GROUND-WATER RECHARGE NEAR SANTA FE, NORTH-CENTRAL NEW MEXICO

by Scott K. Anderholm

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CONTENTS

PLATES

[Plates are in back pocket]

FIGURES

TABLES

TABLES--Concluded

CONVERSION FACTORS AND VERTICAL DATUM

Multiply	By	To obtain
inch (per year)	25.4	millimeter (per year)
foot	0.3048	meter
mile	1.609	kilometer
square inch	0.0006452	square meter
square mile	2.590	square kilometer
cubic foot per second	0.02832	cubic meter per second
gallon	3.785	liter
acre-foot (per year)	0.001233	cubic hectometer (per year)
pound	453.6	gram

Temperature in degrees Fahrenheit (°F) or degrees Celsius (°C) can be converted by the equations:

$$°F = 9/5\ (°C) + 32$$

$$°C = 5/9\ (°F - 32)$$

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.

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ABSTRACT

Sources of recharge to the basin-fill aquifer near Santa Fe, New Mexico, and the relative amounts of recharge to evapotranspiration were estimated on the basis of chloride mass balances and stable isotope compositions. The results of the chloride-balance determinations in the unsaturated zone indicate that no recharge has occurred in the recent past at sites that have neither runoff nor flooding. Recharge does occur in arroyo channels, and chloride concentrations of the recharge water at two such sites ranged from 40 to 60 milligrams per liter. The amount of direct recharge in the Santa Fe area is difficult to estimate because no recharge occurs over large areas. On the basis of chloride concentrations in ground water, arroyo-channel recharge is not a major source of recharge.

Chloride concentration in ground water in the basin-fill aquifer near Santa Fe varies substantially. In several areas, the chloride concentration in ground water is less than 5 milligrams per liter. Larger chloride concentrations in ground water upgradient from the smaller chloride concentrations indicate a change in either the source of recharge water or a change in the chloride concentration in recharge water. Possible changes in the sources of recharge would be the infiltration of septic tank effluent or infiltration of irrigation water, as opposed to infiltration of streamflow alone before these effects of development. In the Buckman area, which is in part of the discharge area for the flow system, chloride concentrations generally are less than 5 milligrams per liter. The small chloride concentrations in this area indicate that arroyo-channel recharge does not significantly affect chloride concentration in ground water. If arroyo-channel recharge were a significant source of recharge, chloride concentration in the Buckman area would be expected to be larger than that measured. Estimates of natural mountain-front recharge, using the chloride-balance method and the assumption of runoff out of the recharge area, are approximately 2,320 acre-feet per year in the Santa Fe River drainage, 690 acre-feet per year in the Rio Tesuque drainage, and 830 acre-feet per year in the Arroyo Hondo drainage.

Stable isotopes of hydrogen and oxygen were used to investigate sources of recharge to the basin-fill aquifer. The relation between stable isotopes of hydrogen (D) and oxygen (^{18}O), referred to as the local meteoric water line ($\delta D=8.0\delta^{18}O+11.1$), was determined from precipitation data collected in the study area. Ground water generally plotted along this meteoric water line, indicating little evaporation of recharge waters. Winter precipitation was isotopically more negative than summer precipitation. The hydrogen and oxygen isotopic composition of ground water was more negative than the annual mean volume-weighted isotopic composition of precipitation, indicating winter precipitation as the source of most of the recharge water. The isotopic composition of ground water in the Buckman area was generally more negative than that in ground water in other parts of the study area. This recharge to the aquifer probably occurred during a time when mean annual temperatures were less than at present.

INTRODUCTION

Because of the increase in population and the subsequent increase in water use in the Santa Fe, New Mexico, area planners and managers have expressed interest in a more detailed understanding of the ground-water system. By knowing the source areas and distribution and quantity of recharge, water managers can improve protection of these areas from potential contamination and also can estimate more accurately recharge and water availability for planning purposes. Identification of sources and volumes of recharge to a particular aquifer is important to the understanding of the ground-water system. The application of a computer model to simulate ground-water flow requires knowledge of the locations and volumes of recharge to the ground-water system. Most recharge studies in New Mexico are based on rainfall-runoff relations. Techniques using chemical properties of precipitation, surface water, and ground water were used to investigate recharge in this study, which was conducted in cooperation with the Santa Fe Metropolitan Water Board and the New Mexico State Engineer Office.

Purpose and Scope

This report describes sources of recharge to the basin-fill aquifer in the vicinity of Santa Fe, New Mexico (fig. 1) and provides estimates of the amount of recharge to the basin-fill aquifer. The approach was to use chemical properties of various sources of recharge and chemical properties of ground water in areas of recharge to investigate sources and amounts of recharge. This approach is based on the premise that various sources of recharge water have unique chemical properties that can be used to examine the amount of recharge and the movement of ground water from recharge areas to discharge areas. With the exception of some of the chloride and nitrate concentrations in ground-water samples, the data used in this study were collected during the study.

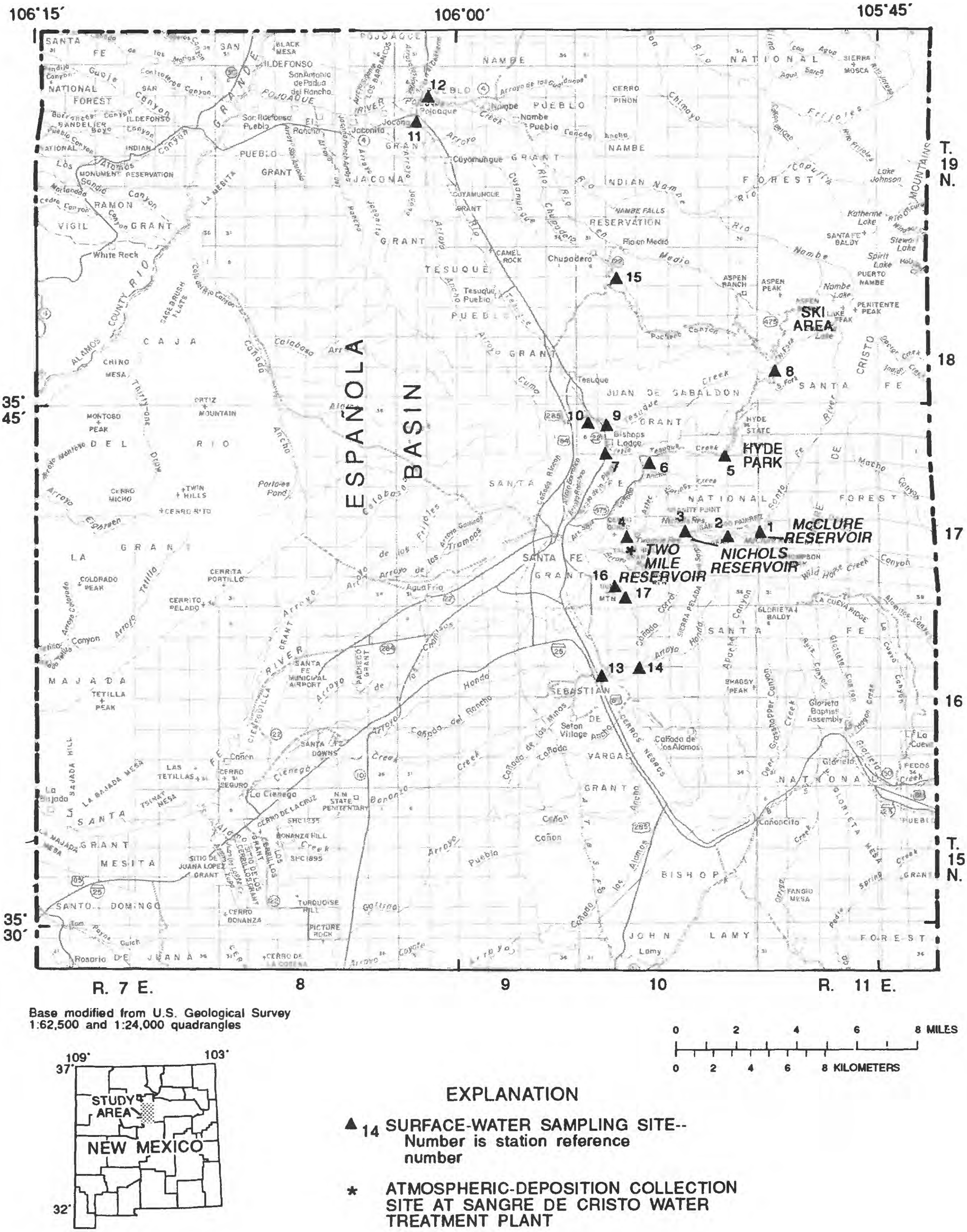


Figure 1.--Location of the study area and surface-water sampling sites.

Description of the Study Area

The study area is within Santa Fe County and extends from the Sangre de Cristo Mountains west to the Rio Grande and from the Pojoaque River south to La Cienega (fig. 1). The study area includes parts of the Sangre de Cristo Mountains and the Española Basin. The Sangre de Cristo Mountains, which are composed of rocks of Precambrian and Paleozoic age, rise to altitudes of more than 12,000 feet and bound the eastern side of the Española Basin. The surface of the Tertiary basin-fill material of the Española Basin slopes westward from the base of the mountains toward the Rio Grande. Several streams and arroyos drain the dissected surface of the basin-fill deposits. The streams are perennial in the mountains to or near the base of the mountains and ephemeral through most of the Española Basin. Arroyos flow only in response to intense summer thunderstorms.

