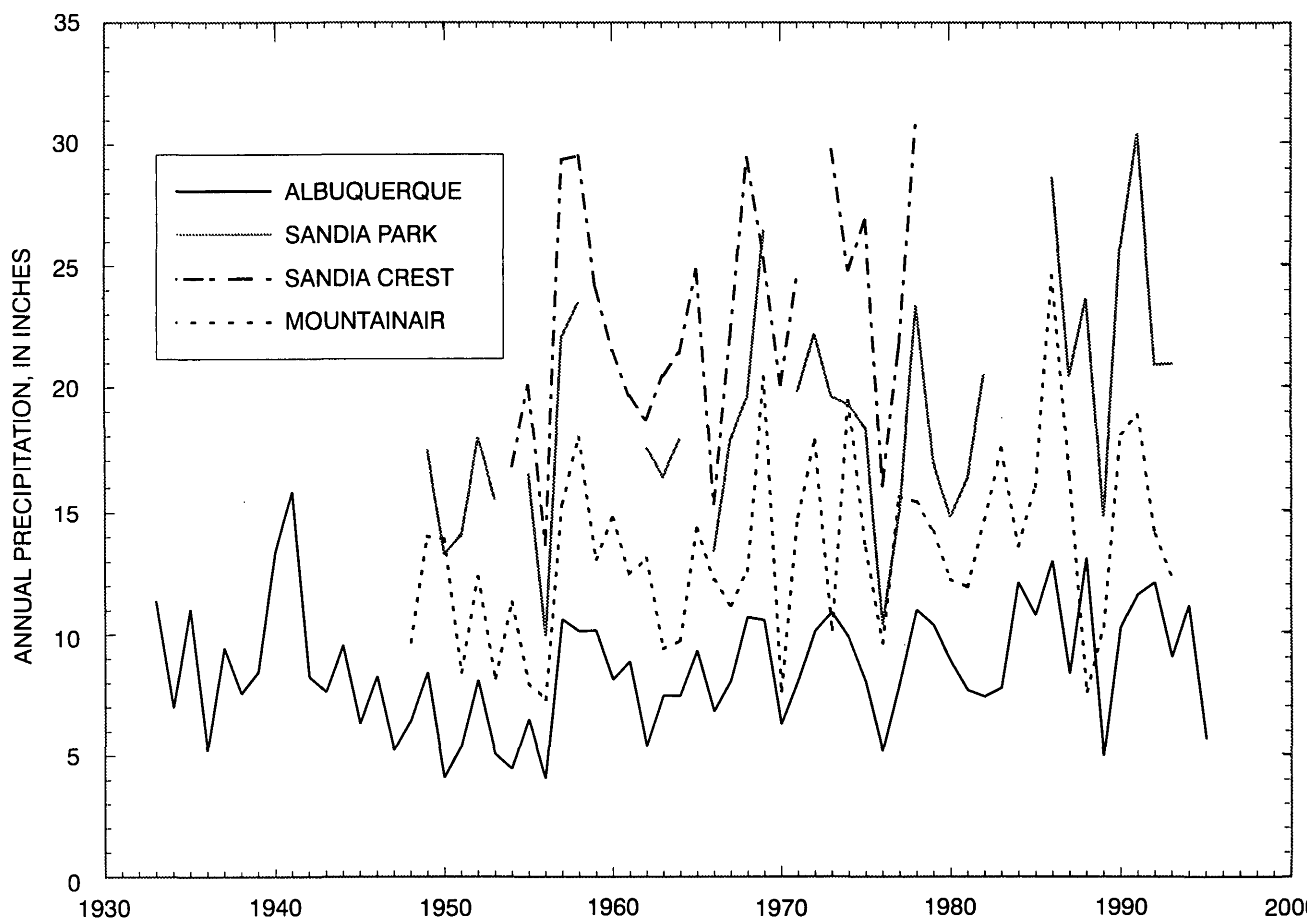

Figure 4. Annual precipitation at selected weather stations, 1933-95.

Acknowledgments

Early discussions with Norman Gaume (formerly with the City of Albuquerque) were useful in defining the problem and scope of the project. Discussions with John Hawley (formerly with the New Mexico Bureau of Mines and Mineral Resources) and Doug McAda, Carol Thomas, Scott Waltemeyer, Jack Veenhuis, and Ward Sanford (U.S. Geological Survey) were beneficial and aided in this analysis. Steve Richey (U.S. Geological Survey) helped determine estimates of precipitation.

MOUNTAIN-FRONT RECHARGE

Mountain-front recharge is a general term that has been used to describe various components of recharge to alluvial aquifers in basins adjacent to mountainous areas. In this report, mountain-front recharge refers to the sum of two components of recharge to the basin-fill aquifer in the Middle Rio Grande Basin. One component is recharge to the basin-fill aquifer resulting from infiltration of flow from streams that have headwaters in the mountainous area adjacent to the basin (mountain-stream-channel recharge). The other component is ground-water inflow from the mountainous area to the basin-fill deposits (subsurface-inflow recharge).

Other types of recharge include direct infiltration of precipitation to basin-fill deposits (direct recharge), infiltration of runoff in arroyos that have headwaters in the alluvial basin (arroyo recharge), and infiltration of water from perennial streams that cross the alluvial basin (river or tributary recharge). The volume of recharge from these other types of recharge is not estimated in this report.

Mountain front refers to the interface between the relatively impermeable bedrock of the mountainous areas and the generally more permeable basin-fill deposits in the basin (fig. 5). Determining the exact location of the mountain front in some areas is difficult because surficial or alluvial deposits cover the interface. Alluvial deposits are generally thickest in the stream channels.

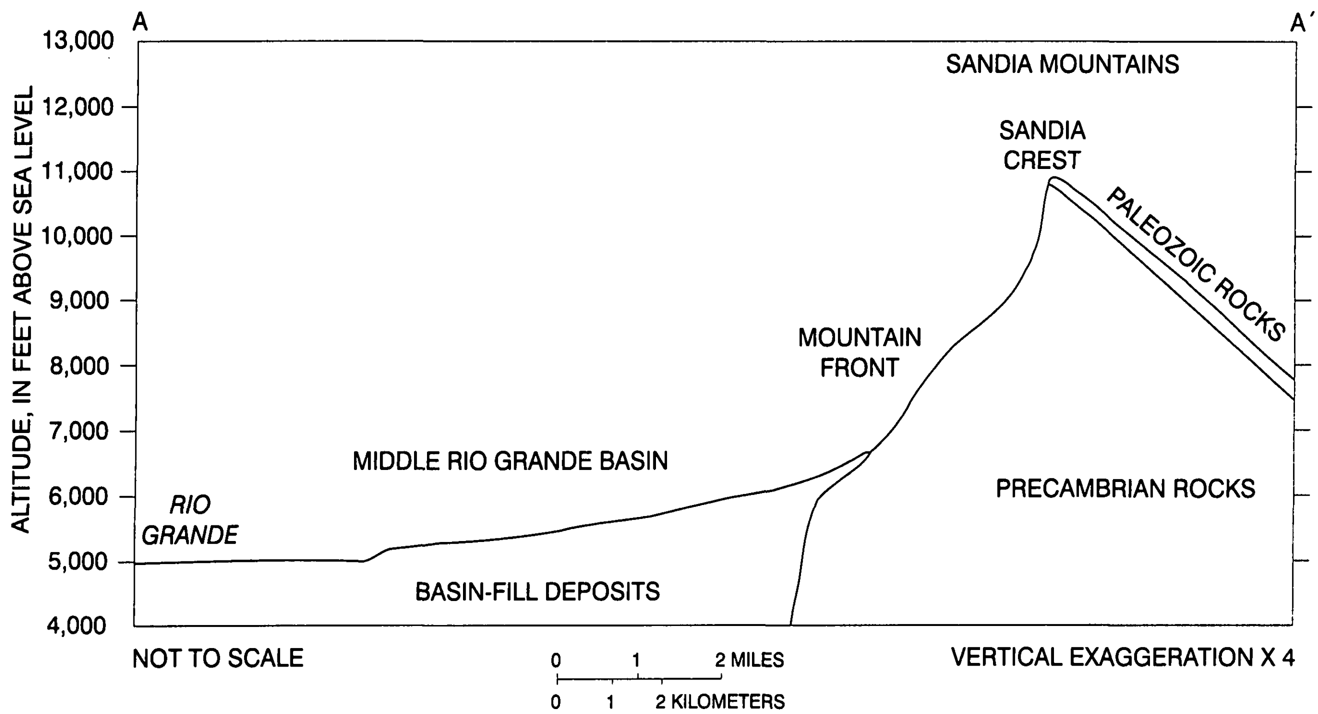

Figure 5. Generalized section showing mountain front (see figure 1 for location of line of section).

The main aquifers in the mountainous area along the eastern side of the Middle Rio Grande Basin can be divided into alluvial aquifers of Cenozoic age (alluvial aquifers) and sedimentary rock aquifers of Paleozoic age (Paleozoic aquifers). Precambrian crystalline rocks crop out in the mountainous area (fig. 6) and have contact with the basin-fill deposits along most of the mountain front on the eastern side of the Middle Rio Grande Basin. They are minor aquifers, however, because most ground water in these rocks is confined to fractures and faults. Caprio (1960, p. 131-133) indicated that most ground water in the crystalline rocks is in fractures and faults within 10 to 200 feet of land surface and that there probably are large volumes of ground water in the alluvial material along the base of the mountains compared with the water in the fractures.

The Cenozoic alluvial aquifers, which consist of weathered bedrock and alluvial material, are the most common aquifers in the watersheds along the eastern side of the Middle Rio Grande Basin. These aquifers generally overlie the Precambrian crystalline rocks and Paleozoic rocks, are relatively thin, and are limited mainly to the area adjacent to stream channels. Alluvial aquifers generally are in hydraulic connection with the basin-fill deposits in the Middle Rio Grande Basin.

The Paleozoic aquifers, which are composed of limestone and sandstone, are significant in only a few watersheds in the area. Limestone aquifers are the most common. Most porosity and permeability are due to solution channels and fractures in these limestones (Titus, 1980, p. 12). Paleozoic aquifers are thicker and more laterally continuous or regional than alluvial aquifers and generally are not in hydraulic connection with the basin-fill deposits in the Middle Rio Grande Basin. These aquifers are, however, in hydraulic connection with the alluvial aquifers in some of the area.

Recharge to the aquifers in the mountainous areas occurs as the result of infiltration of precipitation, infiltration of streamflow, and subsurface flow between the different aquifers. Infiltration of snowmelt is probably more significant as a source of recharge than infiltration of rainfall from summer thunderstorms. Snow generally melts slowly, when evapotranspiration rates are small, thus resulting in little overland flow or runoff because much of the snowmelt infiltrates. In contrast, during intense summer thunderstorms much of the precipitation results in runoff and evapotranspiration rates are large. Streamflow infiltrates to the alluvial aquifers below the stream channels. Based on field observations, the cross-sectional area and thickness of the alluvium vary and generally are not continuous for long distances along the stream channel. In areas where the cross-sectional area of the alluvium decreases or bedrock crops out in the stream channels, ground water discharges from the alluvium to the stream. Ground-water flow between different aquifers is also important, especially along the stream channels where ground water from the Paleozoic and Precambrian aquifers flows into the alluvial aquifers.

Depth to water and ground-water movement vary in the aquifers because of differences in their lateral extent and thickness. Ground water generally is close to land surface in alluvial aquifers, whereas depth to water varies widely in the Paleozoic aquifers. Ground water is close to land surface in alluvial aquifers because the aquifers are thin and ground water is perched in these aquifers by the underlying, relatively impermeable Precambrian rocks. In some areas, springs discharge from the aquifers; in other areas, ground-water levels are greater than 400 feet below land surface in the Paleozoic aquifers (Kues and Garcia, 1995, p. 19). Water in the aquifers in the mountainous areas generally moves toward the stream channels, the lowest areas in the watersheds. Ground water discharges at springs in some of the stream channels, where the aquifers decrease in thickness or are in fault contact with less permeable rocks. Where depth to ground water is great in the Paleozoic aquifers, the direction of ground-water movement and the discharge area for these aquifers are not known. It could take days to years for recharge to discharge to a stream because of variations in the length of flow paths and in the flow rate in the different aquifers.

Flow in the streams along the mountain front can result from snowmelt or runoff from intense summer thunderstorms. Most streams along the eastern side of the Middle Rio Grande Basin are ephemeral or intermittent at the mountain front. Upstream from the mountain front, some reaches of the streams in the larger watersheds are perennial. Streamflow at the mountain front resulting from snowmelt is relatively constant and can last well into the summer months (July and August) after the snow has melted at the higher altitudes. Runoff and increases in streamflow from intense summer thunderstorms, however, occur very quickly (less than 1 day) because of the steep slopes and rapid movement of streamflow in many of the watersheds.

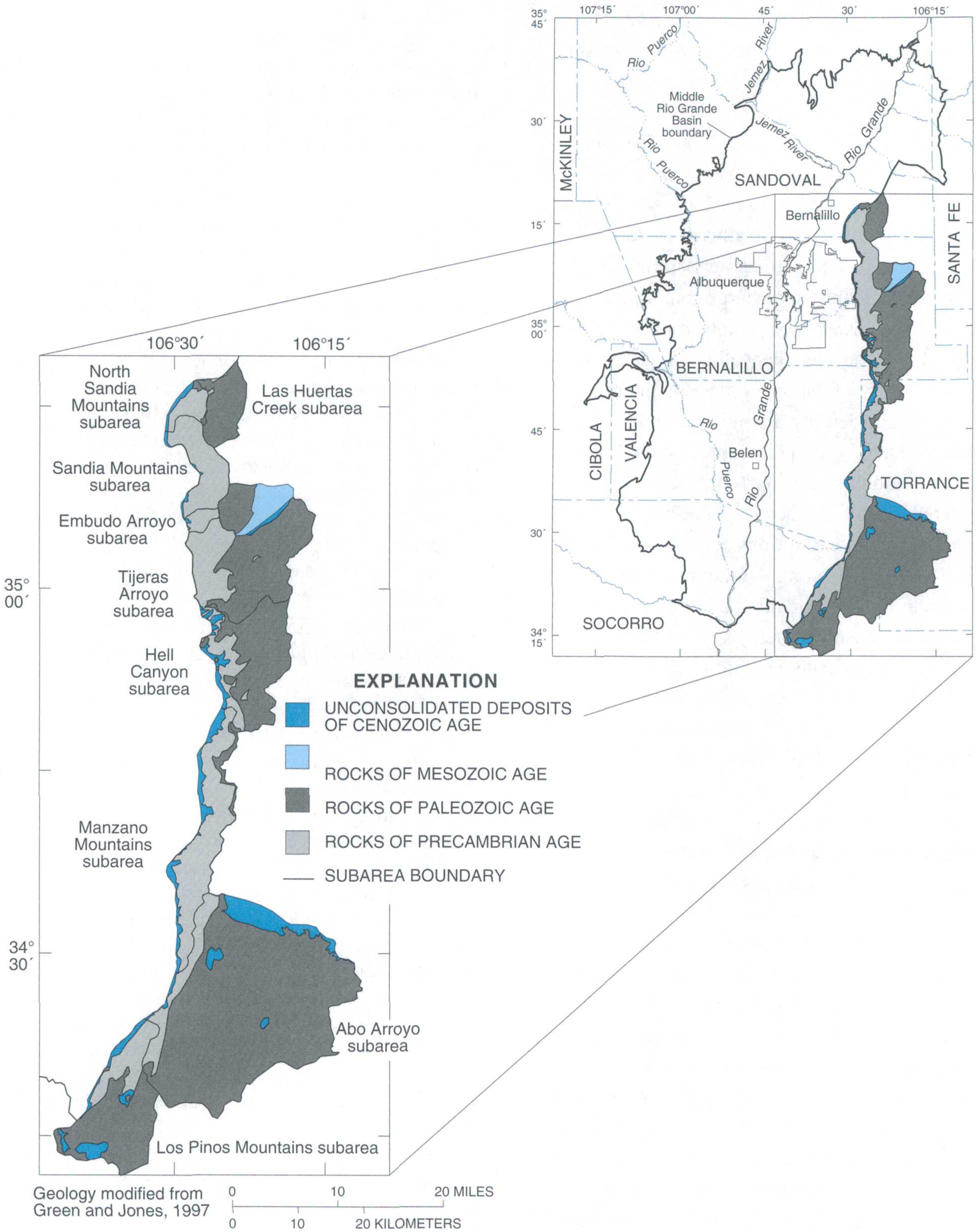

Figure 6. Generalized geology of the eastern side of the Middle Rio Grande Basin.

Flow from streams with headwaters in the mountainous areas generally starts to infiltrate soon after the stream crosses the mountain front. Most infiltration occurs downstream from the mountain front because there is a large thickness of unsaturated alluvium or basin-fill deposits below the stream channels (fig. 5) and the depth to water is typically great. The limiting factor controlling infiltration of streamflow downstream from the mountain front is the hydraulic conductivity of the alluvial material, not the amount of unsaturated permeable material.

Subsurface-inflow recharge can occur along the entire mountain front; most inflow, however, probably is in the alluvial aquifers beneath the stream channels. The permeability of the material along the mountain front varies considerably. The alluvial aquifers beneath the stream channels are permeable and could transmit substantial amounts of water from the mountainous areas to the basin-fill deposits—especially if the cross-sectional area of these aquifers at the mountain front is large. In some areas along the mountain front, the Precambrian rocks in the mountainous area are fractured and transmit water easily; in other areas where these rocks do not contain fractures, little or no water moves from the Precambrian rocks to the basin-fill deposits. Caprio (1960, p. 131) estimated that all ground water in the Precambrian rocks along the west side of the Sandia Mountains is in fractures that represent about 0.5 percent volume of the rock (porosity is about 0.5 percent). Caprio also indicated that fractures control water movement in this area and that no continuous water table is in the area. Although fractures have large permeability, the open fractures represent a small percentage of the total rock volume, which would limit the effective permeability of the Precambrian rocks and thereby the amount of ground water moving through these rocks. The lack of a continuous water table also indicates that flow in the fractured Precambrian rocks is limited and probably localized. Based on the small permeability of the Precambrian rocks compared to that of the alluvial aquifers beneath the stream channels, the amount of subsurface-inflow recharge through the Precambrian rocks probably is small compared to the subsurface recharge though the alluvial aquifers.

Methods Used to Estimate Mountain-Front Recharge

Many methods have been used to estimate mountain-front recharge or components of mountain-front recharge (Water Resources Research Center, 1980). The physical settings where different methods have been applied and the data necessary to apply different methods vary considerably.

Two fundamentally different methods are used to estimate mountain-front recharge or components of mountain-front recharge in this report: (1) the chloride-balance method and (2) the water-yield regression method. The chloride-balance method estimates the sum of mountain-stream-channel recharge and subsurface-inflow recharge. The water-yield regression method estimates streamflow at the mountain front and therefore can be used to estimate only the mountain-stream-channel recharge component of mountain-front recharge. The chloride-balance and water-yield regression methods use different sets of assumptions to estimate recharge; therefore, the estimates are independent, and comparison of the estimates allows the validity of the assumptions used to be evaluated when the different methods are applied.

Two assumptions are common to both methods. Streamflow entering the alluvial basin from the mountainous area is assumed to not flow out of the basin. The estimates of annual precipitation in the mountainous areas are also assumed to be accurate.

Probably little streamflow originating in the mountains flows out of the Middle Rio Grande Basin. Most stream channels that originate in the mountainous area do not have well-defined channels more than several miles west of the mountain front. Several channels that drain the larger watersheds do traverse the piedmont to the Rio Grande. During the spring, while snow is melting, there is generally no flow in these channels more than one-half mile downstream from the mountain front. In the summer, when there is runoff from intense summer thunderstorms, flow in these channels can discharge to the Rio Grande and leave the Middle Rio Grande Basin. Generally, this occurs only several days per year from the larger watersheds such as Tijeras Arroyo, Hell Canyon Wash, and Abo Arroyo. Streamflow to the Rio Grande that originates in the mountains and the effect on recharge calculations in specific areas are discussed later in this report. Not accounting for streamflow originating in the mountainous area that flows into the Rio Grande and out of the Middle Rio Grande Basin would cause mountain-front recharge estimates to be high.

Determining the accuracy of the annual precipitation values used is difficult. Precipitation was determined from maps published by the U.S. Department of Commerce (no date). These maps present the normalized mean annual precipitation, based on data collected at precipitation stations from 1931 to 1960 and precipitation/altitude relations. The mountainous areas have few control points and precipitation varies in different areas with similar altitudes, so precipitation estimates could have some error in these areas. Precipitation volume was estimated by determining the area between each set of lines of equal precipitation and multiplying the area by the average of the lines of equal precipitation bounding the area. The error in the recharge estimates would be directly related to the error in the precipitation estimates for both the chloride-mass-balance and water-yield regression methods.

Chloride-Balance Method

The chloride-balance method, which has been used to estimate mountain-front recharge in desert basins in Nevada (Dettinger, 1989), estimates mountain-front recharge by calculating a chloride mass balance on a watershed or drainage basin scale. Bulk precipitation, which includes wet and dry deposition, is the source of chloride to the watersheds. Chloride in precipitation is concentrated in recharge water by evaporation or transpiration. Chloride leaves the watersheds in ground-water discharge and streamflow (mountain-front recharge). Data required to apply this technique include estimates of the mean annual precipitation in the mountainous watershed, the chloride concentration in bulk precipitation, and the chloride concentration in mountain-front recharge (ground water from the basin-fill aquifer near the mountain front). Mountain-front recharge is estimated by the equation:

$$Rmf = P\ Cp / Cr \qquad (1)$$

where Rmf is the volume of mountain-front recharge, in acre-feet per year; P is the volume of precipitation in the mountainous watershed, in acre-feet per year; Cp is the chloride concentration in bulk precipitation, in milligrams per liter (mg/L); and Cr is the chloride concentration in mountain-front recharge, in mg/L (Dettinger, 1989).

Critical assumptions of the chloride-balance method include (1) precipitation is the only source of chloride to ground water or the mountainous watershed (no chloride sources are in the system); (2) there are no chloride sinks or long-term changes in chloride stored in the watershed; (3) all ground-water discharge from the mountainous area is into the basin-fill deposits of the Middle Rio Grande Basin; (4) estimates of the chloride concentration in bulk precipitation are accurate; and (5) chloride concentrations in ground water from basin-fill deposits represent the chloride concentration of average mountain-front recharge for the mountainous watershed. These assumptions are discussed below.

Precipitation is probably the only source of chloride in mountain-front recharge along the eastern side of the Middle Rio Grande Basin except for the Tijeras Arroyo and possibly the Las Huertas Creek watersheds. The rocks in the mountainous area, which are mainly igneous and metamorphic Precambrian rocks, Paleozoic sedimentary rocks, or alluvium derived from these rocks, would not contain large amounts of chloride. Feth (1981, p. 10-12) indicated that the weathering of most rocks and minerals (not including evaporites) is not a likely source of chloride in water. Some chloride could leach from the Paleozoic rocks because these rocks are of marine origin and could contain chloride trapped in the rocks during deposition. Most ground water in Paleozoic rocks, however, is in solution channels and fractures and would not be in contact with the bulk of the rocks, thereby reducing the chance for leaching of chloride trapped in the rocks during deposition. Anthropogenic sources of chloride such as road salt or septic effluent are probably not significant in most mountainous watersheds along the eastern side of the Middle Rio Grande Basin because, with the exception of the Tijeras Arroyo and Las Huertas Creek watersheds, there has been little human activity or development in most of the watersheds. Much of the area is part of a wilderness area where entry is limited to hiking or horseback riding. There has been a substantial amount of development in the Tijeras Arroyo watershed, especially in the last 30 years, that could have affected chloride concentrations in mountain-front recharge and streamflow at the mountain front. Development in the Las Huertas Creek watershed is limited to a relatively small area (less than 2 square miles) near the mountain front so sources of chloride due to anthropogenic activities are probably insignificant. Chloride sources in addition to precipitation would result in underestimation of mountain-front recharge.

The mountainous watersheds along the eastern side of the Middle Rio Grande Basin probably have no chloride sinks or long-term changes in storage of chloride, although chloride could be stored in the mountainous watersheds in the solid phase or in solution. Hem (1985, p. 118) probably best summarized the chemical nature of chloride in natural waters when he said "Chloride ions do not significantly enter into oxidation or reduction reactions, form no important solute complexes with other ions unless the chloride concentration is extremely high, do not form salts of low solubility, are not significantly adsorbed on mineral surfaces, and play few biochemical roles. The circulation of chloride ions in the hydrologic cycle is largely through physical processes."

Chloride stored in the solid phase could include chloride removed from the water as the result of chemical reactions, chloride included in plant biomass, or chloride minerals that precipitated from water infiltrating the unsaturated zone. The amount of plant biomass probably changes little on a long-term basis in the area. During the summer when evapotranspiration rates are large, chloride could precipitate as chloride salts in the unsaturated zone; however, there is probably no long-term storage of chloride because chloride salts tend to dissolve during infiltration of snowmelt or precipitation. Chloride storage in the solid phase in the watersheds would result in overestimation of mountain-front recharge.

Long-term changes in the volume of water stored in the unsaturated zone or in aquifers in the mountainous watersheds would result in changes in storage of chloride in solution. On a short-term or annual basis, there would obviously be changes in the volume of ground water stored in the aquifers in the mountainous watersheds, but on a long-term basis there is probably little change in storage. Shortly after snowmelt, the aquifers in the mountainous areas contain more water than in late summer when evapotranspiration is large and much of the recharge from snowmelt has discharged to streams. The long-term net change in storage in most of the aquifers, however, is expected to be small because of the local extent of the aquifers and the rapid ground-water movement from these aquifers to the streams. In the watersheds along the eastern side of the Middle Rio Grande Basin where the Paleozoic aquifers are present, ground-water storage could change. Increases in storage of ground water in these watersheds would cause recharge estimates to be high and decreases would cause recharge estimates to be low.

In most of the area along the eastern side of the Middle Rio Grande Basin, all ground-water discharge from the mountainous areas is into the basin-fill deposits. Ground water could discharge from the Paleozoic aquifers to areas other than the basin in some areas. Available water-level maps and water-level data (Spiegel, 1955; Titus, 1963) indicate ground-water divides coinciding with the surface-water divides. However, these maps were based on a limited amount of data, and estimated locations of the ground-water divides could change if more data were available. Ground-water discharge to areas other than the Middle Rio Grande Basin would result in overestimation of mountain-front recharge.

The chloride concentration in bulk precipitation was assumed to be 0.3 mg/L. Anderholm (1994) determined the chloride concentration in bulk precipitation to be about 0.3 mg/L near Santa Fe, New Mexico. Phillips (1994, p. 22) determined that chloride concentrations in bulk precipitation ranged from 0.35 to 0.41 mg/L in New Mexico and southwestern Texas. Phillips (p. 23) pointed out that the chloride concentration in precipitation generally decreases with increasing precipitation. His estimates of chloride concentration in precipitation were for areas that receive less precipitation than the mountainous area along the eastern side of the Middle Rio Grande Basin; therefore, the chloride concentrations probably are higher than the values in the mountainous areas. The magnitude of error in mountain-front recharge calculations resulting from errors in chloride-concentration calculations in mountain-front recharge would affect recharge calculations by the same relative proportion.

Chloride concentrations in ground water from the basin-fill deposits near the mountain front were assumed to be equal to those in mountain-front recharge. Ground-water-quality data in the U.S. Geological Survey National Water Information System data base were used to determine chloride concentrations in ground water near the mountain front. Areal plots of available data indicated variations in the availability of data and in chloride concentrations in ground water from the basin-fill aquifer of the Middle Rio Grande Basin and from the aquifers in the mountainous area. Although the chloride concentrations in ground water from aquifers in the mountainous area generally were not used to determine the chloride concentration in mountain-front recharge, these data are useful for determining ranges in the chloride concentration in possible recharge water. No rigorous method was used to assign a chloride concentration to mountain-front recharge. Based on the range of most available data, an intermediate chloride concentration in ground water from the basin-fill deposits in the Middle Rio Grande Basin was chosen as the chloride concentration used to calculate mountain-front recharge. In areas for which little data were available, the chloride concentration used in the calculation was assumed to be equal to that in ground water adjacent to the area. In some areas, chloride concentrations in ground water a considerable distance downgradient from the mountain front were used. The chloride concentration in ground water could change as water moves through the aquifer; however, where data are sufficient, there do not appear to be large changes in chloride concentration in ground water along a flow path in the Middle Rio Grande Basin (Anderholm, 1988). Error in the mountain-front recharge estimates resulting from error in the chloride concentration of mountain-front recharge is inversely proportional to the relative error in the chloride concentration used in the calculations.

Water-Yield Regression Method

The water-yield regression method has been used to estimate mountain-front recharge by determining the volume of streamflow derived from the mountainous watersheds that infiltrates and recharges the basin-fill aquifer. This method estimates only the mountain-stream-channel component of mountain-front recharge; however, this is probably the largest component of recharge in areas where the bedrock in the mountainous areas is relatively impermeable (subsurface-inflow recharge is small).