The aquifer of interest in this study is the Tesuque aquifer system in the Española Basin, which includes the Tesuque and Ancha Formations of Tertiary age. The Tesuque Formation consists of several thousand feet of pinkish-tan, arkosic, silty sandstone and minor conglomerate and siltstone (Spiegel and Baldwin, 1963, p. 39). The Ancha Formation, which overlies the Tesuque Formation, is unsaturated in most of the study area. It consists of gravel, sand, and silt (Spiegel and Baldwin, 1963, p. 45).

Most recharge to the Tesuque aquifer system occurs at the eastern edge (fig. 2) of the aquifer system along the mountain front (area where the Tesuque aquifer system is in contact with older rocks of the mountains). Arroyo Hondo, Arroyo de los Chamisos, Santa Fe River, Little Tesuque Creek, Tesuque Creek, Rio Tesuque, Rio Chupadero, Rio en Medio, Rio Nambe, and Pojoaque Creek are the major drainages in the study area that have headwaters in the Sangre de Cristo Mountains. Infiltration of water from these streams is a major source of recharge to the ground-water system in the study area (McAda and Wasiolek, 1988). The Rio Grande is the major discharge area for the aquifer system; however, ground water also discharges to the Pojoaque River, Rio Tesuque, and Santa Fe River along the lower reaches of these drainages (McAda and Wasiolek, 1988, p. 13). North of the Santa Fe River, ground water flows west-northwest from the mountain front to the Rio Grande; south of the Santa Fe River, ground water flows west-southwest from the mountain front toward the lower Santa Fe River and the La Cienega area (McAda and Wasiolek, 1988, p. 13) (fig. 3).

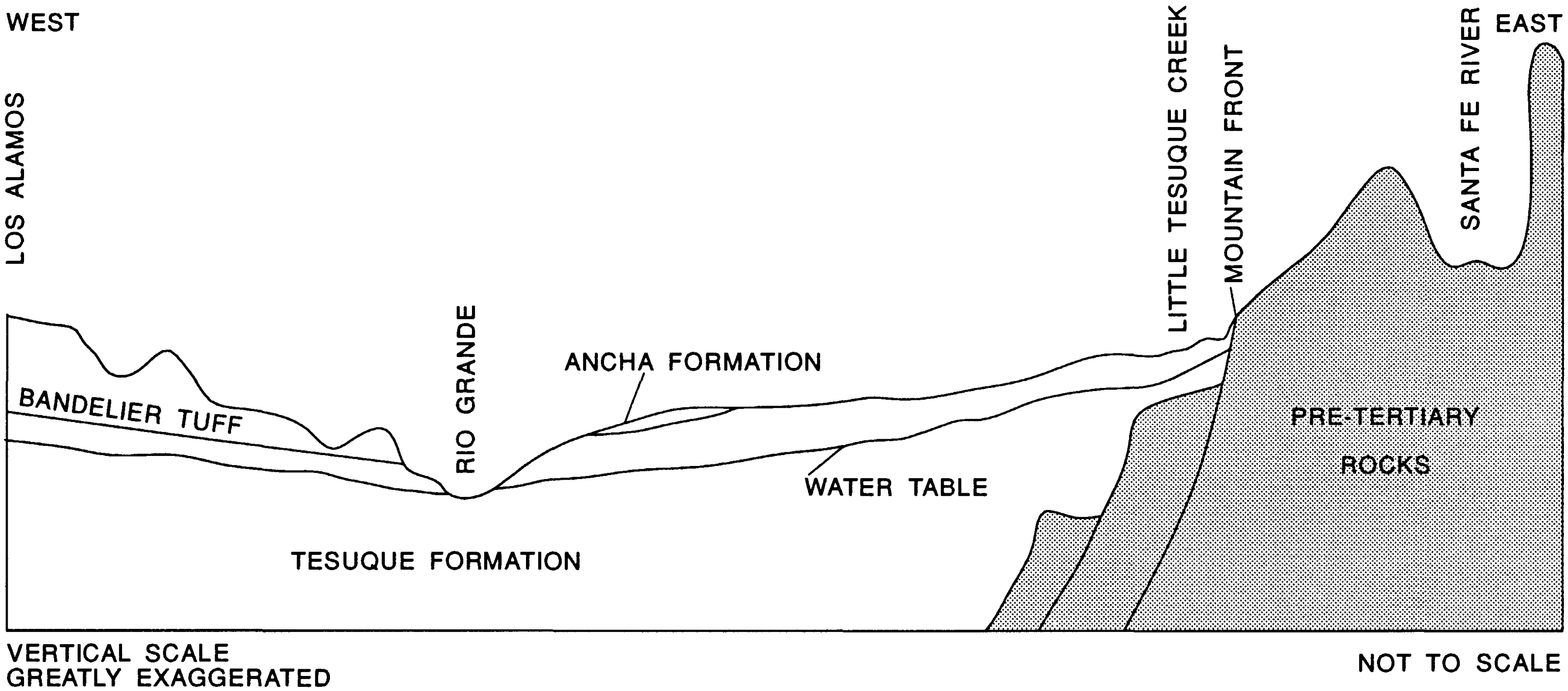
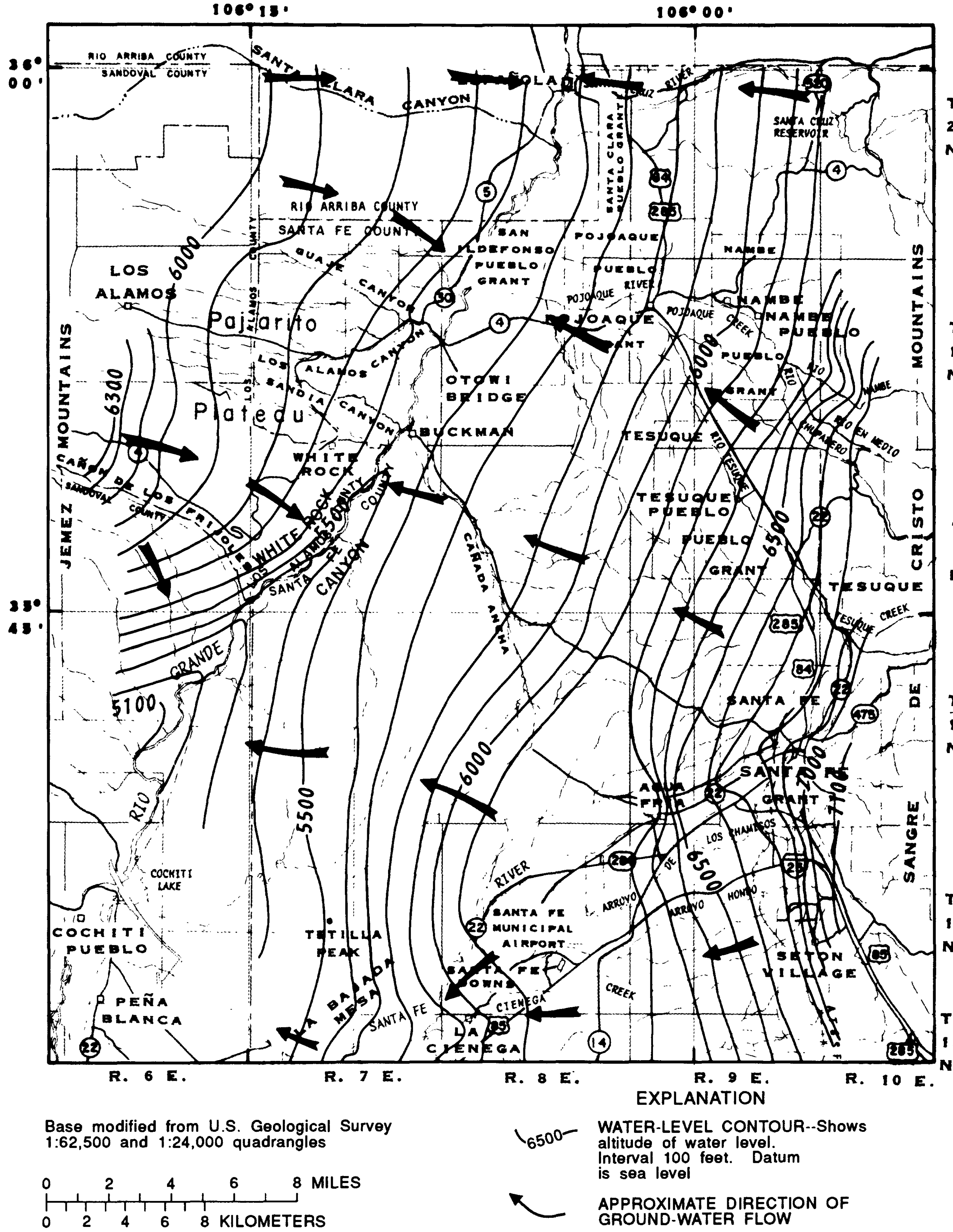


Figure 2.--Diagrammatic section of the study area.



Base modified from U.S. Geological Survey 1:62,500 and 1:24,000 quadrangles

Figure 3.--Predevelopment potentiometric surface of the Tesuque aquifer system (modified from McAda and Wasiolek, 1988, figure 6).