Critical assumptions of the water-yield regression method include (1) estimates of streamflow at the mountain front using previously developed water-yield regression equations are accurate for the Middle Rio Grande Basin and (2) the amount of streamflow that evaporates or is transpired downstream from the mountain front can be determined or is small enough to be ignored. Streamflow at the mountain front is estimated using water-yield regression equations determined from precipitation, drainage area, and streamflow measured at or upstream from the mountain front. After the equations are developed using streamflow data for gaged watersheds, the equations can be used to estimate streamflow at the mountain front in ungaged watersheds that have characteristics similar to those of gaged watersheds. Estimates of the amount of streamflow that evaporates or transpires downstream from the mountain front can be subtracted from the total streamflow at the mountain front to determine the amount of recharge.

Water-yield regression equations have been determined for watersheds in southern Colorado and northern New Mexico (Hearne and Dewey, 1988) and for watersheds in southern New Mexico (Waltemeyer, 1994). The equation developed by Hearne and Dewey (1988, p. 31-32) was determined using data for 16 watersheds underlain by crystalline rock. The authors assumed that the amount of ground water moving out of these watersheds was negligible and that the measured streamflow would represent total water yield from these basins. Hearne and Dewey (1988) used average winter precipitation for the entire watershed (Pw), in inches, and watershed area (A), in square miles, to estimate streamflow at the mountain front (Q), in acre-feet per year:

$$Q = 0.0552\, A^{0.977}\, Pw^{3.596} \qquad (2)$$

Waltemeyer (1994) used average annual precipitation for the entire watershed (Pa), in inches, and A from 13 watersheds in southern New Mexico to estimate Q:

$$Q = 0.123\, A^{1.35}\, Pa^{1.65} \qquad (3)$$

Waltemeyer (1994, p. 6) developed the equation using watersheds with areas between 20.7 and 184 square miles and indicated that application of the equation should be limited to watersheds with areas in this range.

Inspection of the two equations allows for evaluation of the effect of variation in precipitation and watershed area on the recharge estimates. Drainage basin or watershed area is used in both equations. Variations in drainage basin area have a greater effect on the estimates derived using the equation developed by Waltemeyer (1994) than on those derived using the equation developed by Hearne and Dewey (1988). In Hearne and Dewey's equation, drainage basin area is essentially taken to the first power, whereas in Waltemeyer's equation, drainage basin area is taken to the 1.35 power. The equation developed by Waltemeyer uses annual precipitation, whereas the equation developed by Hearne and Dewey uses winter precipitation. Waltemeyer (1994, p. 3) pointed out that in areas where precipitation is primarily snowfall (southern Colorado and northern New Mexico), the relation between mean winter precipitation and streamflow at the mountain front has greater statistical significance than annual precipitation, whereas in areas where precipitation is primarily rainfall (southern New Mexico), annual precipitation is more significant. In watersheds where winter precipitation is a larger percentage of annual precipitation (generally higher altitude watersheds), the runoff estimated using Hearne and Dewey's equation would be larger than that estimated using Waltemeyer's equation. Precipitation is also weighted more (larger exponent) in the equation developed by Hearne and Dewey than in the equation developed by Waltemeyer.

Part of the streamflow estimated to enter the alluvial basin at the mountain front evaporates or is transpired. Thomas (1995, p. 12) measured infiltration, evaporation, and evapotranspiration rates along Tijeras Arroyo to determine the amount of streamflow resulting in recharge and the amount lost to evaporation or evapotranspiration. Thomas found the amount of streamflow lost to evaporation and evapotranspiration to be less than one-tenth of 1 percent to 2 percent of the infiltration rate and, in general, the amount of streamflow lost to evaporation and evapotranspiration to be insignificant relative to infiltration of streamflow. The measurements along Tijeras Arroyo were made near the mountain front during prolonged periods of continuous flow in the channel. The estimates of evaporation and evapotranspiration loss along Tijeras Arroyo are probably valid for most of the area along the eastern side of the Middle Rio Grande Basin because much of the recharge is from infiltration of streamflow near the mountain front where streamflow is present for prolonged periods. Where streamflow (infiltration) occurs for a short period of time (1 or 2 days), such as during runoff from an intense summer thunderstorm, evaporation and evapotranspiration are probably a more significant part of total infiltration. In watersheds where runoff from summer thunderstorms is a large part of annual streamflow, water-yield regression methods could overestimate recharge.

Streamflow along the mountain front was estimated using the regression equations developed by both Hearne and Dewey (1988) and by Waltemeyer (1994). The equation developed by Hearne and Dewey is probably more appropriate for the higher altitude watersheds along the eastern side of the Middle Rio Grande Basin where much of the streamflow along the mountain front results from snowmelt. The regression equation developed by Waltemeyer is probably more appropriate for the areas in the southern part of the basin and for watersheds lower in altitude where rainfall is the dominant type of precipitation.

Estimation of Mountain-Front Recharge In Subareas

The area along the eastern side of the Middle Rio Grande Basin was divided into subareas (fig. 6) on the basis of surface-water drainage, geology, precipitation, and altitude. Most of the subareas contain more than one drainage basin or watershed. In subareas underlain by Precambrian rocks (fig. 6), the alluvial aquifers are important; in subareas underlain by Paleozoic rocks, the Paleozoic aquifers and alluvial aquifers are important. Although characteristics of the individual watersheds in a particular subarea have some variation, most of the watersheds in a particular subarea are similar and recharge processes are similar.

For each subarea, mountain-front recharge was calculated using the chloride-balance method and streamflow at the mountain front was calculated using the equations developed by Hearne and Dewey (1988) and Waltemeyer (1994). On the basis of work by Thomas (1995), evapotranspiration was assumed to be negligible; therefore, all streamflow at the mountain front was assumed to recharge the basin-fill deposits. No data are available that can be used to determine the amount of subsurface-inflow recharge along the mountain front. Although the subsurface-inflow component of recharge cannot be quantified, it is probably small relative to the streamflow-infiltration component of recharge in many subareas because (1) the bedrock in the area along the mountain front is relatively impermeable (Precambrian crystalline rock) and (2) there is no large thickness of permeable weathered bedrock or alluvial deposits in the stream channels at the mountain front. In the Los Pinos Mountains and Las Huertas Creek subareas, Paleozoic rocks are in contact with the basin-fill deposits along the mountain front. The subsurface-inflow-recharge component could be important in these two subareas.

Recharge estimates derived using the chloride-balance method and the water-yield regression method are compared in the following discussion. The chloride-balance method underestimates mountain-front recharge if the chloride concentration in precipitation used is low, the chloride concentration in mountain-front recharge used is high, or if there is a source of chloride in the watersheds. Similarly, water-yield regression equations can underestimate mountain-front recharge if the subsurface-inflow component of recharge is substantial.

Los Pinos Mountains Subarea

The Los Pinos Mountains subarea (fig. 7) includes the Los Pinos Mountains and the area adjacent to the Los Pinos Mountains along the southeastern part of the Middle Rio Grande Basin (fig. 1). The subarea is about 45,000 acres (70 square miles) (table 1). The highest point in the subarea is about 7,500 feet above sea level, although the altitude of most of the subarea is less than 7,000 feet. Many small watersheds along the northwest side of the Los Pinos Mountains discharge water to the Middle Rio Grande Basin. Palo Duro Canyon is a large watershed in this subarea that drains the southern and eastern sides of the Los Pinos Mountains. This drainage enters the Middle Rio Grande Basin west of the Los Pinos Mountains. The rock types in the subarea include Precambrian crystalline rocks and Paleozoic sedimentary rocks (fig. 6). There is little or no development in the Los Pinos Mountains subarea.

The area has little variation in precipitation (fig. 7). Precipitation is greater than 12 inches in most of the subarea. Average annual precipitation for the entire watershed is 13.5 inches (table 1).

The chloride concentration in ground water in and adjacent to the subarea ranges from 32 to 130 mg/L (fig. 7). A sample from a well in Palo Duro Canyon near the mountain front had a chloride concentration of 34 mg/L, and a sample from basin-fill deposits in the Middle Rio Grande Basin north of the Los Pinos Mountains had a chloride concentration of 34 mg/L; thus, 34 mg/L was used in the chloride-balance equation (C_r in eq. 1) to estimate mountain-front recharge.

The estimated annual mountain-front recharge from the Los Pinos subarea ranges from 450 to 2,800 acre-feet (table 2). The estimate calculated using the chloride-balance method is the smallest value. The recharge estimate derived from the Waltemeyer (1994) water-yield regression equation is much larger than the estimate derived from the Hearne and Dewey (1988) equation because of the relatively large area and small winter precipitation (table 1).

Abo Arroyo Subarea

The Abo Arroyo subarea (fig. 8) comprises about 160,000 acres (248 square miles) (table 1). Manzano Peak is the highest point in the subarea (about 10,100 feet), although most of the watershed is less than 6,600 feet. The Abo Arroyo subarea essentially contains one watershed, Abo Arroyo, which is the largest watershed along the eastern side of the Middle Rio Grande Basin (fig. 1). The dominant rock type is Paleozoic sedimentary rocks, although some Precambrian crystalline rocks are along the mountain front (fig. 6). Development in the subarea includes roads and widely scattered homes and ranches.

Altitude, precipitation, and vegetation have a wide range in the Abo Arroyo subarea. For example, the higher areas along the eastern slopes of the Manzano Mountains are heavily forested and precipitation is greater than 16 inches per year, whereas in the southern part of the watershed, shrubs and grass are the dominant vegetation and precipitation is less than 16 inches per year. Precipitation ranges from greater than 12 to 25 inches per year in the subarea. Average annual precipitation for the entire subarea is 14.5 inches (table 1).

The Abo Arroyo subarea probably has local and regional ground-water flow systems. Many springs in the watershed indicate numerous localized ground-water flow systems. Many of the springs are located in the northern part of the watershed at higher altitudes, although some springs are along drainages near the confluence with Abo Arroyo. Spiegel (1955) indicated a regional ground-water flow system in the Abo Arroyo watershed. Most subsurface inflow to the Middle Rio Grande Basin from the Abo Arroyo watershed is probably limited to the area along the stream channel because Abo Arroyo enters the Middle Rio Grande Basin through a narrow gap in the Precambrian crystalline rocks.

Data collected from October 1996 through September 1997 (fig. 9) at a streamflow-gaging station operated near the mountain front (fig. 8) is useful for determining variations in streamflow throughout the year and estimating annual streamflow at the mountain front. The site has a small amount of perennial flow and several large, short-duration flow events during the summer (fig. 9). By assuming a discharge of 0.7 acre-foot per day, water entering the Middle Rio Grande

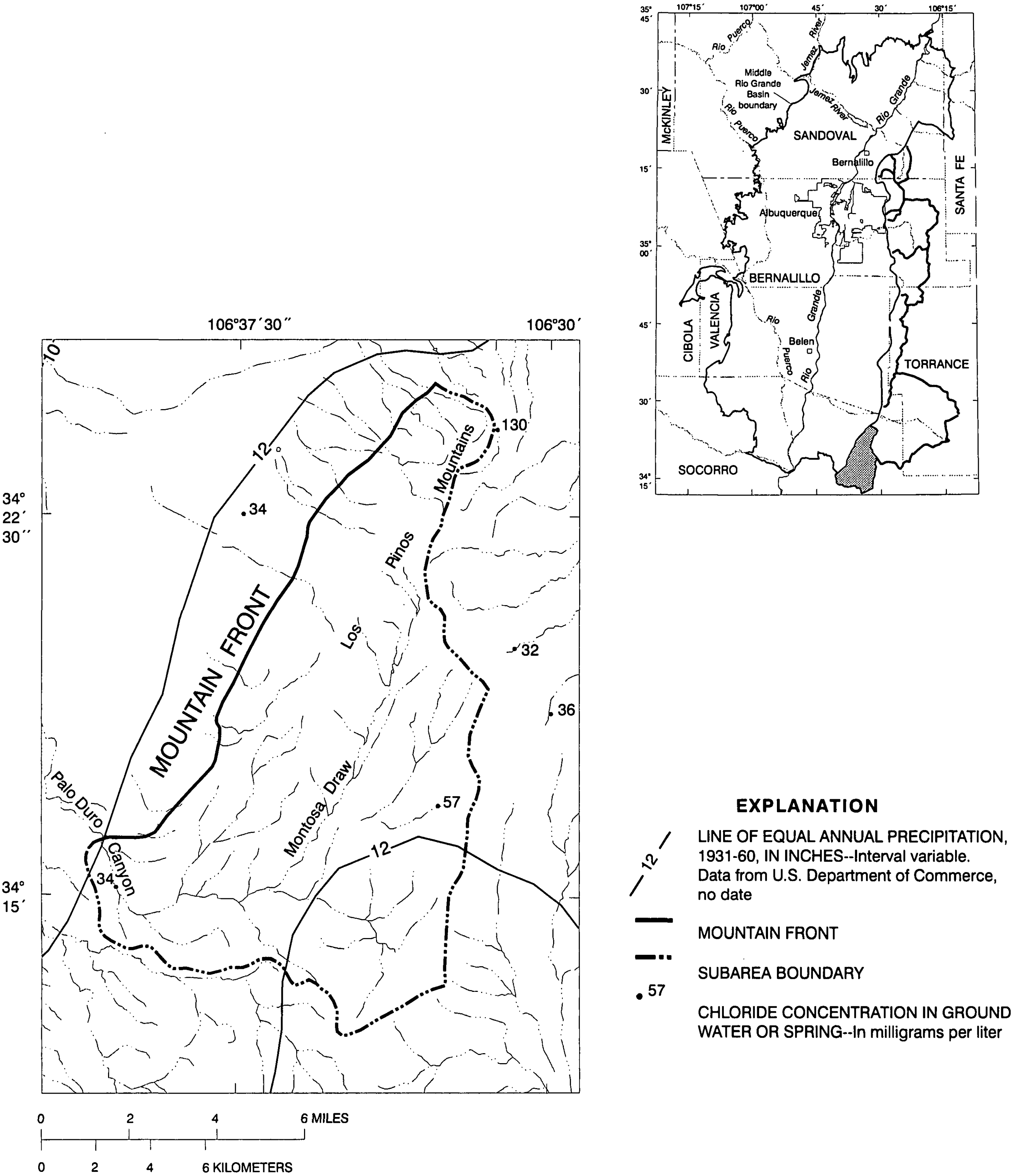

Figure 7. Los Pinos Mountains subarea.

Table 1. Area, annual precipitation, and winter precipitation for subareas

Subarea (fig. 6)	Area		Annual precipitation		Winter precipitation	
	Acres	Square miles	Total (acre-feet)	Average (inches)	Total (acre-feet)	Average (inches)
Los Pinos Mountains	44,940	70.2	50,500	13.5	17,670	4.7
Abo Arroyo	158,730	248	192,300	14.5	67,710	5.1
Manzano Mountains	38,900	60.8	65,250	20.1	28,580	8.8
Hell Canyon	41,910	65.5	62,830	18.0	28,730	8.2
Tijeras Arroyo	63,560	99.3	89,250	16.8	41,100	7.8
Embudo Arroyo	2,970	4.6	4,730	19.1	2,270	9.2
Sandia Mountains	17,570	27.4	29,450	20.1	13,620	9.3
North Sandia Mountains	6,180	9.7	9,350	18.1	4,090	7.9
Las Huertas Creek	13,890	21.7	24,600	21.2	10,420	9.0

Table 2. Estimated mountain-front recharge for subareas

[mg/L, milligrams per liter; na, not applicable]

Subarea (fig. 6)	Annual recharge (acre-feet) (Hearne and Dewey, 1988)	Annual recharge (acre-feet) (Waltemeyer, 1994)	Mountain-front-recharge chloride concentration (mg/L)	Annual recharge (acre-feet)
Los Pinos Mountains	920	2,800	34	450
Abo Arroyo	4,220	[1]17,320	45	1,280
Manzano Mountains	7,600	4,450	9	2,180
Hell Canyon	6,340	4,100	15	1,260
Tijeras Arroyo	7,960	6,420	15	1,790
Embudo Arroyo	720	[1]130	10	140
Sandia Mountains	4,260	1,520	6	1,470
North Sandia Mountains	860	[1]310	6	470
Las Huertas Creek	3,010	1,210	3.5	2,110
Total (rounded)	36,000	38,000	na	11,000

[1]Estimate could be in error because size of subarea is outside the range for which equation was developed (Waltemeyer, 1994)

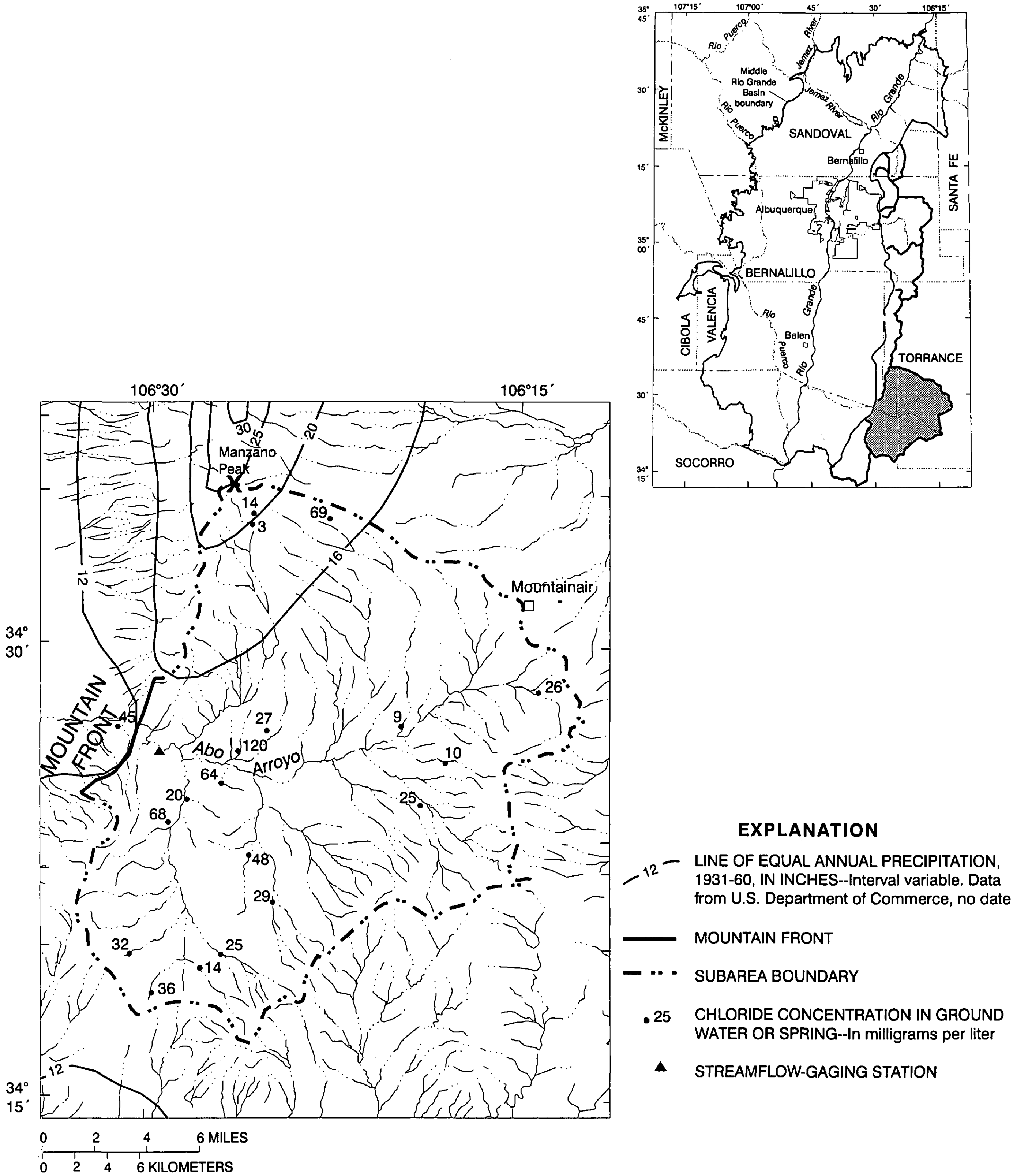

Figure 8. Abo Arroyo subarea.

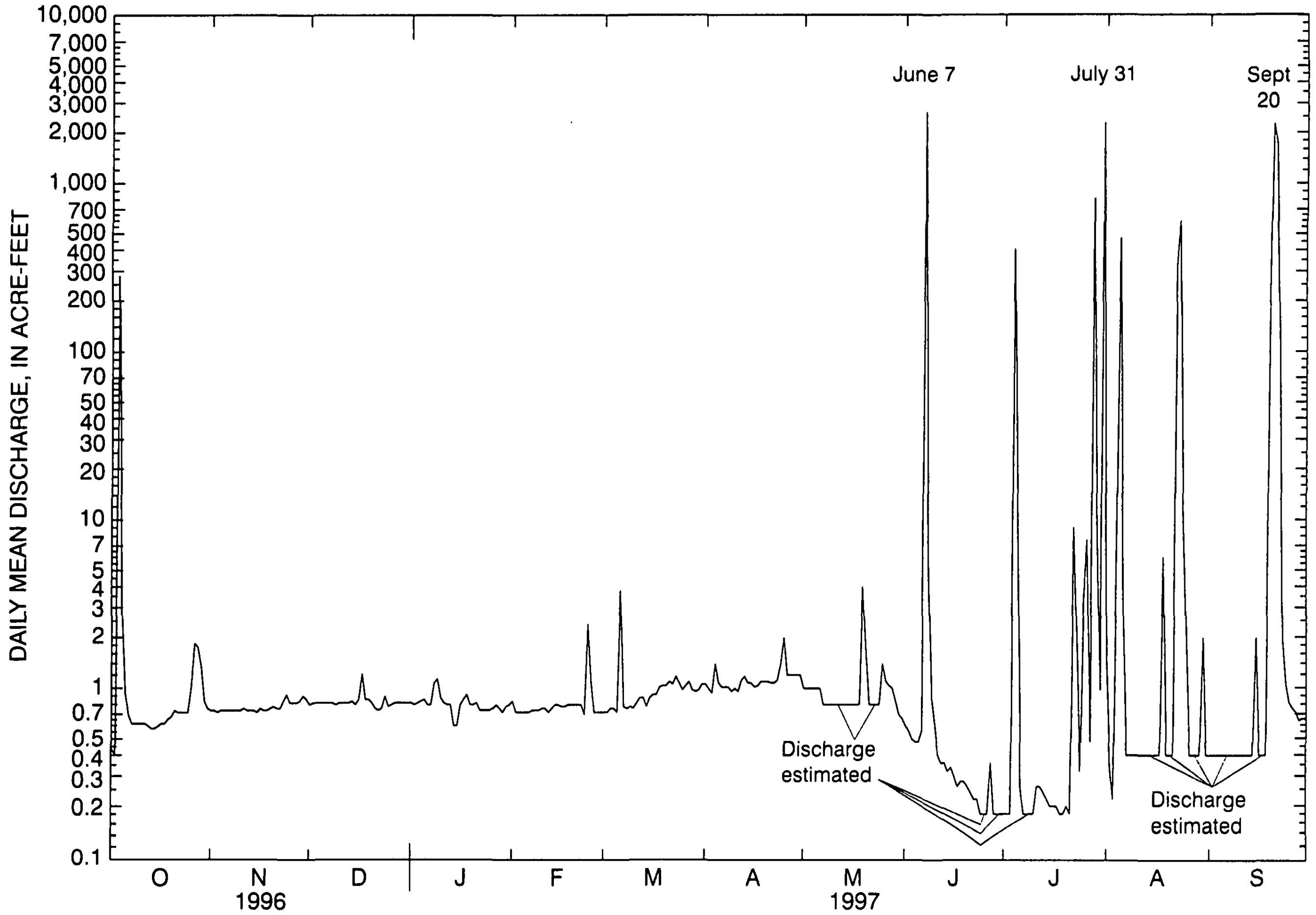

Figure 9. Daily mean discharge for Abo Arroyo, October 1996 through September 1997.

Basin as the result of base flow is about 255 acre-feet per year. The data indicate a very slight increase in flow during spring (March and April) resulting from snowmelt in the higher parts of the watershed. This small increase in flow during the spring demonstrates that snowmelt has little effect on streamflow at the mountain front and indicates that much of the snowmelt is lost to evapotranspiration or does not discharge to the streams. Streamflow decreases in May and June (fig. 9) probably as the result of evapotranspiration along the channel. Intense summer thunderstorms result in large flows (as much as 2,640 acre-feet) at the mountain front (fig. 9). These flow events generally do not last more than 1 or 2 days, but several of these events in 1 year can result in substantial volumes of water that could infiltrate and recharge the basin-fill deposits in the Middle Rio Grande Basin. The sum of the three largest 1-day flow events (June 7, July 31, and September 20) was about 7,200 acre-feet. The total streamflow at the gaging station was about 12,400 acre-feet for October 1, 1996, through September 30, 1997 (water year 1997) (Ortiz and others, 1998, p. 231). Most flow at the gaging station was runoff from intense summer thunderstorms. Mean annual streamflow at the site is probably less than the 12,400 acre-feet measured in water year 1997 because precipitation in July, August, and September (when 75 percent of the flow occurred) was about 150 percent greater than normal in Mountainair (U.S Department of Commerce, 1997), which is adjacent to the Abo Arroyo subarea (fig. 8).

Chloride concentrations in water from springs and wells in the subarea also vary widely (fig. 8). Chloride concentrations in water from springs in the higher altitudes of the watershed are as small as 3 mg/L. Chloride concentrations as high as 120 mg/L were detected in ground water along Abo Arroyo near the mountain front. The large variability in chloride concentrations in ground water in the subarea indicates large variations in evapotranspiration rates and possibly some sources of chloride in the watershed. The chloride concentration in ground water from the basin-fill deposits about 1 mile downstream from the mountain front was 45 mg/L. This value was used for the calculation of mountain-front recharge (table 2).

Estimates of mountain-front recharge range from 1,280 to 17,320 acre-feet per year (table 2). The mountain-front recharge calculated using the chloride-balance method is 1,280 acre-feet per year. The recharge estimate calculated using the equation developed by Waltemeyer (1994) is the largest and probably is not valid because the area of the Abo Arroyo subarea (about 250 square miles, table 1) is larger than the watersheds Waltemeyer used to develop his equation. The measured annual streamflow at the mountain front in water year 1997 was about 12,400 acre-feet (Ortiz and others, 1998), which is also much less than the estimate of streamflow derived using the equation developed by Waltemeyer (1994). The small amount of base flow at the mountain front and slight increase in streamflow resulting from snowmelt indicate that infiltration of summer thunderstorm runoff could be the most important source of recharge along Abo Arroyo.

The amount of summer thunderstorm runoff that infiltrates along the Abo Arroyo channel in the Middle Rio Grande Basin can be estimated using streamflow data for the mountain front and some assumptions. Examination of streamflow data indicates that daily mean streamflow was greater than 100 acre-feet about 10 days in water year 1997 (fig. 9). If flow in the entire length of the channel from the mountain front to the Rio Grande occurs for 10 days per year, the channel is about 10 feet wide and 15 miles long, and the infiltration rate is 5 feet per day (Thomas, 1995), the annual infiltration of summer thunderstorm runoff is about 900 acre-feet. This is considerably less than the discharge of about 12,000 acre-feet at the mountain front measured during water year 1998. Based on the estimate of infiltration of summer thunderstorm runoff, much of the streamflow measured at the mountain front discharges to the Rio Grande.

Evaporation or transpiration of water from the unsaturated zone in the bed of Abo Arroyo could be substantial relative to the amount of infiltration. As mentioned previously, Thomas (1995) measured infiltration and evapotranspiration rates along Tijeras Arroyo, which had perennial flow during the measurements. For relatively constant streamflow and infiltration, Thomas determined that evaporation and transpiration were minor compared to infiltration rates. In Abo Arroyo, flow or infiltration generally occurred for 1 day or less, whereas evaporation or transpiration continued for several days. The sum of evaporation/transpiration over a period of many days could be substantial relative to the infiltration occurring during 1 day.

Based on calculations of infiltration and amount of evaporation and transpiration, streamflow data, and the recharge estimate derived using the chloride-balance method, recharge estimates derived using water-yield regression methods probably are overestimates of mountain-front recharge from the Abo Arroyo subarea. In the Abo Arroyo watershed, the amount of flow that enters the basin as the result of some of the larger summer thunderstorms is much greater than the amount of water that can infiltrate through the stream channel. Little or no streamflow at the mountain front resulting from snowmelt runoff indicates essentially no mountain-front recharge resulting from winter precipitation. The equation developed by Hearne and Dewey (1988) is probably not appropriate for estimating streamflow at the mountain front in the Abo Arroyo subarea because the equation uses winter precipitation to estimate runoff and winter precipitation in the subarea seems to have no effect on streamflow at the mountain front. The short duration of increased flow at the mountain front as the result of summer precipitation events indicates that much of the flow at the mountain front is due to runoff and there is little increase in flow at the mountain front as the result of discharge from the shallow aquifers adjacent to the stream channels. Infiltration of precipitation to deep or more extensive aquifers in the subarea (increases in ground-water storage in the subarea) probably results in less runoff from this watershed than would be predicted using the water-yield regression equations. The chloride concentration of mountain-front recharge indicates that a large proportion of precipitation is evaporated or transpired in the watershed and that less than 1 percent of annual precipitation results in mountain-front recharge.