Recharge Processes

Recharge is a process that results in the addition of water to an aquifer or the zone of saturation (Meinzer, 1923). Recharge to an aquifer can result from the inflow of water from adjacent aquifers or infiltration of water from the land surface to the aquifer. In the Santa Fe area, inflow of water to the Tesuque aquifer system from aquifers in the Sangre de Cristo Mountains could occur. This is referred to as subsurface inflow from the mountains.

Recharge to the Tesuque aquifer system due to the infiltration of water from the land surface can be divided into two types: direct recharge and channel-bed recharge. Direct recharge is the process of direct infiltration of precipitation through the unsaturated zone to the saturated zone. If the thickness of the unsaturated zone is large and the amount of precipitation that infiltrates below the root zone of plants is small, it can take thousands of years for water to move from land surface to the saturated zone. Channel-bed recharge is the process of infiltration of surface water in an arroyo or stream through the bed material and down to the saturated zone. In the study area, channel-bed recharge can be divided into two types on the basis of the source of water in the channel: mountain-stream-channel recharge and arroyo-channel recharge.

If the source of water in the channel is runoff from the mountains, recharge from these channels is called mountain-stream-channel recharge. Many channels crossing the Tesuque aquifer system have their headwaters in the Sangre de Cristo Mountains and most of the water in these channels near the mountain front is from runoff of precipitation that falls on the mountains. Channels of this type generally contain water near the mountain front most of the year; however, a large part of this water infiltrates and recharges the ground-water system close to the mountain front. Arroyo Hondo, Santa Fe River, Little Tesuque Creek, Tesuque Creek, Rio Tesuque, Rio Chupadero, Rio en Medio, Rio Nambe, and Pojoaque Creek are the major channels where mountain-stream-channel recharge is dominant (fig. 1). Mountain-front recharge is the sum of mountain-stream-channel recharge and subsurface inflow from the mountains.

If the source of water in the channel is runoff from nonmountainous areas underlain by basin-fill sediments, recharge from these channels is called arroyo-channel recharge. In general, these channels have flow only as the result of runoff from intense summer precipitation.

Acknowledgments

The cooperative support of the Santa Fe Metropolitan Water Board and the New Mexico State Engineer Office for this study is greatly appreciated. Dr. Crayton Yapp of the University of New Mexico analyzed some of the water samples for hydrogen and oxygen isotopic composition, and his willingness to discuss the data and possible interpretations was very beneficial to the completion of this study. The cooperation of the many landowners who allowed us to sample their wells is greatly appreciated. Phil Soice, Max Lucero, and Warren Churchhill of the Sangre de Cristo Water Company were helpful in setting up the atmospheric-deposition station and the sampling of wells owned by the water company. Joseph Mirabal, Paul Williams, and Chester Granjean of the U.S. Bureau of Land Management Office in Taos were helpful in obtaining permission to drill test holes on Bureau of Land Management lands.

PREVIOUS ESTIMATES OF RECHARGE

Several estimates of rates of recharge to the Tesuque aquifer system have been published. Summaries of these estimates of recharge are provided so the estimates can be compared.

Spiegel and Baldwin (1963) studied in detail the hydrology of the Santa Fe area and estimated several rates of recharge. They estimated (p. 143) that 96 percent of precipitation in the Santa Fe area is returned to the atmosphere by evapotranspiration, or approximately 4 percent of the precipitation is available for direct recharge (0.04 x 14.27 inch per year = 0.57 inch per year). Spiegel and Baldwin (1963, p. 136) indicated that direct recharge per unit area is likely to be greater on the Ancha Formation, which crops out over much of the Santa Fe area, than on the Tesuque Formation. The Ancha Formation is generally more permeable and crops out in areas having less surface relief, resulting in less runoff. In the La Cienega area, direct recharge was estimated to be approximately 0.7 inch per year (Spiegel and Baldwin, 1963, p. 191). In the Arroyo Hondo area, direct recharge was estimated to be approximately 0.5 inch per year (Spiegel and Baldwin, 1963, p. 192). Arroyo-channel recharge was not estimated by Spiegel and Baldwin (1963) and may be included in their estimate of direct recharge, although that is not clear in their report.

Mountain-stream-channel recharge along the Santa Fe River has changed in response to changes in land use along the river. Spiegel and Baldwin (1963, p. 173) estimated that under natural conditions in a reach of 4 miles from the mountain front, approximately 5,800 acre-feet per year would have been the maximum sustained loss of flow (recharge) and 2,900 acre-feet per year would have been the "optimum" recharge to the ground-water system (table 1). As irrigation was developed (after settlement of the Spanish in 1609), water was diverted from the river and natural flow was reduced in the channel; because of ditch leakage and extensive water spreading (as the result of irrigation), however, the proportion of streamflow resulting in recharge was probably larger (possibly 30 to 50 percent) than it was under natural conditions, in which more water flowed down the Santa Fe River and out of the basin (Spiegel and Baldwin, 1963, p. 173). During the time of large-scale irrigation along the Santa Fe River (1800's and early 1900's), the springs at La Cieneguita and Agua Fria were apparently larger and more dependable than they were in the 1950's (Spiegel and Baldwin, 1963, p. 173). After the enlargement of McClure Dam on the Santa Fe River (1947), which is located upstream from the mountain front on relatively impermeable bedrock and used to store water for municipal use in Santa Fe, Spiegel and Baldwin (1963, p. 175) estimated that the reservoir spill rate probably would not exceed 2,900 acre-feet per year ("optimum" recharge); however, most of the reservoir spill would result in recharge. A flow of 0.5 cubic foot per second in the Santa Fe River downstream from the reservoirs due to springs and snowmelt also would recharge the aquifer during the winter months (6 months, 180 acre-feet per year); however, this water would be consumed by evapotranspiration in the summer months (Spiegel and Baldwin, 1963, p. 175). Spiegel and Baldwin (1963, p. 175) noted that a part of the water delivered by the municipal system to homes could result in recharge as the result of infiltration of water used for lawn and garden watering and infiltration of water from septic systems and cesspools; most of the sewage, however, is routed to the city sewage-treatment plant. Part of the effluent from the treatment plant is used for irrigation and the remainder is discharged to the Santa Fe River where the effluent infiltrates and recharges the aquifer. Thirty to 50 percent of the effluent from the water-treatment plant was estimated to recharge the ground-water system during the summer and 100 percent during the winter (Spiegel and Baldwin, 1963, p. 176).

Mountain-stream-channel recharge along the Tesuque drainage also was investigated by Spiegel and Baldwin (1963). They indicated that streamflow in the Tesuque drainage is less than that in the Santa Fe drainage because the drainage area is smaller and lower in altitude. Using streamflow records, Spiegel and Baldwin (1963, p. 155) estimated the natural streamflow in Tesuque Creek upstream from diversions to be approximately 2,800 acre-feet per year and the natural streamflow in Little Tesuque Creek upstream from diversions to be approximately 900 acre-feet per year (table 1). The Tesuque drainage has no storage reservoirs upstream from the mountain front, and the majority of streamflow is the result of snowmelt and spring precipitation (Spiegel and Baldwin, 1963, p. 193). A maximum of 1,450 acre-feet per year was estimated to recharge the ground-water system along the Tesuque drainage near the mountain front (Spiegel and Baldwin, 1963, p. 197) (table 1).

Lee Wilson and Associates (1978, p. 1-61 - 1-66) estimated direct and mountain-front recharge in the Santa Fe area on the basis of a review of existing literature and examination of streamflow records for the area. They estimated 0.28 inch per year of direct recharge for the Santa Fe area; however, they indicated this to be a conservative estimate (Lee Wilson and Associates, 1978, p. 1-62). Mountain-front recharge was estimated to be 2,700 acre-feet per year for the Nambe-Pojoaque drainage, 1,500 acre-feet per year for the Tesuque drainage, and 3,500 acre-feet per year for the Santa Fe River drainage (Lee Wilson and Associates, 1978, p. 1-65) (table 1).