Manzano Mountains Subarea

The Manzano Mountains subarea (fig. 10) comprises about 39,000 acres (61 square miles) (table 1). Manzano Peak, which is along the boundary of the subarea, is the highest point in the subarea (about 11,000 feet). The subarea contains many small watersheds (less than 10 square miles) that discharge to the Middle Rio Grande Basin. Most of the stream channels that enter the basin from the Manzano Mountains subarea do not extend more than 2 or 3 miles west of the mountain front. Little or no runoff from the subarea discharges to the Rio Grande because most of the stream channels do not extend to the river. Most watersheds in the subarea are greater than 6,600 feet above sea level; many have headwaters near the crest of the Manzano Mountains. Precambrian crystalline rocks are the most common rock type (fig. 6). The subarea has no development.

Precipitation in the subarea ranges from about 16 to greater than 30 inches (fig. 9). Average annual precipitation in the subarea is 20.1 inches (table 1). Streamflow during the spring at the mountain front occurs in many of the drainages as the result of snowmelt. Several springs also are along the mountain front, indicating discharge of ground water near the mountain front.

Few data are available in the subarea for chloride concentrations in ground water. No samples were collected from springs in the subarea. The chloride concentration in water from wells in the basin-fill deposits near the mountain front ranges from 7.3 to 26 mg/L. Chloride concentrations in ground water farther west from the mountain front generally range from 5 to 12 mg/L (Anderholm, 1988, pl. 1). A chloride concentration of 9 mg/L was used to estimate mountain-front recharge (table 2).

Mountain-front recharge estimates range from 2,180 to 7,600 acre-feet per year (table 2). The estimate calculated using the chloride-balance method is the smallest. The estimates of streamflow at the mountain front derived using the water-yield regression method are about two to three times the estimate derived using the chloride-balance method.

Hell Canyon Subarea

The Hell Canyon subarea (fig. 11) comprises about 42,000 acres (about 66 square miles) (table 1). Mosca Peak (about 9,500 feet) is the high point in the subarea; most of the subarea is below 7,500 feet above sea level. The subarea contains two main drainages, Hell Canyon Wash and Cañon de Sanchez (fig. 11). Both Precambrian crystalline rocks and Paleozoic sedimentary rocks are in the subarea. Paleozoic sedimentary rocks generally are more common in the headwaters of the watersheds (fig. 6). With the exception of about 3 square miles of housing developments in the headwaters of Hell Canyon Wash, there is no development in the subarea. Hell Canyon Wash has a well-defined channel to the Rio Grande, indicating that runoff from intense summer thunderstorms probably discharges to the Rio Grande.

Precipitation ranges from less than 16 to greater than 20 inches per year. Average annual precipitation in the subarea is 18.0 inches (table 1). Several springs in the upper parts of the watershed indicate localized ground-water flow systems in the Paleozoic sedimentary rocks. Depths to water in other parts of the upper watershed are as great as 460 feet (Kues and Garcia, 1995, p. 19). The presence of springs in areas of the upper watershed and the large depths to water in the same general area could indicate local and regional ground-water flow systems in this watershed.

Chloride concentrations in ground water in the subarea range from 19 to 52 mg/L (fig. 11). Chloride concentrations in ground water near the mountain front in the Middle Rio Grande Basin range from 9 to 120 mg/L. The chloride concentration in ground water from basin-fill deposits west of the area shown in figure 11 generally ranges from about 9 to 30 mg/L (Anderholm, 1988). A chloride concentration of 15 mg/L was used to calculate mountain-front recharge.

Mountain-front recharge estimates range from 1,260 to 6,340 acre-feet per year (table 2). The estimate derived using the chloride-balance method is the smallest. The two estimates derived using the water-yield regression method differ by about 2,000 acre-feet per year.

Tijeras Arroyo Subarea

The Tijeras Arroyo subarea (fig. 12) comprises about 64,000 acres (about 99 square miles) (table 1). South Sandia Peak (about 9,800 feet) is the highest point in the subarea. Most of the subarea is less than 7,500 feet above sea level. The Tijeras Arroyo subarea contains two main drainages, Tijeras Arroyo and Arroyo del Coyote (fig. 12). Tijeras Arroyo enters the Middle Rio Grande Basin through a narrow gap in the Precambrian rocks along the mountain front (fig. 6). Paleozoic sedimentary rocks are the most common rock type in the subarea, although Precambrian crystalline rocks are present along Tijeras Arroyo and Arroyo del Coyote near the mountain front. The subarea has extensive development, especially along the Tijeras drainage.

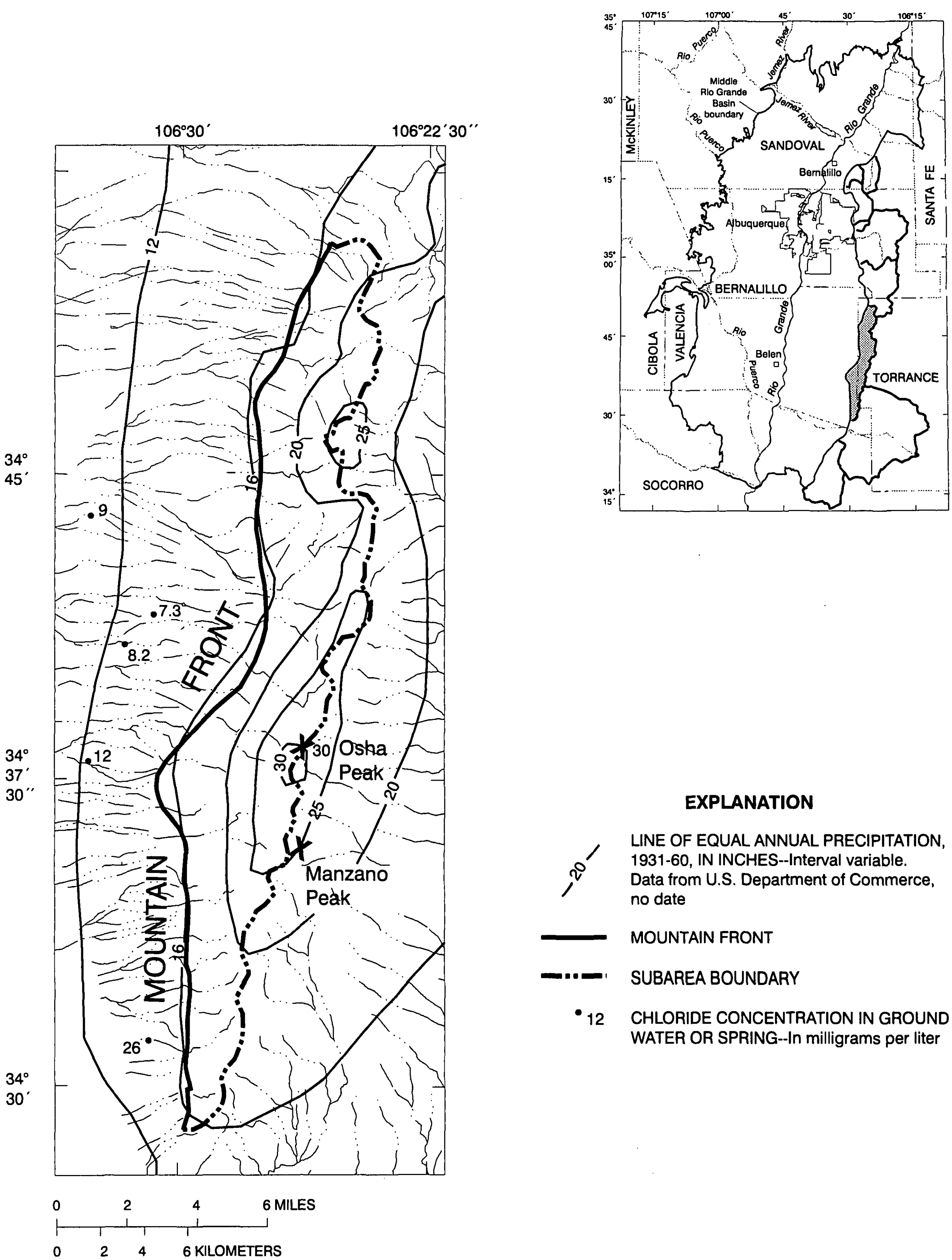

Figure 10. Manzano Mountains subarea.

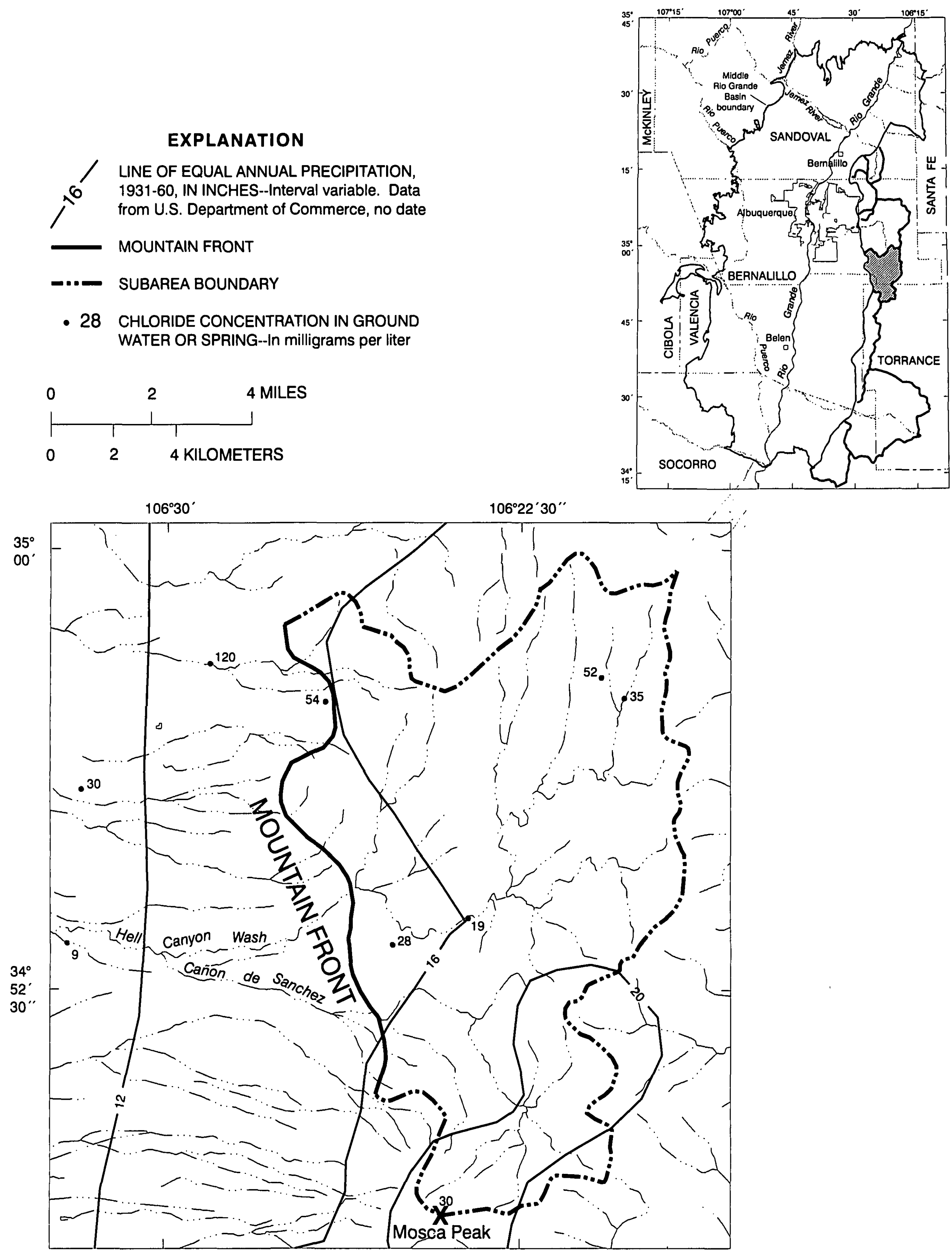

Figure 11. Hell Canyon subarea.

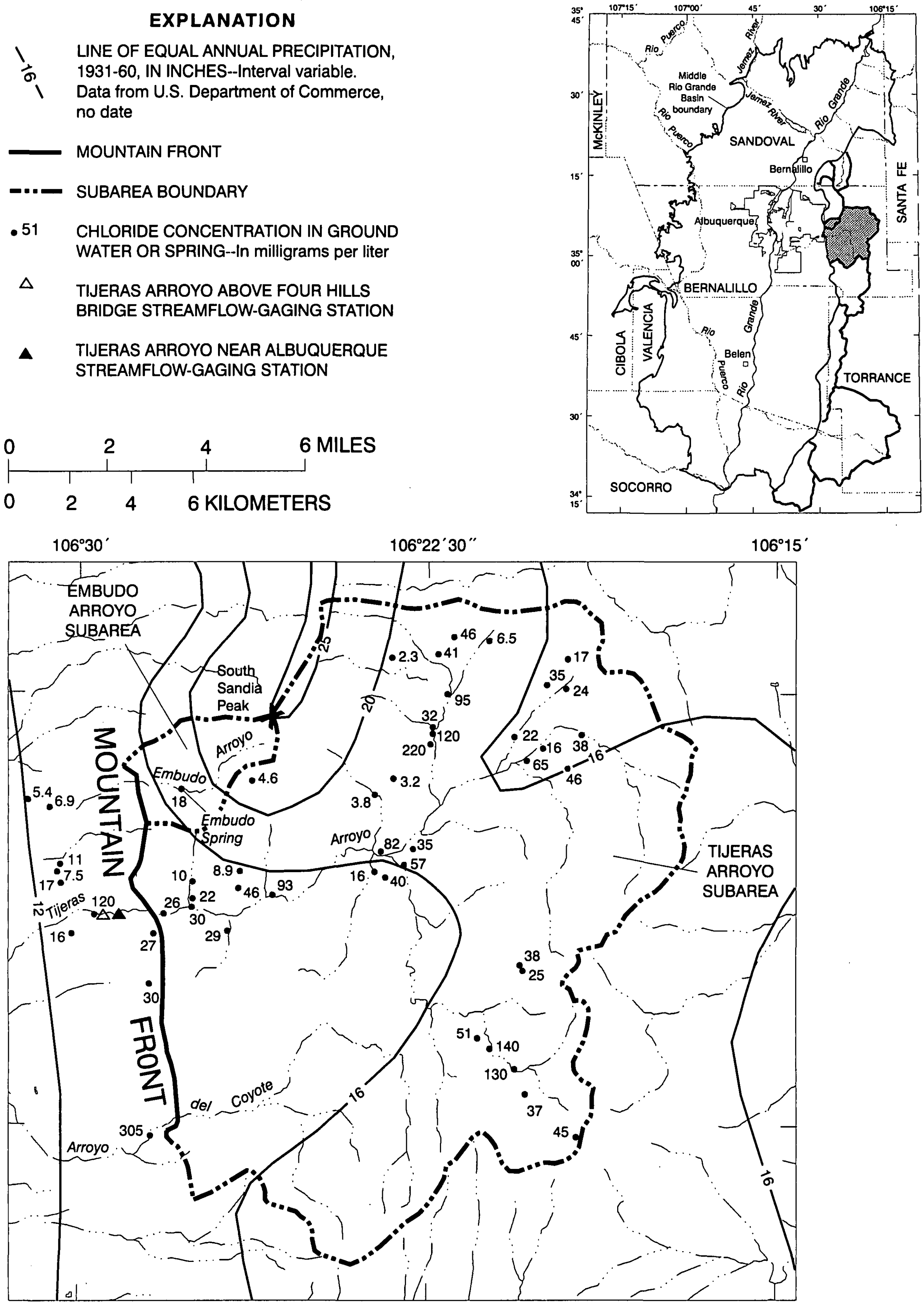

Figure 12. Tijeras Arroyo subarea and Embudo Arroyo subarea.

Annual precipitation ranges from less than 16 to greater than 25 inches (fig. 12). Average annual precipitation for the entire watershed is 16.8 inches (table 1). Many springs are located throughout the subarea. The perennial flow in the lower reaches of Tijeras Arroyo probably results from large springs that discharge to the stream channel and from ground-water discharge to the channel. Two streamflow-gaging stations have been operated at different times on Tijeras Arroyo near the mountain front (fig. 12).

Data collected at the two gaging stations on Tijeras Arroyo are useful for determining how streamflow varies throughout the year at the mountain front. Data were collected from April 1943 through June 1949 at a site near the mountain front, Tijeras Arroyo near Albuquerque (fig. 13), and from May 1989 to September 1991 at a site about 1,500 feet downstream from the earlier site, Tijeras Arroyo above Four Hills Bridge at Albuquerque (fig. 14). Because examination of the data indicates no increase in flow from March through June, snowmelt probably does not result in increases in streamflow at the mountain front. Based on data collected in the 1940's, streamflow decreases from February or March to July, which probably indicates increases in evapotranspiration along the channel, resulting in less streamflow at the mountain front. Data for both time periods indicate large and rapid increases in streamflow resulting from runoff from summer thunderstorms. The data collected in the 1940's indicate that summer thunderstorms also resulted in sustained increases in streamflow during some summers. These sustained increases in streamflow at the mountain front probably indicate that summer precipitation infiltrated into the aquifers in the watershed and slowly discharged to the stream during the summer.

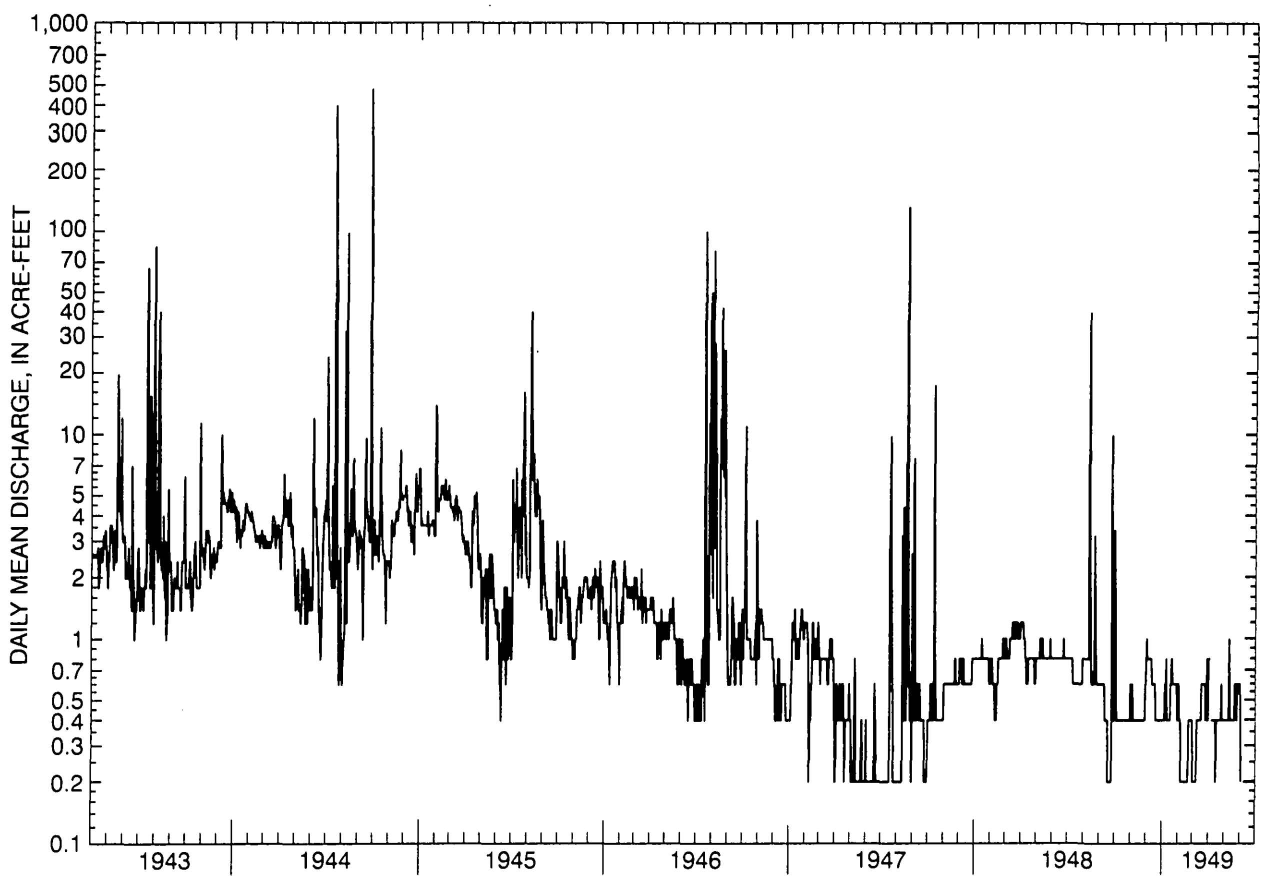

Figure 13. Daily mean discharge for Tijeras Arroyo near Albuquerque, April 1943 through June 1949 (discharge less than 0.2 acre-foot represents no flow).

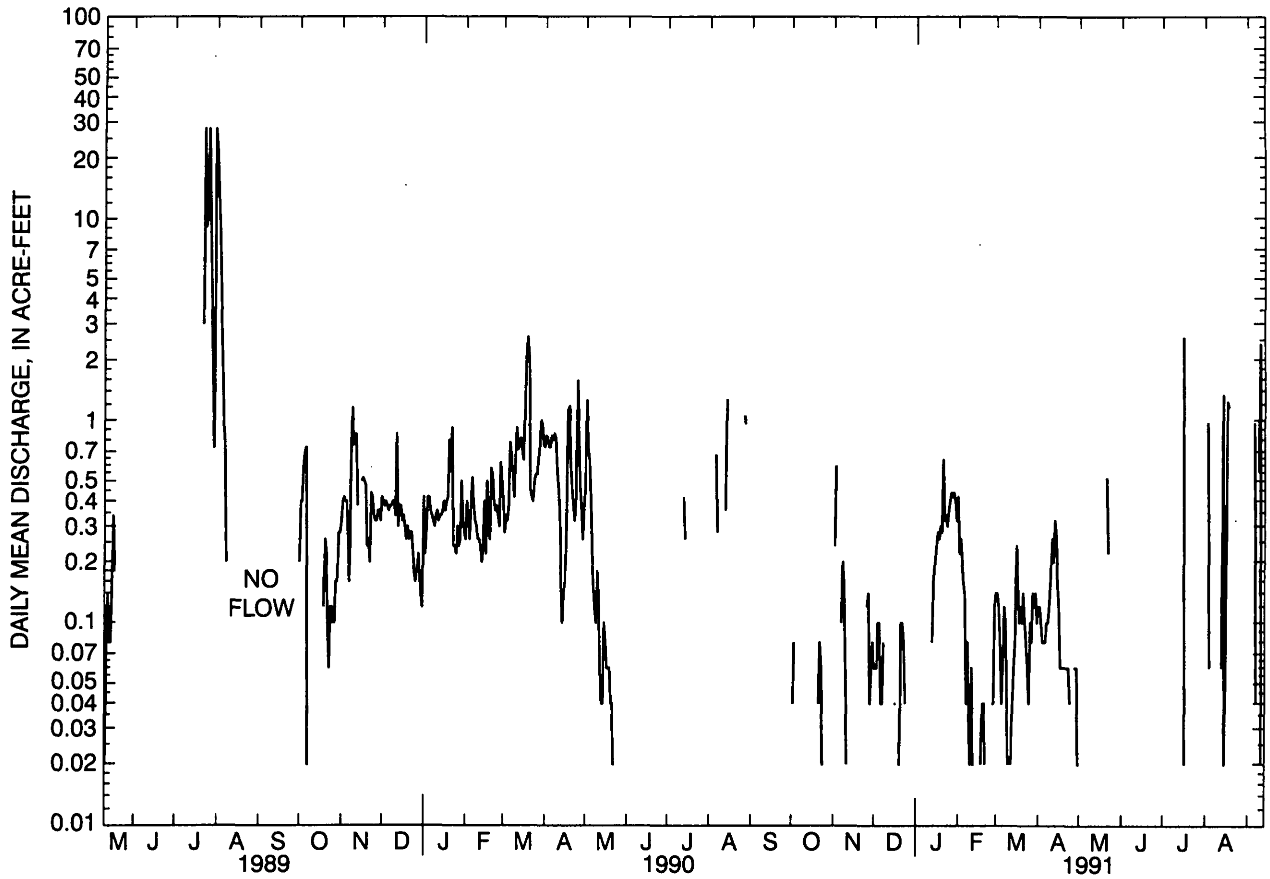

Figure 14. Daily mean discharge for Tijeras Arroyo above Four Hills Bridge at Albuquerque, May 1989 through September 1991 (discharge less than 0.02 acre-foot and missing parts of the record represent no flow).

Streamflow in Tijeras Arroyo was much larger in the 1940's than from 1989 to 1991 (figs. 13 and 14), and the difference probably is not due to infiltration of streamflow between the two gaging stations. Daily mean discharge from October to March ranged from about 0.4 to 5 acre-feet in the 1940's at the upstream sampling site and from about 0.04 to 0.4 acre-foot from 1989 to 1991 at the downstream sampling site (figs. 13 and 14). Streamflow at the upstream gaging station was not perennial in 1989-91 (Carol Thomas, U.S. Geological Survey, oral commun., 1998), but was perennial during the 1940's (fig. 13). By assuming a daily infiltration rate of 5 feet per day (Thomas, 1995), a stream-channel width of 5 feet, and a distance of 1,500 feet between the sites, the infiltration between the two gaging stations would be about 0.86 acre-foot per day or about 300 acre-feet per year, which is less than the difference in flow at the two stations. From 1943 to 1946 daily mean discharge at the upstream station generally was greater than 0.86 acre-foot (fig. 13), indicating flow at the downstream station most of this time. From 1947 to 1949 daily mean discharge was generally less than 0.86 acre-foot, indicating infiltration of much of the streamflow and little or no flow at the downstream station. Precipitation in Albuquerque in 1947 and 1948 was smaller than normal (fig. 4), possibly resulting in less streamflow in Tijeras Arroyo. During 1989-91 the downstream station had many days of no flow (fig. 14), indicating possible decreases in flow in Tijeras Arroyo between the 1940's and 1989-91. The smaller flow in Tijeras Arroyo during 1989-91 relative to flow in the early to mid-1940's could be due to climatic conditions (variations in precipitation) or development in the watershed.

Comparison of seasonal precipitation in Albuquerque and seasonal streamflow in Tijeras Arroyo indicates that seasonal streamflow generally increases with seasonal precipitation during the 1940's, but has no clear relation during 1989-91 (fig. 15). Precipitation and streamflow for June through September and October through May were summed and plotted to evaluate the relation between precipitation and streamflow. For a given amount of precipitation, the streamflow during the 1940's is generally much greater than streamflow during 1989-91 (fig. 15). Summer precipitation in Albuquerque generally was larger during 1990 and 1991 than during the 1940's; however, streamflow during the summers of 1990 and 1991 was generally much less than predicted from the relation between precipitation and streamflow using data collected during the 1940's (fig. 15). Based on the calculated infiltration rate between the two gaging stations and the relation between seasonal precipitation and seasonal streamflow, development in the Tijeras Arroyo watershed has probably resulted in decreases in streamflow at the mountain front.

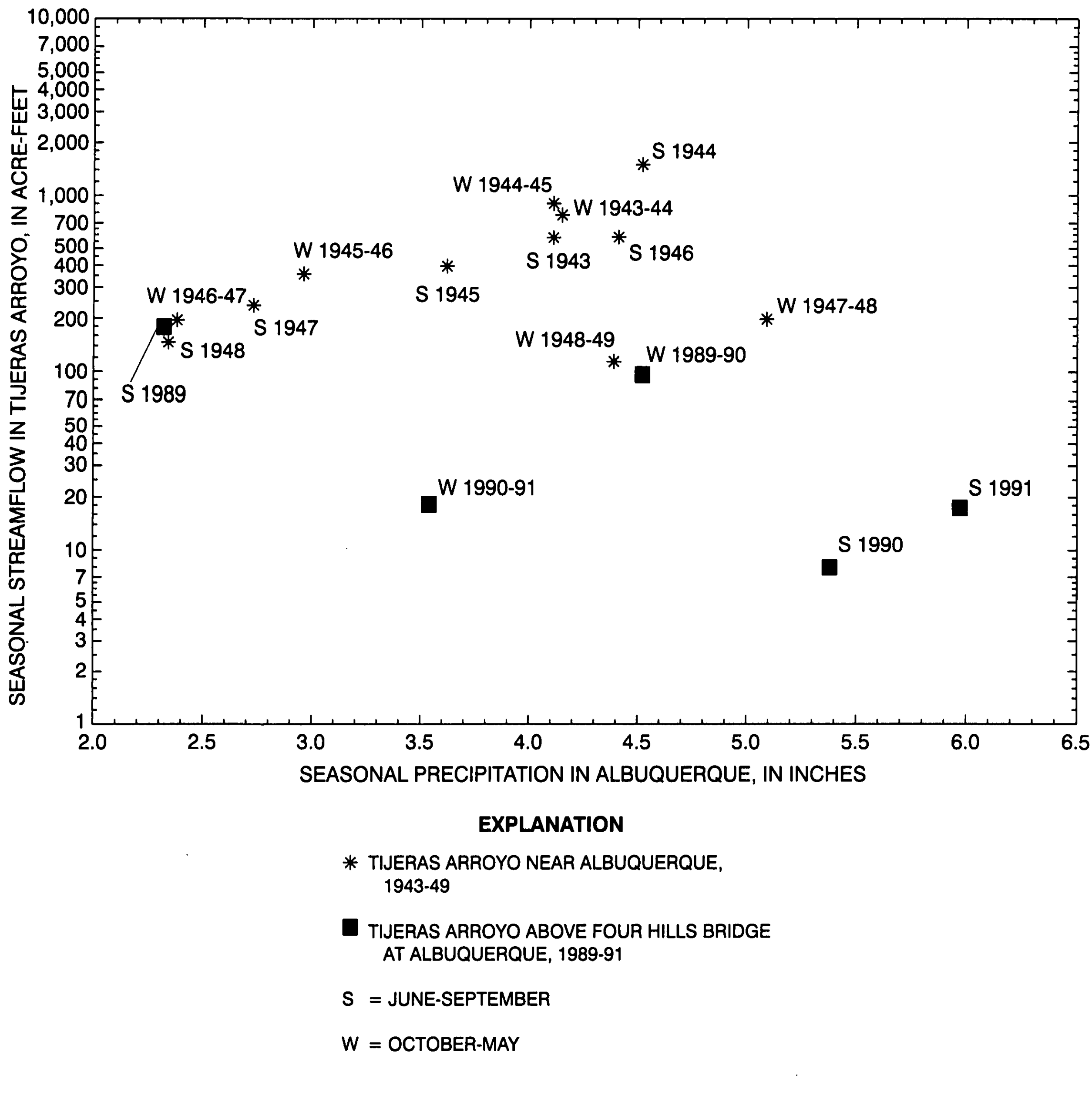

Figure 15. Relation between seasonal precipitation in Albuquerque and seasonal streamflow in Tijeras Arroyo.