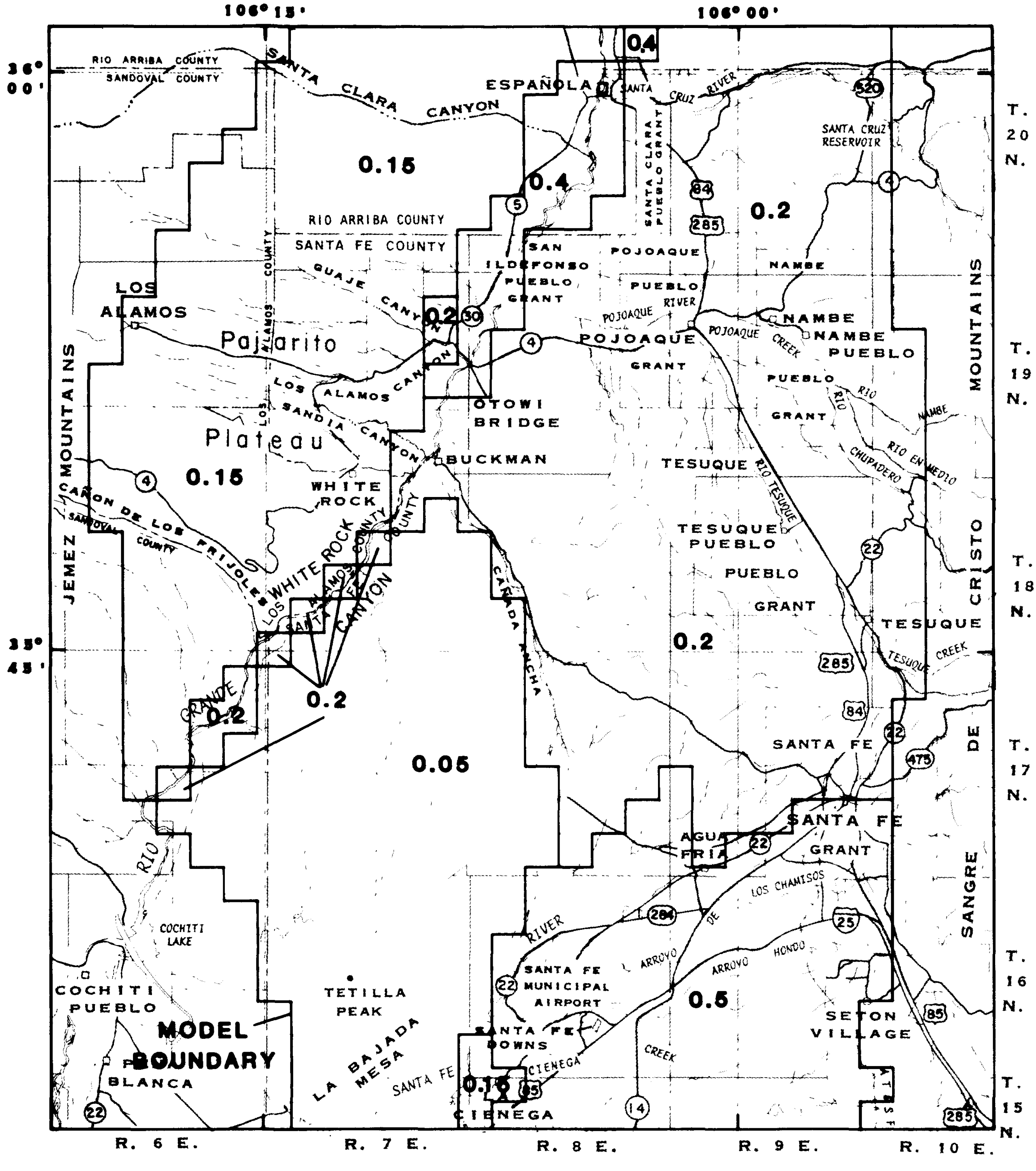
Reiland (1975) and Reiland and Koopman (1975) estimated natural mean monthly discharge and mean annual discharge at several sites in the Pojoaque drainage using linear regression analysis of streamflow records and rainfall-runoff relations (table 1). These estimates were used by later investigators to estimate mountain-stream-channel recharge (Hearne, 1985; McAda and Wasiolek, 1988).

Hearne (1985) used the streamflow-discharge estimates of Reiland (1975) and Reiland and Koopman (1975) in a mathematical model of the Tesuque aquifer system, in which the model calculated the amount of recharge and discharge along the Pojoaque River and its tributaries (table 1). The results of this simulation indicated that the Rio Tesuque drainages contribute approximately 1,800 acre-feet per year (400 + 303 + 1,090, table 1) of mountain-stream-channel recharge to the ground-water system. Discharge from the Tesuque aquifer system to the Rio Tesuque drainages was calculated to be approximately 250 acre-feet per year (table 1). Mountain-stream-channel recharge to the ground-water system along the Rio Chupadero and Rio en Medio was calculated to be approximately 390 and 890 acre-feet per year, respectively (Hearne, 1985, table 8). The ground-water system discharges approximately 950 acre-feet per year of water to the Rio Nambe and 330 acre-feet per year of water to Pojoaque Creek (table 1) (Hearne, 1985, table 8). Approximately 725 acre-feet per year of ground water discharges to the Pojoaque River based on the simulation (Hearne, 1985, table 8). An estimated 800 acre-feet of ground water in the Pojoaque River Basin is discharged by evapotranspiration (Hearne, 1985, p. 26). Hearne (1985, p. 17-18) estimated arroyo recharge and direct recharge to be approximately 2,225 acre-feet per year in the Pojoaque River Basin; however, this recharge was applied along the eastern boundary of the modeled area. On the basis of these figures, the difference between total recharge (mountain-stream-channel plus direct recharge) and total discharge is approximately 2,250 acre-feet per year.

In the upper reaches, near the mountain front, the Santa Fe River recharges approximately 5,220 acre-feet per year of water to the ground-water system, and the ground-water system discharges approximately 3,150 acre-feet per year of water to the Santa Fe River in the lower reaches, based on the simulations (Hearne, 1985, p. 25-26) (table 1). Based on these figures, net recharge to the ground-water system from the Santa Fe River is approximately 2,070 acre-feet per year; however, the amount of mountain-stream-channel recharge to the aquifer is 5,220 acre-feet per year.

McAda and Wasiolek (1988, p. 29-33) estimated mountain-stream-channel recharge and direct recharge. They also estimated the amount of subsurface inflow from the mountains to the basin-fill aquifer, which they called mountain-front recharge, to be approximately 6,080 acre-feet per year in the Pojoaque River Basin and 5,390 acre-feet per year in the Santa Fe River Basin (McAda and Wasiolek, 1988, p. 37-38). McAda and Wasiolek (1988, p. 43) estimated approximately 5,900 acre-feet per year of mountain-stream-channel recharge in the Pojoaque River Basin (table 1) and approximately 5,300 acre-feet per year of ground-water discharge to the Pojoaque River and its tributaries. They estimated approximately 5,430 acre-feet per year of mountain-stream-channel recharge from the Santa Fe River, 1,010 acre-feet per year from Arroyo de los Chamisos, and 510 acre-feet per year from Arroyo Hondo (McAda and Wasiolek, 1988, p. 37-38) (table 1). Ground-water discharge to the Santa Fe River was estimated to be 4,700 acre-feet per year (McAda and Wasiolek, 1988, p. 36). The direct recharge rate estimated by McAda and Wasiolek (1988, p. 33) varied from 0.05 to 0.5 inch per year to account for differences in the amount and distribution of precipitation, permeability of the basin-fill deposits and soil cover, and evapotranspiration rates (fig. 4). The total direct recharge estimated by McAda and Wasiolek (1988, p. 36) was 7,700 acre-feet per year, which includes arroyo-channel recharge.

Wasiolek (in press) estimated the amount of recharge due to subsurface inflow from the mountains, using a water balance method. Annual precipitation falling on selected drainage basins in the mountains and amount of evapotranspiration and sublimation in the drainage basins were estimated using techniques outlined by Troendle and Leaf (1980). The annual rate of subsurface inflow from the mountains was assumed to be the residual of annual precipitation minus the sum of evapotranspiration, sublimation, and annual surface-water runoff that was measured or estimated at the mountain front. Wasiolek (in press) estimated the annual rate of recharge due to subsurface inflow from the mountains to be 4,170 acre-feet per year for the Santa Fe River drainage (Santa Fe River only--does not include Arroyo de los Chamisos or Arroyo Hondo drainages), 1,530 acre-feet per year for the Tesuque Creek drainage, 1,790 acre-feet per year for the Little Tesuque Creek drainage, and 1,710 acre-feet per year for the Rio en Medio drainage.



Base modified from U.S. Geological Survey
1:62,500 and 1:24,000 quadrangles

0 2 4 6 8 MILES

0 2 4 6 8 KILOMETERS

EXPLANATION

0.15 ESTIMATED RATE OF DIRECT RECHARGE, IN INCHES PER YEAR

Figure 4.--Location and rate of direct recharge in the study area (modified from McAda and Wasiolek, 1988, figure 13).

ESTIMATES OF DIRECT RECHARGE USING CHLORIDE MASS BALANCE

Several investigators (Allison and Hughes, 1978 and 1983; Stone, 1984; Allison and others, 1985; and Stone, 1986) have estimated direct recharge using chloride concentrations in water from the unsaturated zone. The basic principle of the chloride mass-balance method is that chloride is constantly being deposited on land surface as the result of bulk precipitation (dryfall and wet precipitation), and this chloride (dissolved in water) is transported downward through the unsaturated zone to the saturated zone by recharge resulting from the infiltration of precipitation (fig. 5). Only a small part of precipitation becomes recharge in the arid Southwest because most precipitation is evaporated or transpired and returned to the atmosphere. Evaporation and transpiration concentrate the chloride in precipitation that has infiltrated (water in the unsaturated zone) because water, but not chloride, is returned to the atmosphere by these processes. Recharge occurs in an area if water percolates downward below the influence of transpiring plants and evaporation. The chloride concentration in water in the unsaturated zone (soil water) should become relatively constant below the influence of evaporation and transpiration (that is, steady state), assuming no changes in the rate of recharge or in the concentration of chloride in precipitation.

The average annual rate of direct recharge can be estimated using the following equation (Allison and Hughes, 1978, p. 190):

$$R = \frac{P\,Cp}{Csw}\,, \qquad (1)$$

where R = average annual rate of recharge, in inches per year;
P = average annual rate of precipitation, in inches per year;
Cp = average concentration of chloride in bulk precipitation, in milligrams per liter; and
Csw = concentration of chloride in water in the unsaturated zone (soil water) below the influence of plants and evaporation, in milligrams per liter.

Several critical assumptions are necessary to apply the chloride mass-balance method: (1) all precipitation that falls on the land surface either infiltrates and recharges the ground-water system, evaporates, or transpires; (2) average annual precipitation and chloride concentration in precipitation have not changed with respect to time; (3) the rate of recharge has not been significantly affected by human activities such as changes in land use; (4) the only source of chloride in the water in the unsaturated zone is from precipitation; (5) chloride is conservative or nonreactive in the unsaturated zone; and (6) piston flow is the dominant flow mechanism in the unsaturated zone. Some justification for the above assumptions is necessary. In some cases no data exist to prove that individual assumptions are correct, and collecting these data is beyond the scope of this project. The chloride mass-balance method is one technique to estimate direct recharge, and estimates of direct recharge obtained using this technique need to be evaluated in conjunction with other estimates of direct recharge.

$$R = \frac{P\ Cp}{Csw}$$

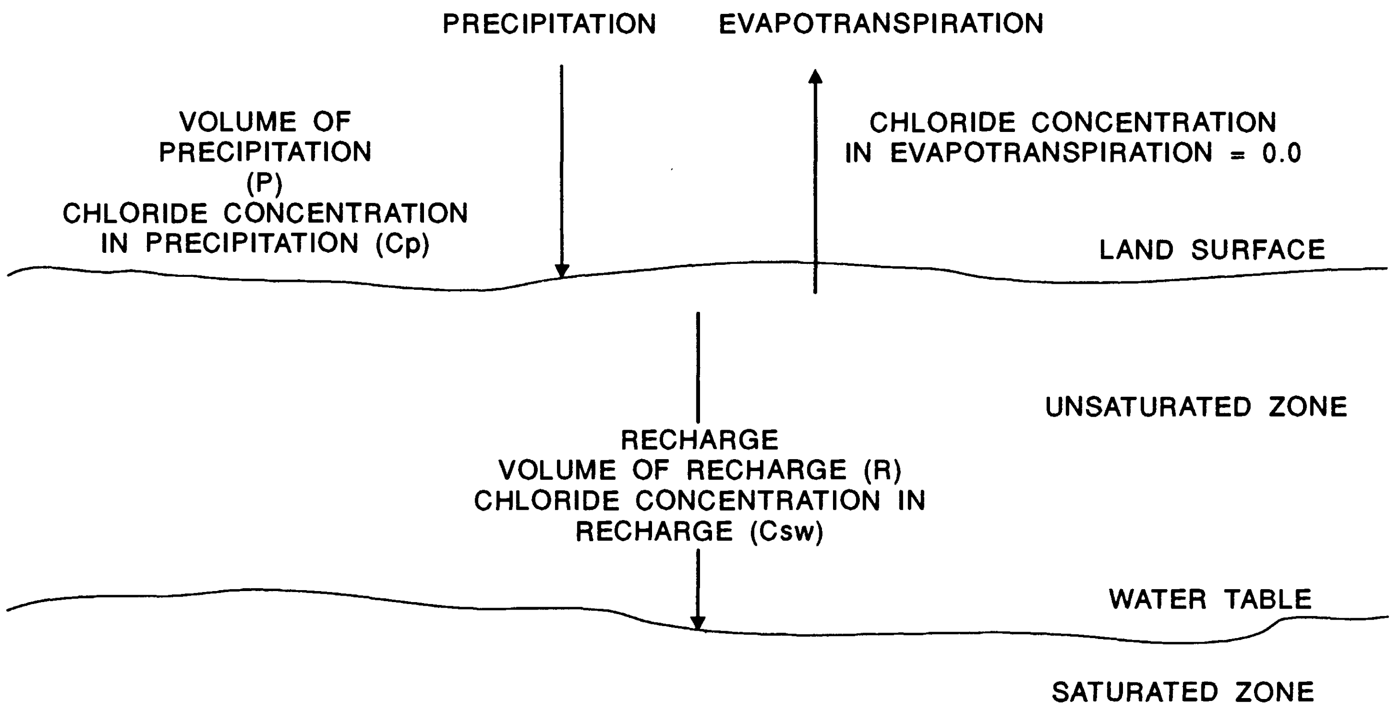


Figure 5.--Schematic diagram of direct recharge to ground water and chloride mass balance.

The assumption that all precipitation that falls on the land surface either infiltrates and recharges the ground-water system, evaporates, or transpires probably is valid for several of the sites where the method was applied because an attempt was made to select those sites where runoff would be minimal and no water would flow onto the sites from adjacent areas. The arroyo channel sites are in areas where water flows onto the sites from adjacent areas. These sites were selected to enable the investigation of recharge processes in arroyos. Recharge estimates using the chloride mass-balance method at these sites underestimate recharge to the basin-fill aquifer because a larger amount of water than mean annual precipitation (P in eq. 1) contributes to recharge in the arroyo channel.

It is difficult to evaluate the changes with time in precipitation amount and chloride concentration in precipitation. Phillips and others (1986) estimated that the climate (temperature and possibly precipitation) has indeed changed in the last 20,000 years. Pack rat middens collected in northwestern New Mexico (Betancourt and others, 1983, p. 207-217) indicate a major turnover in flora and probably a change in climate between 8,300 and 10,000 years ago. Changes in climate (precipitation amount) also probably have affected the chloride concentration in precipitation or the mass flux of chloride to the land surface. On the basis of these studies, climate has changed in the past, and these changes probably have affected the recharge rates. Attempting to determine the effects of these changes on recharge rates, however, was beyond the scope of this project. Increases or decreases in precipitation would cause the recharge calculations to be in error by the same relative proportion.

The rate of recharge has certainly been affected by human activities in areas where streams have been diverted for irrigation or ground water is used for irrigation. In these areas recharge rates would be different than under natural conditions. Recharge rates in the areas where the chloride mass-balance technique was applied have not been affected by human activities because these areas are in undeveloped areas that represent natural conditions.

The assumption that all chloride in the unsaturated zone is from bulk precipitation probably is valid in areas where the chloride mass-balance method was used. Other sources of chloride to the unsaturated zone could be road salt, fertilizers, irrigation water applied to the land surface, or chloride derived from the weathering of minerals in the unsaturated zone. Road salt and fertilizers are not very likely to have affected the areas where the chloride mass-balance method has been applied because these areas are relatively undeveloped with little or no human impact (land use has not changed in these areas). Animal waste could be one possible source of contamination; however, no dense population of large animals lives in the study area, and the magnitude of this effect probably is minimal. Chloride derived from the weathering of minerals also probably is minimal because (a) chloride is not abundant in the materials in the areas where the chloride mass-balance method has been applied (Feth, 1981, p. 10-12), and (b) any water-soluble chloride would have previously leached from the materials because these sites have been exposed to leaching a relatively long time. Chloride also generally is considered nonreactive or conservative compared to most common ions (Feth, 1981, p. 2).

The assumption of piston flow is that water in the unsaturated zone moves vertically (one-dimensional flow) and dispersion and diffusion are negligible. Allison and Hughes (1983, p. 170-171), in a study of recharge using chloride and tritium concentrations, found that piston flow occurred in agricultural areas but some non-piston flow occurred in an area of native eucalyptus trees. Mattick and others (1987) found that soil-water movement is approximated by piston flow in some cases but that vapor transport may be important. The validity of piston flow is difficult to evaluate, but for these initial estimates the assumption of piston flow was assumed to be reasonable. The validity of this assumption is discussed in more detail later.

Approach

Chloride concentration in bulk precipitation, volumes of precipitation through time, and chloride concentration in water in the unsaturated zone were measured. Chloride concentration in bulk precipitation and amount of precipitation were measured for approximately 1.5 years at the Sangre de Cristo Water Treatment Plant in Santa Fe (fig. 1). Bulk precipitation was collected using a 5-gallon bucket approximately 18 inches above land surface. Approximately every 2 weeks, the sampler was checked; if water was in the bucket it was removed, the volume was measured, and a sample was taken for chloride analysis. Measurement of the volumes of water in the sample bucket was necessary to correct the measured chloride concentration in the sample for the effect of evaporation. Precipitation amount was measured using a tipping-bucket rain gage and a wedge rain gage. Average chloride concentration of precipitation was calculated by the following equation:

$$Cp = \frac{\sum_{i=1}^{n} Cb_i \ Vs_i}{\sum_{i=1}^{n} KAP_i} , \qquad (2)$$

where Cp = average chloride concentration in bulk precipitation, in milligrams per liter;
Cb_i = chloride concentration in bulk precipitation in the ith sampling period, in milligrams per liter;
Vs_i = volume of the bulk precipitation sample collected during the ith sampling period, in liters;
K = conversion factor (0.016387 liter per cubic inch);
A = surface area of sampling container (98.52 square inches); and
P_i = amount of precipitation that occurred during the ith sampling period as measured by the wedge rain gage, in inches.

Holes were drilled to approximately 50 feet using a hollow-stem auger that collected continuous cores to obtain samples for measurement of the chloride concentration in water from the unsaturated zone (hereafter referred to as soil water). The core barrel (split spoon) on the drilling rig was 2 feet long. After drilling 2 feet, the core barrel was retrieved by wire line and a new core barrel was installed in the augers. The core barrel was opened at the surface, the core was measured and briefly described, and samples were taken of the core. Samples always were taken from the center of the core to minimize the effects of moisture loss due to heat buildup.