Chloride concentrations in ground water in the subarea and ground water west of the mountain front have large variations (fig. 12). Chloride concentrations range from 2.3 to 220 mg/L in ground water in the Tijeras Arroyo subarea. The smallest chloride concentrations generally are in samples from the headwater areas of the Tijeras Arroyo watershed. Differences in ground-water chloride concentrations in aquifers in the mountainous area are relatively large in short lateral distances, indicating possible sources of chloride in the subarea. Chloride concentrations in ground water along Tijeras Arroyo 1 mile or less upstream from the mountain front range from about 10 to 30 mg/L. Chloride concentrations in the basin-fill deposits downstream from the Tijeras Arroyo subarea mountain front range from 7.5 to 305 mg/L, excluding concentrations west of Embudo Arroyo. The chloride concentration in mountain-front recharge presently (1999) is probably greater than that in mountain-front recharge prior to the extensive development in the Tijeras Arroyo watershed. A chloride concentration of 15 mg/L was used to estimate mountain-front recharge (table 2).

The recharge estimates for the Tijeras Arroyo subarea range from 1,790 to 7,960 acre-feet per year (table 2). The estimate derived using the chloride-balance method is the smallest and that derived using the equation developed by Hearne and Dewey (1988) is the largest.

The estimates of streamflow at the mountain front calculated using the water-yield regression method are considerably larger than streamflow measured at the gaging stations. Annual streamflow in the 1940's ranged from 319 to 2,320 acre-feet at the gaging station Tijeras Arroyo near Albuquerque (U.S Geological Survey, 1960, p. 457-458) and in 1990 was about 80 acre-feet (Borland and others, 1992). The estimates of streamflow at the mountain front for the Tijeras Arroyo subarea, which includes the Tijeras Arroyo drainage and the Arroyo del Coyote drainage (about one-fifth of the subarea), were 6,420 and 7,960 acre-feet per year. Based on streamflow measurements at the mountain front, streamflow estimates for Tijeras Arroyo at the mountain front derived using the water-yield regression method are overestimated; therefore, the recharge estimates derived using the water-yield regression method probably are overestimates of mountain-front recharge.

Embudo Arroyo Subarea

The Embudo Arroyo subarea (fig. 12) includes about 3,000 acres (about 5 square miles) (table 1). The subarea consists of the Embudo Arroyo watershed. South Sandia Peak (about 9,800 feet) is the highest point in the watershed. About one-half the watershed is greater than 7,500 feet above sea level. This subarea was delineated to allow recharge estimates for a single, small watershed that has headwaters at a high altitude, is underlain by Precambrian crystalline bedrock (fig. 6), and has no development.

Precipitation ranges from about 16 to 25 inches (fig. 12). Average annual precipitation in the entire subarea is 19.1 inches (table 1). Embudo Spring, which is near the mountain front, flows most of the year. Streamflow in Embudo Arroyo at the mountain front increases in the spring from snowmelt.

Chloride concentrations have been determined in several samples collected from Embudo Spring, which is in the channel of Embudo Arroyo near the mountain front. These chloride concentrations in water from Embudo Spring and in ground water downstream from the mountain front probably represent the chloride concentration in mountain-front recharge. Chloride concentrations in three water samples from Embudo Spring ranged from 11.1 to 22.0 mg/L (table 3) and in water from two wells in the basin-fill deposits downstream from the mountain front were 5.4 and 6.9 mg/L (fig. 12). The chloride concentration in mountain-front recharge from the Embudo Arroyo subarea was assumed to be 10 mg/L (table 2).

Table 3. Chloride concentrations in water from Embudo Spring

[(1) Data from Caprio, 1960; (2) data from Bjorklund and Maxwell, 1961]

Date	Chloride concentration, in milligrams per liter
May 1936	11.1 (1)
November 1955	22.0 (1)
May 1956	18.0 (2)

Recharge estimates range from 130 to 720 acre-feet per year (table 2). The estimate derived using the equation developed by Waltemeyer (1994) is the smallest and may not be valid because the area of Embudo Arroyo (4.6 square miles, table 1) is smaller than the watershed areas for which the equation was developed (20.7 to 184 square miles).

Sandia Mountains Subarea

The Sandia Mountains subarea includes about 17,600 acres (about 27 square miles) (table 1). Sandia Crest (about 10,700 feet) is the highest point in the subarea. The subarea consists of many small watersheds that have similar characteristics (fig. 16). About two-thirds of the subarea is less than 7,500 feet above sea level. Precambrian crystalline rocks are the dominant rock type (fig. 6). The subarea has no development.

Precipitation ranges from less than 16 to more than 30 inches in the subarea (fig. 16). Average annual precipitation for the entire subarea is 20.1 inches (table 1). Near the mountain front, many drainages have springs in the channels. Streamflow at the mountain front increases during the spring from snowmelt.

Chloride concentrations in water from wells completed in the basin-fill deposits near the mountain front range from 5.1 to 15.0 mg/L (fig. 16). The chloride concentration in mountain-front recharge was assumed to be 6 mg/L for the calculation of mountain-front recharge (table 2).

The recharge estimates range from 1,470 to 4,260 acre-feet per year for the Sandia Mountains subarea (table 2). The estimates derived using the chloride-balance method and the equation developed by Waltemeyer (1994) are similar. The estimate derived using the equation developed by Hearne and Dewey (1988) is about two and one-half times larger than the other estimates.

North Sandia Mountains Subarea

The North Sandia Mountains subarea comprises about 6,200 acres (about 10 square miles) (table 1). Sandia Crest (about 10,700 feet) is the highest point in the subarea. About two-thirds of the subarea is less than 7,500 feet. The subarea contains several small watersheds (fig. 16). Precambrian crystalline rocks are the dominant rock type (fig. 6). The subarea has no development.

Annual precipitation ranges from less than 16 to more than 25 inches (fig. 16). Average annual precipitation for the entire subarea is 18.1 inches (table 1).

No data are available pertaining to chloride concentrations in ground water within or adjacent to the area. A chloride concentration of 6 mg/L was assumed for the calculation of mountain-front recharge (table 2) because of the similarity of this subarea to the Sandia Mountains subarea.

Recharge estimates for the North Sandia Mountains subarea range from 310 to 860 acre-feet per year (table 2). The recharge estimated by the equation developed by Waltemeyer (1994) is the smallest. This equation probably does not apply to this subarea because its area is less than the minimum area used to calibrate the equation. The estimate of recharge using the equation developed by Hearne and Dewey (1988) is about twice as large that derived using the chloride-balance method.

Las Huertas Creek Subarea

The Las Huertas Creek subarea comprises about 14,000 acres (about 22 square miles) (table 1). Sandia Crest is the highest point in the subarea. About one-half the area is less than 7,500 feet. The subarea contains several watersheds, the largest of which is Las Huertas Creek (fig. 16). Paleozoic sedimentary rocks are the dominant rock type in the subarea (fig. 6). There is some residential development along Las Huertas Creek near the mountain front; most of the area, however, has no development.

Annual precipitation ranges from about 16 to greater than 30 inches (fig. 16). Average annual precipitation for the entire watershed is 21.2 inches (table 1). Las Huertas Creek is perennial in several reaches in the drainage and there are springs in the upper parts of the Las Huertas watershed. The perennial flow and springs indicate discharge of ground water from the Paleozoic rocks to Las Huertas Creek.

Chloride concentrations in ground water range from 1.4 to 4.3 mg/L in the subarea (fig. 16) and generally increase as altitude decreases. Ground water north of the mountain front has a chloride concentration of 2.3 mg/L. A chloride concentration of 3.5 mg/L was used for the calculation of mountain-front recharge (table 2).

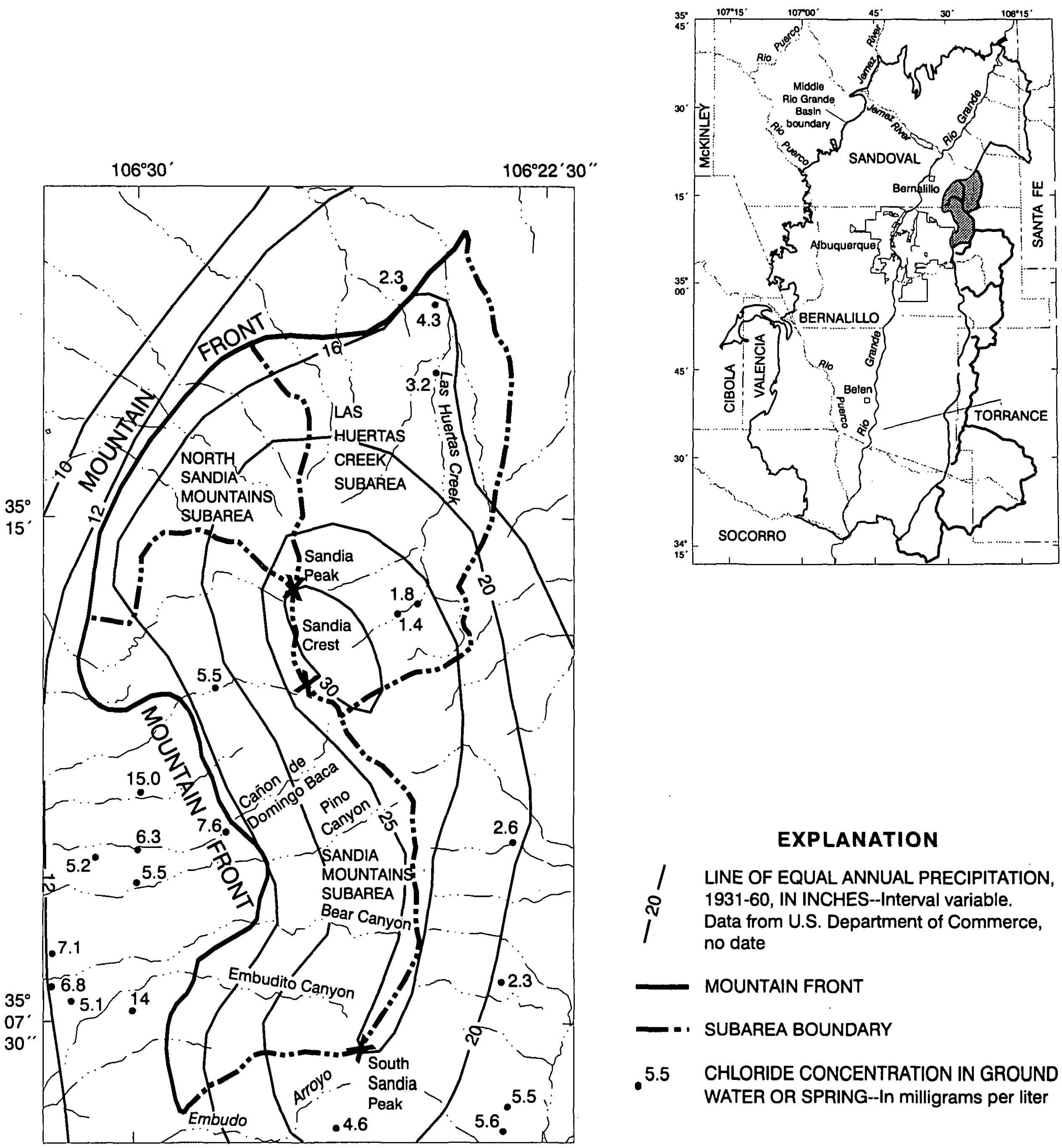

Figure 16. Sandia Mountains subarea, North Sandia Mountains subarea, and Las Huertas Creek subarea.

Recharge estimates for the Las Huertas Creek subarea range from 1,210 to 3,010 acre-feet per year (table 2). The recharge estimate derived using the equation developed by Waltemeyer (1994) is the smallest. Recharge estimates for this subarea are in better agreement than those for any of the other subareas.

Evaluation of Recharge Estimates

Total recharge along the eastern side of the Middle Rio Grande Basin ranges from about 11,000 to 38,000 acre-feet per year, depending on the method used (table 2). The estimate derived using the chloride-balance method is the smallest, and the estimates derived using the water-yield regression method are similar.

There generally is a large range in recharge estimates and in the percentage of annual precipitation resulting in mountain-front recharge in a particular subarea using the different methods (fig. 17 and table 4). Recharge estimates for the Embudo Arroyo, North Sandia Mountains, and Las Huertas Creek subareas are in closest agreement (fig. 17); however, this comparison is deceptive because these are some of the smaller estimates. The percentage of annual precipitation for the entire subarea that results in mountain-front recharge (percent recharge, eq. 4) is a normalized value that can be used to compare the different recharge estimates for the subareas.