The samples were immediately put into an air-tight plastic bag that previously had been checked for leaks and then put into another air-tight plastic bag that also had been checked for leaks. The bag was then labeled and put into a large plastic bag that was stored in an ice-filled cooler. The large plastic bags containing the samples from a hole were stored in a freezer after completion of the hole until they were analyzed for soil moisture. Core recovery generally was less than 100 percent. In the case of less than 100-percent core recovery, the core interval was measured from the top of the cored interval. For example, if drilling from 22.0 feet to 24.0 feet resulted in 1.4 feet of core recovered, the depth from 22.0 to 23.4 was the assumed interval sampled. In some cases it was necessary to remove the core barrel and use a solid bit to ream the hole out and drill through a hard zone. In this case no core was collected.

Measurement of the chloride concentration of water in the unsaturated zone is a three-step process. The first step is to measure the amount of water in the sample by weighing the sample as collected, drying the sample overnight in an oven at 105 degrees Celsius, then weighing the dried sample. The difference in weight is the amount of water or soil moisture that was in the sample. The gravimetric soil moisture is this difference divided by the weight of the dried sample. The second step is to redissolve the chloride that was originally in the soil water by adding a known amount of deionized water to the sample and shaking the sample. A shaking time of 8 hours was found to be optimum by McGurk and Stone (1985, p. 15). A shaking time of 6 to 8 hours was used for this study. The third step is to measure the chloride concentration in the extract water using a specific ion electrode and a specific ion meter. Ionic strength adjustor was added to all samples and standards. Standards were run every 20 samples to check calibration of the meter. The laboratory procedures used for this study were based on the results of evaluations by McGurk and Stone (1985) of laboratory procedures for determining the soil-water chloride. The chloride concentration in the soil water in the sample is calculated using the following equation:

$$\mathrm{Clsw} = \mathrm{Clext}\ \mathrm{Vadded}/\mathrm{Vorig}, \tag{3}$$

where Clsw = chloride concentration in the sample, in milligrams per liter;
Clext = chloride concentration in the extract, in milligrams per liter;
Vadded = volume of deionized water added to the sample, in milliliters; and
Vorig = original volume of water in the sample, in milliliters.

Bulk density was measured on several samples from various drill holes. The bulk density of the samples (ρ_s) was approximately 1.8 grams per cubic centimeter. This value was used to calculate volumetric soil moisture (SMv) from the gravimetric soil moisture (SMg), measured as discussed earlier, by the following equation:

$$SMv = \frac{SMg \times \rho_s}{\rho w}, \tag{4}$$

where SMv = volumetric soil moisture, in grams per cubic centimeter;
SMg = gravimetric soil moisture, in grams per gram;
ρ_s = bulk density of sample, in grams per cubic centimeter; and
ρw = density of water, in grams per cubic centimeter.

Chloride concentration in soil water versus depth and volumetric soil moisture versus depth were plotted to aid in the interpretation and presentation of the data.

Plots of cumulative chloride as a function of cumulative water amount in the unsaturated-zone profiles can be used to determine changes in recharge rates over time (Allison and others, 1985; Stone, 1986; and Johnston, 1987). Cumulative water is plotted instead of depth to remove the effect of vertical variations in water content in the soil (Allison and others, 1985, p. 10). Cumulative chloride and cumulative water were calculated by the following equations:

$$CMcl = SMv_1\ Clsw_1\ I_1 + \left(\sum_{i=2}^{n-1} (SMv_i\, Clsw_i\, I_i)\right) + SMv_n\, Clsw_n\, I_n \tag{5}$$

$$CMw = SMv_1\, I_1 + \left(\sum_{i=2}^{n-1} (SMv_i\, I_i)\right) + SMv_n\, I_n \tag{6}$$

$$I_1 = d_1 + (d_2 - d_1)/2 \tag{7}$$

$$I_i = (d_i - d_{i-1})/2 + (d_{i+1} - d_i)/2 \tag{8}$$

$$I_n = (d_n - d_{n-1})/2, \tag{9}$$

where $CMc1$ = cumulative water, in grams per square meter;
SMv_i = volumetric soil moisture at sample i, in cubic centimeters/cubic centimeters;
$Clsw_i$ = chloride concentration in sample i, in grams per cubic meter;
I_i = sample interval length at sample i, in meters;
CMw = cumulative water, in meters; and
d_i = depth below land surface of sample i, in meters.

The length of time required for accumulation of the mass of chloride observed above any point in a particular profile can be calculated using the following equation (Allison and others, 1985):

$$T = \frac{Mcl}{Pr\,Cp}, \qquad (10)$$

where T = length of time required for accumulation of the mass of chloride above a particular point in profile, in years;

Mcl = mass of chloride above a particular point in profile, in grams per square meter;

Pr = average annual rate of precipitation, in liters per square meter per year; and

Cp = average concentration of chloride in bulk precipitation, in grams per liter.

Results of Precipitation Sampling

Precipitation amount and samples of bulk precipitation were collected at the Sangre de Cristo Water Treatment Plant from November 20, 1987, through March 29, 1989 (table 2). Comparison of the precipitation amounts measured by the tipping-bucket and wedge rain gages shows small differences in the amount measured for a particular sampling period; however, precipitation amounts measured from March 4, 1988, through March 29, 1989, for the tipping-bucket and wedge rain gages are approximately the same, 19.73 and 19.86 inches, respectively. Because of these small differences measured by the two gages over a long period of record, data from the wedge precipitation gage were used because of its longer sampling period.

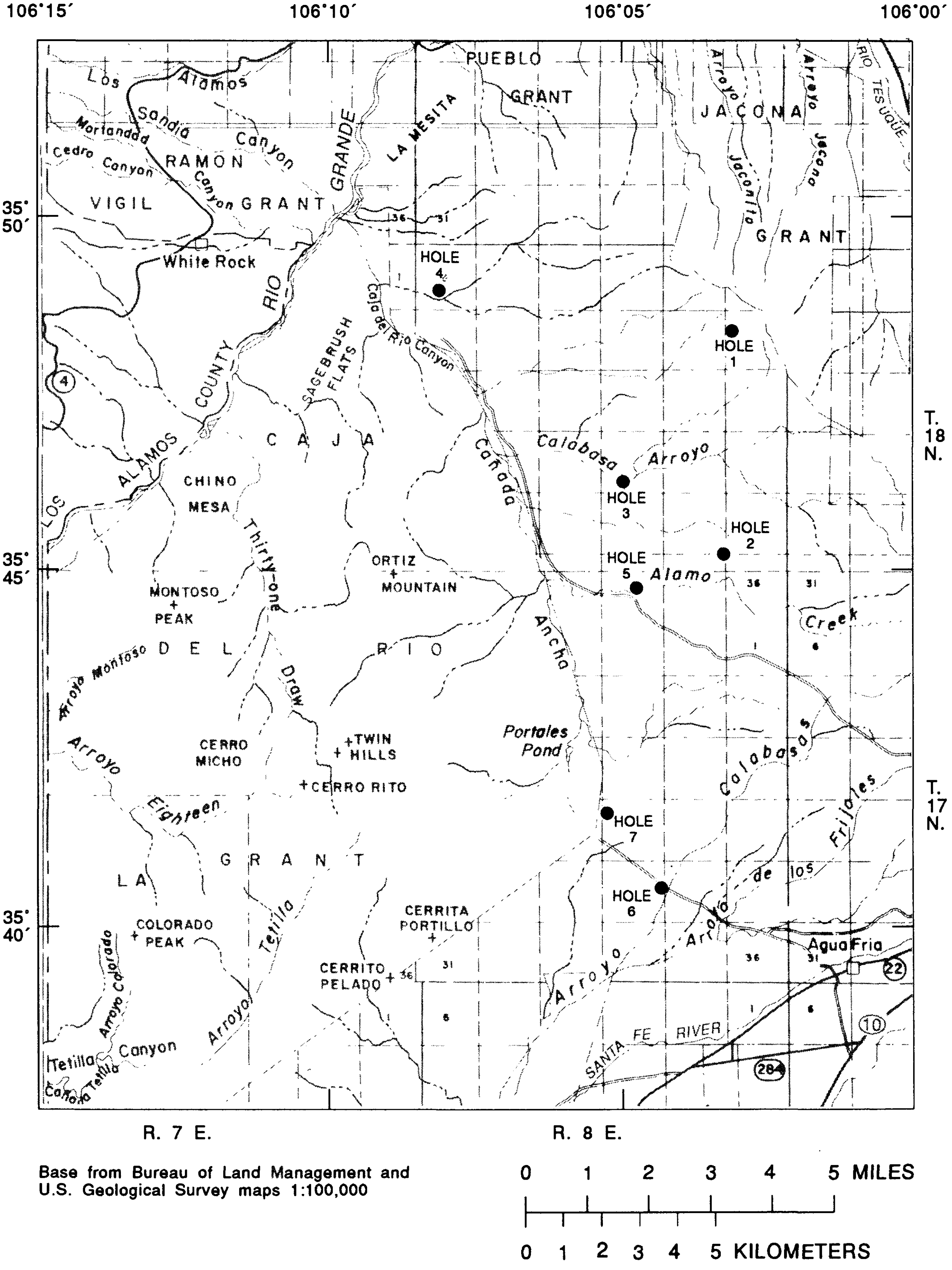
Precipitation amount from November 20, 1987, through November 30, 1988, was 18.81 inches. Precipitation amount from January 15, 1988, through January 23, 1989, was 18.61 inches. Spiegel and Baldwin (1963, p. 16) reported the average annual precipitation at Santa Fe from 1853 to 1960 to be 14.27 inches, indicating a larger amount of precipitation during the study than the average annual precipitation.