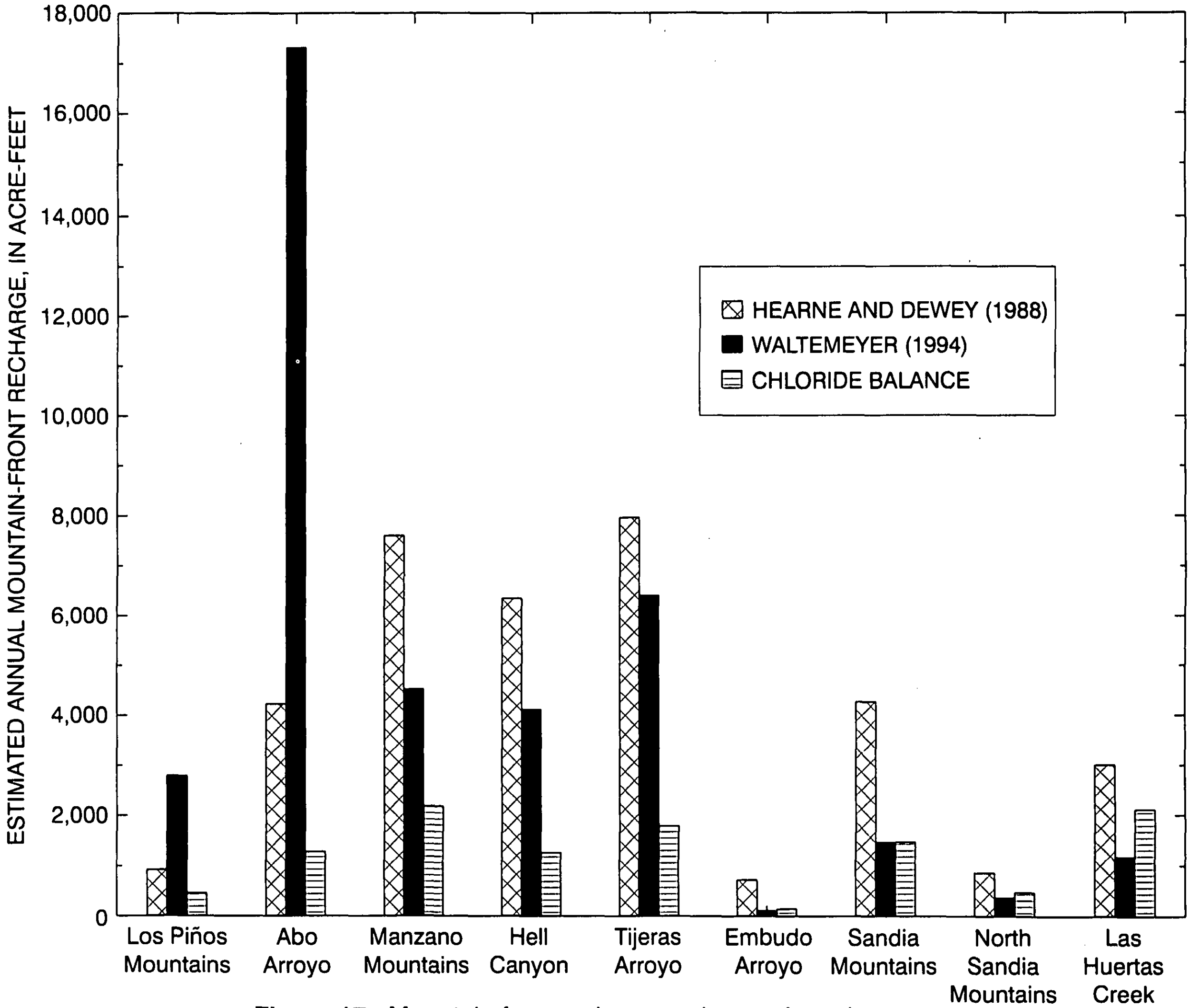

Figure 17. Mountain-front recharge estimates for subareas.

Table 4. Percentage of annual precipitation resulting in mountain-front recharge

Subarea (fig. 6)	Hearne and Dewey (1988)	Waltemeyer (1994)	Chloride-balance method
Los Pinos Mountains	1.8	5.6	0.9
Abo Arroyo	2.2	[1]9.0	0.7
Manzano Mountains	12	6.8	3.3
Hell Canyon	10	6.5	2.0
Tijeras Arroyo	8.9	7.2	2.0
Embudo Arroyo	15	[1]2.7	3.0
Sandia Mountains	15	5.2	5.0
North Sandia Mountains	9.2	[1]3.3	5.0
Las Huertas Creek	12	4.9	8.6

[1]Estimate could be in error because size of subarea is outside the range for which equation was developed (Waltemeyer, 1994)

$$\text{Percent recharge} = \frac{\text{Annual recharge (table 2)}}{\text{Total annual precipitation (table 1)}} \times 100 \qquad (4)$$

Percent recharge can be considered a measure of basin yield. The difference between 100 percent and percent recharge is the percentage of annual precipitation that is evaporated or evapotranspired from the subarea assuming no change in ground-water storage in the subarea.

The range in percent recharge is smallest for the estimates derived using the equation developed by Waltemeyer (1994) (2.7 to 9.0 percent) (table 4). The range is even smaller (4.9 to 7.2 percent) if the subareas that were outside the range of calibration of the equation (Abo Arroyo, Embudo Arroyo, and North Sandia Mountains subareas) are not taken into account. The equation developed by Waltemeyer (1994) may underestimate recharge in subareas where winter precipitation (snowfall) is a large percentage of annual precipitation because his equation was calibrated with data for watersheds in southern New Mexico, where rainfall is the dominant form of precipitation.

The percent recharge ranges from 1.8 to 15 percent for the equation developed by Hearne and Dewey (1988) (table 4). Mountain-front recharge could be underestimated in watersheds in the southern part of the area because winter precipitation is a small percentage of annual precipitation (table 1) and the equation developed by Hearne and Dewey was calibrated with data for watersheds where snowfall is the dominant form of precipitation. The smallest percent-recharge values were for the Los Pinos Mountains and Abo Arroyo subareas. Average winter precipitation is a smaller percentage of annual precipitation in these subareas than in the other subareas, and average winter precipitation also is small in these subareas because of their low altitude and southern location. Measured streamflow in Abo Arroyo near the mountain front did not increase substantially in the spring, indicating little effect from snowmelt or winter precipitation at the mountain front. The largest percent-recharge values were for the subareas with the larger average winter precipitation relative to annual precipitation—generally those at higher altitudes.

The percent-recharge values range from 0.7 to 8.6 percent for the chloride-balance method (table 4). The smallest values are in the Abo Arroyo and Los Pinos Mountains subareas where winter precipitation is a small percentage of annual precipitation (about 35 percent); the largest is in the Las Huertas Creek subarea where winter precipitation is about 42 percent of annual precipitation. The small values in the Abo Arroyo and Los Pinos Mountains subareas indicate that a large amount of annual precipitation evaporates or transpires from these subareas, which generally are lower in altitude than the other subareas. The small value in the Abo Arroyo subarea also could be due to the large size of the drainage, which results in longer travel times for water to move through the watershed and, thereby, more time for evapotranspiration to occur. The large value for the Las Huertas Creek subarea could mean that precipitation quickly infiltrates into the Paleozoic aquifer in the subarea and that there is little evaporation or transpiration from the aquifer or along Las Huertas Creek compared with the other subareas.

The estimates derived using the water-yield regression method were expected to be smaller than those derived using the chloride-balance method because the chloride-balance method estimates total mountain-front recharge, whereas the water-yield regression method estimates only the mountain-stream-channel recharge component of mountain-front recharge. However, estimates derived using the chloride-balance method generally are smaller than those derived using the water-yield regression method. Because evapotranspiration was assumed to be negligible, estimates of recharge derived using the water-yield regression method could be high if evapotranspiration of summer thunderstorm runoff that infiltrates into the basin-fill deposits along stream channels downstream from the mountain front is large. Evapotranspiration was assumed to be negligible on the basis of data collected by Thomas (1995) along Tijeras Arroyo where streamflow was present for prolonged periods near the mountain front. Streamflow data for Abo Arroyo and Tijeras Arroyo indicate that runoff from intense summer thunderstorms can be a large part of total streamflow at the mountain front. This runoff occurs for a short period of time, usually 1 day or less, and the flow sometimes extends from the mountain front to the Rio Grande. In this scenario the amount of evapotranspired water that infiltrates into the channel bed could be substantial because of the lack of continuous streamflow (recharge) and the large channel areas where evapotranspiration could occur for many days between flow events. Conversely, the mountain-front recharge estimates derived using the chloride-balance method are underestimates if the assumed chloride concentration in precipitation is too small, the estimated chloride concentration in mountain-front recharge is too large, or there is a source of chloride in the subareas.

Part of the runoff from intense summer thunderstorms from watersheds that have stream channels extending to the Rio Grande (Abo Arroyo, Hell Canyon Wash, Tijeras Arroyo, and Las Huertas Creek) discharges to the Rio Grande, based on estimates of infiltration along the channels. The well-defined channels that extend from the mountain front to the Rio Grande also indicate that these drainages discharge to the Rio Grande. Runoff from mountainous watersheds discharging to the Rio Grande would cause estimates derived using both the chloride-balance and the water-yield regression methods to be high by the same relative amount if the chloride concentration in mountain-front recharge is assumed to be the same as that in water discharging to the river.

The estimates derived using the equation developed by Waltemeyer (1994) might not be valid in the Abo Arroyo, Embudo Arroyo, and North Sandia Mountains subareas because the drainage areas of these subareas are outside the range of drainage areas used to develop the equation. The effect of drainage areas of different sizes can be seen in the recharge estimates. The drainage area of Abo Arroyo is larger than the range of drainage areas Waltemeyer used to calibrate his equation, and the recharge estimate derived using Waltemeyer's equation was significantly larger than the other recharge estimates (fig. 17). The opposite is true for the Embudo Arroyo and North Sandia Mountains subareas.

The equations of Hearne and Dewey (1988) and Waltemeyer (1994) were developed to estimate streamflow at the mountain front for a single drainage area, so applying these equations to subareas with several drainage areas could affect the estimates. In the Los Pinos Mountains, Manzano Mountains, Sandia Mountains, and North Sandia Mountains subareas, these equations were applied to an area containing several or many drainage basins. This probably would not affect the estimates made using the equation developed by Hearne and Dewey because drainage area is essentially taken to the first power ($A^{0.977}$ in eq. 2).

However, the effect on the estimate made using the equation developed by Waltemeyer (1994) could be significant because drainage area is taken to the 1.35 power. For example, consider a drainage area consisting of three watersheds, A_1, A_2, and A_3. Assuming average annual precipitation (Pa) is relatively uniform over the watersheds:

$$A_1^{1.35}Pa^{1.65} + A_2^{1.35}Pa^{1.65} + A_3^{1.35}Pa^{1.65} < (A_1 + A_2 + A_3)^{1.35}Pa^{1.65} \qquad (5)$$

Thus, applying the equation developed by Waltemeyer to an area containing several watersheds could result in high estimates of recharge.

With existing information, determining which mountain-front recharge estimate is most accurate and the reason for discrepancies among the different estimates is not possible. More information about recharge and ground-water movement in the mountainous watersheds, the amount and chemistry of streamflow at the mountain front, infiltration rates and evapotranspiration rates of runoff from intense summer thunderstorms, and the amount of subsurface-inflow recharge would be useful for refining the mountain-front recharge estimates and understanding mountain-front recharge in the arid Southwest.

SUMMARY

Mountain-front recharge, which generally occurs along the margins of alluvial basins, can be a large part of total recharge to the aquifer system in such basins. The mountain front is the interface between the relatively impermeable bedrock in the mountainous areas and the generally more permeable basin-fill deposits in the alluvial basin. Mountain-front recharge occurs as the result of infiltration of flow from streams that have headwaters in the mountainous areas adjacent to alluvial basins and subsurface ground-water flow from the aquifers in the mountainous areas to the aquifer in the alluvial basin.

This report presents estimates of mountain-front recharge to the basin-fill aquifer along the eastern side of the Middle Rio Grande Basin in central New Mexico. The basin contains a large thickness of basin-fill deposits, which compose the main aquifer in the basin. The basin is bounded along the eastern side by mountains composed of crystalline rocks of Precambrian age and sedimentary rocks of Paleozoic age. Precipitation is much larger in the mountains than in the basin. Many stream channels debouch from the mountainous area to the basin.

Chloride-balance and water-yield regression methods were used to estimate mountain-front recharge. The chloride-balance method was used to calculate a chloride mass balance on watersheds in the mountainous areas along the eastern side of the Middle Rio Grande Basin. The source of chloride to these watersheds is bulk precipitation. Chloride leaves these watersheds as mountain-front recharge. The water-yield regression method was used to determine the volume of streamflow from the mountainous watersheds at the mountain front. This streamflow is then assumed to infiltrate and result in mountain-front recharge. A water-yield regression equation developed for gaged watersheds in southern Colorado and northern New Mexico and a water-yield regression equation developed for gaged watersheds in southern New Mexico were used to estimate streamflow at the mountain front. These equations use watershed area and average annual winter precipitation or average annual precipitation to estimate streamflow. The equation developed for gaged watersheds in southern Colorado and northern New Mexico is probably more appropriate for higher altitude watersheds within the Middle Rio Grande Basin where much of the annual streamflow is due to snowmelt. The equation developed for gaged watersheds in southern New Mexico is probably more appropriate for the southern part of the Middle Rio Grande Basin where rainfall is the dominant form of precipitation.

The mountainous area along the eastern side of the Middle Rio Grande Basin was divided into nine subareas, and mountain-front recharge to the basin was estimated for each subarea. Some of the subareas contain only one drainage and other subareas contain many drainages that have similar characteristics. The different subareas have a wide range in area, annual precipitation, and geology.

Total mountain-front recharge along the eastern side of the basin was estimated to be about 11,000 acre-feet per year using the chloride-balance method and about 36,000 and 38,000 acre-feet per year using two different water-yield regression equations. Mountain-front recharge ranged from 0.7 to 15 percent of total annual precipitation in the subareas (percent recharge). Some of the smallest values of percent recharge were for the subareas in the southern part of the basin, which generally have low altitudes. The larger percent-

recharge values were for subareas with higher altitudes where winter precipitation is a larger percentage of annual precipitation.

Some of the large variation in recharge estimates for a subarea could be due to violation of several of the assumptions necessary to apply the different methods used to estimate mountain-front recharge. The estimates made using the equation developed for southern Colorado and northern New Mexico for the Los Pinos Mountains and Abo Arroyo subareas could be biased low because winter precipitation is a small percentage of annual precipitation in the Los Pinos Mountains subarea and winter precipitation has little effect on streamflow in Abo Arroyo at the mountain front. Sources of chloride other than precipitation in any of the subareas would cause the estimates made using the chloride-balance method to be low. Evapotranspiration of streamflow that infiltrates into the basin-fill deposits in the Middle Rio Grande Basin would cause the estimates made using the water-yield regression method to be high. The area of three of the subareas was outside the range of areas used to calibrate one of the water-yield regression equations, making mountain-front recharge estimates in these subareas questionable.

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