The average chloride concentration in bulk precipitation was calculated using equation 2 for several time periods. The average chloride concentration in bulk precipitation for November 20, 1987, through November 10, 1988, was 0.271 milligram per liter; for November 20, 1987, through November 30, 1988, was 0.290 milligram per liter; for January 15, 1988, through January 23, 1989, was 0.300 milligram per liter; and for March 4, 1988, through March 7, 1989, was 0.290 milligram per liter. A value of 0.29 milligram per liter was used as the average chloride concentration in bulk precipitation.

The annual mass flux of chloride was calculated to be 0.1051 gram per square meter. An average chloride concentration of 0.29 milligram per liter in bulk precipitation and an average annual precipitation amount of 14.27 inches were assumed in the calculation. Some error may be introduced by using an average chloride concentration in bulk precipitation that was calculated from the data collected for approximately 1.5 years during a time of above-normal precipitation. Chloride concentration in bulk precipitation is probably a function of the amount of precipitation; however, the value of average chloride concentration in bulk precipitation was calculated for several different time periods during the study and was consistent. Graustein (1981, p. 44) collected precipitation chemistry data at the Santa Fe airport and estimated the average chloride concentration in precipitation to be 0.33 milligram per liter. Lewis and others (1984, p. 1701) found the average chloride concentration of precipitation in southern Colorado to be 0.71 milligram per liter and the annual mass flux of chloride to be 0.130 gram per square meter. Mattick and others (1987, p. 16) found the average chloride concentration in precipitation to be 0.35 milligram per liter in Las Cruces, New Mexico. Average annual precipitation was used instead of annual precipitation measured at the sampling site during 1987 through 1989 because average annual precipitation probably is more representative of long-term annual precipitation.

Results of Unsaturated Zone Sampling

Seven holes for sampling the unsaturated zone were drilled northwest of Santa Fe (fig. 6). Their locations were chosen to represent several different settings where recharge may be occurring. Three holes (1, 2, and 7) were drilled in relatively flat, topographically high areas (mesas) that have little or no dissection of the old physiographic surface. These areas have little or no runoff and most precipitation that falls on the land surface would be expected to infiltrate or evaporate. These holes will be referred to as mesa sites. Two holes (3 and 5) were drilled in arroyo channels (fig. 6). These sites represent areas where the largest amount of recharge would be expected to occur. During intense precipitation, water runs off the land surface and collects in and flows down the arroyos. Therefore, the amount of water that could infiltrate at these sites is greater than the precipitation that falls on the land surface at these sites. The channels of these arroyos consist of coarse sand; thus, there is infiltration when water is flowing in the arroyos. These holes will be referred to as arroyo channel sites. Two holes (4 and 6) were drilled in areas adjacent to arroyos where little flooding would be expected. These holes will be referred to as arroyo margin sites.



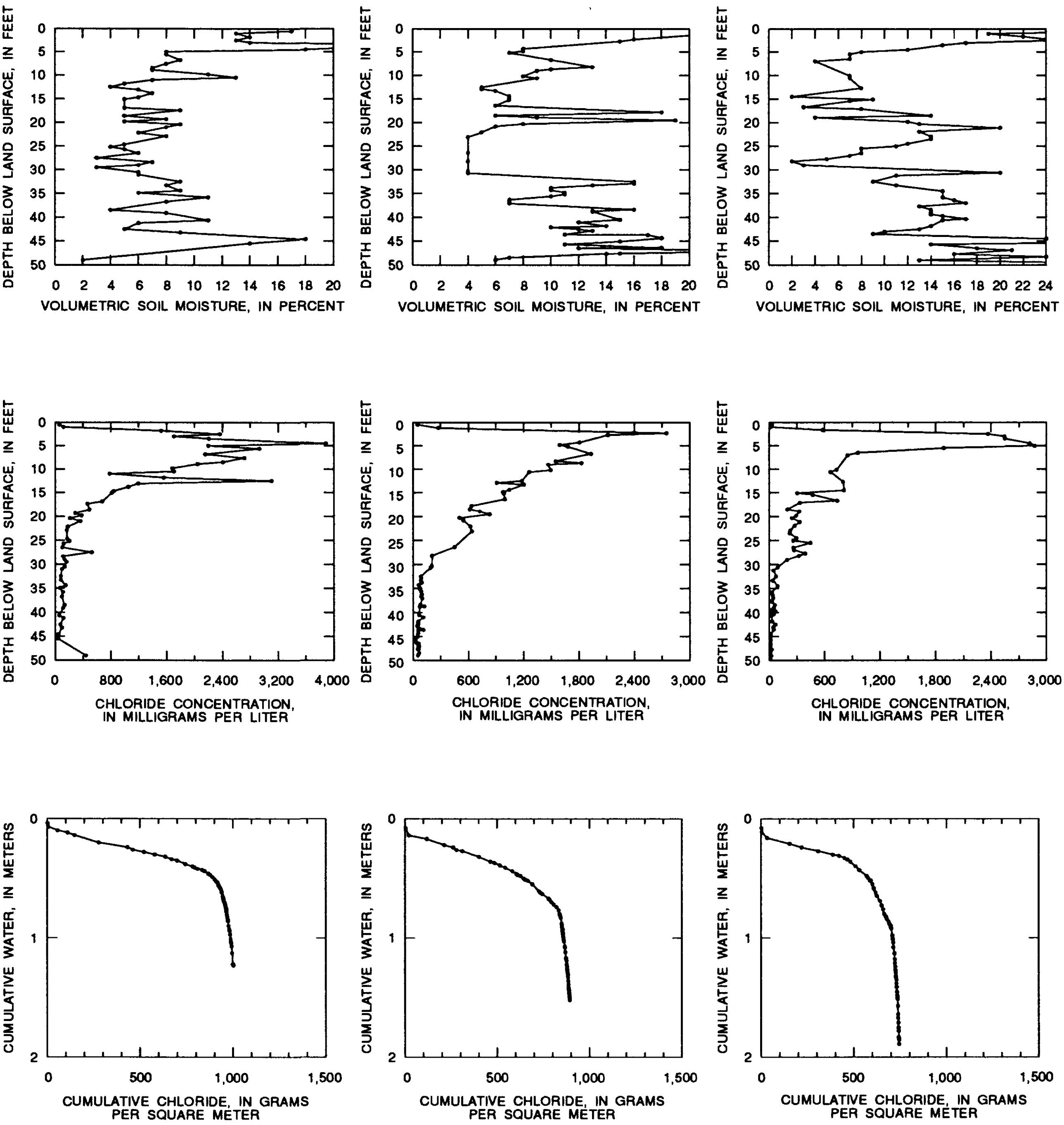
Base from Bureau of Land Management and U.S. Geological Survey maps 1:100,000

Figure 6.--Location of the drill holes used for unsaturated zone sampling.

Mesa Sites

Holes 1, 2, and 7, representing mesa sites, were located on the Divide surface of Spiegel and Baldwin (1963, p. 56). These holes contained a large number of caliche zones (zones where sediments are cemented with calcium carbonate) throughout the total depths drilled. The variation in volumetric soil moisture with depth in the holes (fig. 7) is a function of the dominant grain size. Soil moisture of less than 11 percent was observed in sand and greater than 11 percent in silt and clay. Although the chloride concentrations in soil water differ at specific depths in the different holes, the general shape of the plots of chloride concentration as a function of depth is similar for all of the holes (fig. 7). Chloride concentrations are less than 600 milligrams per liter just below the surface, then increase (as much as approximately 4,000 milligrams per liter in hole 1) 2 to 5 feet below land surface. Chloride concentrations decrease to less than 150 milligrams per liter 25 to 35 feet below land surface. The concentrations are relatively constant below this depth. The shape of the cumulative chloride as a function of cumulative water plots also is similar for these holes (fig. 7). Two relatively straight line segments can be recognized on the plots for holes 1 and 2, and three relatively straight line segments can be recognized on the plot for hole 7. The change in slope of the straight-line segments of the plots for holes 1 and 2 represents the depth at which chloride concentration becomes relatively constant (less than 150 milligrams per liter). The graph for hole 7 has three straight-line segments because the chloride concentration becomes a relatively constant value of about 320 milligrams per liter from 15.1 to 29 feet and a relatively constant value of about 40 milligrams per liter from 30.6 to 49.7 feet (fig. 7). Equation 10 was used to calculate the length of time required for the accumulation of chloride in the profiles corresponding to the break in slope in the cumulative chloride as a function of cumulative water plots. These calculations for holes 1, 2, and 7 indicate that it took 8,800 years, 8,090 years, and 6,660 years, respectively, for the chloride in the upper 25 to 35 feet of the soil at those sites to accumulate (table 3). This indicates that, for practical purposes, no recharge presently occurs at these locations.

Small chloride concentrations in the lower parts of the holes are additional evidence of no recharge presently at these locations. If recharge occurs in these areas and the assumption of piston flow in the unsaturated zone is valid, the chloride concentration should increase from the surface to a depth where evaporation and transpiration do not occur due to the removal of water and the concentration of chloride by these processes. Below this depth, chloride concentrations should be constant because recharge water would not leave solutes in the upper parts of the unsaturated zone but instead transport the solutes downward. Decreases in chloride concentrations with depth, as indicated by the data, would not be observed because solutes would not accumulate in the upper parts of the hole but instead move downward with the recharge water. For cases in which chloride concentrations decrease significantly below a depth where evaporation and transpiration do not occur, recharge probably should not be estimated using equation 1.



HOLE 1

HOLE 2

HOLE 7

Figure 7.--Relation of soil moisture, chloride concentration in soil water, and cumulative chloride in the unsaturated zone at mesa sites.

If the assumption of piston flow as the only transport mechanism is not valid, recharge water may flow through preferred pathways (Allison and others, 1985). In this case, recharge flows through cracks or root tubes relatively quickly after infiltration and chloride in the water is not significantly concentrated by evaporation or transpiration because the water flows downward below the area in the unsaturated zone affected by evaporation and transpiration. This could result in the small chloride concentrations measured at depth. No large cracks or large root tubes were observed in the cores obtained from these holes, although small root tubes were noted in several core samples collected throughout the depth of the holes. These root tubes, even at depths as great as 40 to 50 feet, contained carbonaceous material and white deposits of mineral precipitate that probably would be dissolved and flushed downward if a significant amount of water were moving downward. The small chloride concentrations measured in the lower parts of these holes also would require that water moving through preferred pathways not remove a significant amount of chloride stored in the sediments near the surface as it moved downward. On the basis of the field observations and the data collected, recharge through preferred pathways probably would not result in the relatively small chloride concentrations observed in the unsaturated zone 25 to 35 feet below land surface.

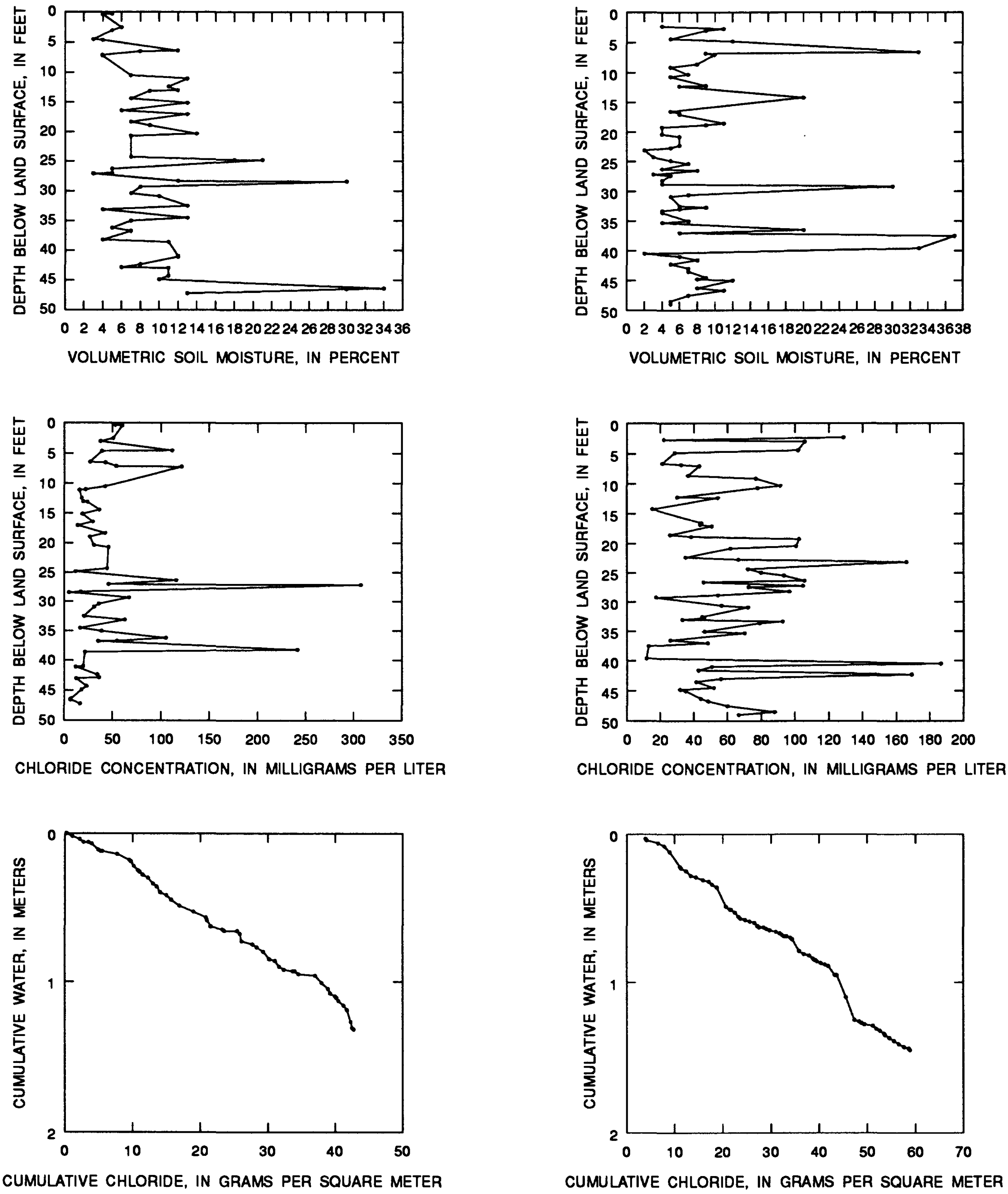
Mattick and others (1987) discussed the possibility that vapor transport may be important in recharge processes in New Mexico. Large chloride concentrations found from the surface to 25 to 35 feet below land surface and small chloride concentrations below this at these sites could be the result of vapor transport. Data are insufficient to evaluate the role of vapor transport at these sites.

The profiles yield useful information about recharge in the mesa site setting. The mass of chloride stored in the upper parts of the holes would take approximately 6,700 to 8,800 years to accumulate (table 3). If the assumptions used in this method are correct, this indicates no direct recharge in the recent past (last 6,700 to 8,800 years). The small chloride concentrations below 25 to 30 feet may represent recharge that occurred during a time when recharge rates were much greater than at present. Phillips and others (1986, p. 185) indicated that present recharge rates in northwestern New Mexico generally are smaller than those of the past. Phillips and others (1986, p. 188) estimated that recharge was relatively large approximately 3,000 to 5,000 years ago and 11,000 to 28,000 years ago.

Arroyo Channel Sites

Hole 3 was drilled in Calabasa Arroyo and hole 5 was drilled in Alamo Creek (fig. 6). Flow in these two major drainages is the result of runoff of precipitation that falls on the basin-fill deposits; no water is derived from the mountainous areas adjacent to the basin. The number and thickness of caliche zones penetrated in these holes were much less than in holes at the mesa and arroyo margin sites, which may indicate that the caliche zones have been dissolved by recharge water or were never formed in these areas. Chloride-concentration profiles for these two holes are similar (fig. 8). Chloride concentration in water from the unsaturated zone ranges from approximately 5 to approximately 300 milligrams per liter in hole 3 and from 15 to approximately 190 milligrams per liter in hole 5. No large increase is observed in chloride concentration from 2 to 5 feet below land surface as at the mesa sites. The mean chloride concentration in soil water is 45.5 milligrams per liter in hole 3 and 62.7 milligrams per liter in hole 5 (table 3). The chloride-concentration profiles from these two holes indicate that the chloride concentration in soil water does not vary significantly with depth, thus suggesting recharge in these two arroyos. The plots of cumulative chloride and cumulative water show no substantial changes in slope (fig. 8), indicating no significant changes in the recharge rate with time. These data show that recharge does occur in these arroyos and, by inference, other arroyos in the area.

Although it is not possible to calculate accurately the rate of recharge in these arroyos, the minimum rate of recharge at these sites can be estimated. This is an estimate of the minimum amount of recharge water because only precipitation intercepting the channel of the arroyo at these sites is assumed to infiltrate and recharge ground water. Obviously, this is not a valid assumption because large volumes of water flow in these arroyos as the result of runoff from adjacent areas during intense thunderstorms. Part of this runoff infiltrates through the bed of the arroyos and recharges ground water. Calculating the rate of recharge resulting from infiltration of water flowing in arroyo channels is not possible with the available data. The minimum estimates, however, are useful because they indicate the minimum rate of recharge at these sites. The average chloride concentration for the entire depth in hole 3 was 45.5 milligrams per liter and in hole 5 was 62.7 milligrams per liter. Using these values and equation 1, the minimum recharge rate for these arroyo channels is approximately 0.09 inch per year at hole 3 and 0.07 inch per year at hole 5 (table 3). Although these estimates do not accurately reflect the true recharge rates at these sites, the data collected at these sites do indicate recharge in arroyo channels. Chloride concentrations in soil water in these holes indicate that ground-water recharge resulting from arroyo recharge contains chloride concentrations in the range of 40 to 60 milligrams per liter.



HOLE 3

HOLE 5

Figure 8.--Relation of soil moisture, chloride concentration in soil water, and cumulative chloride in the unsaturated zone at arroyo channel sites.

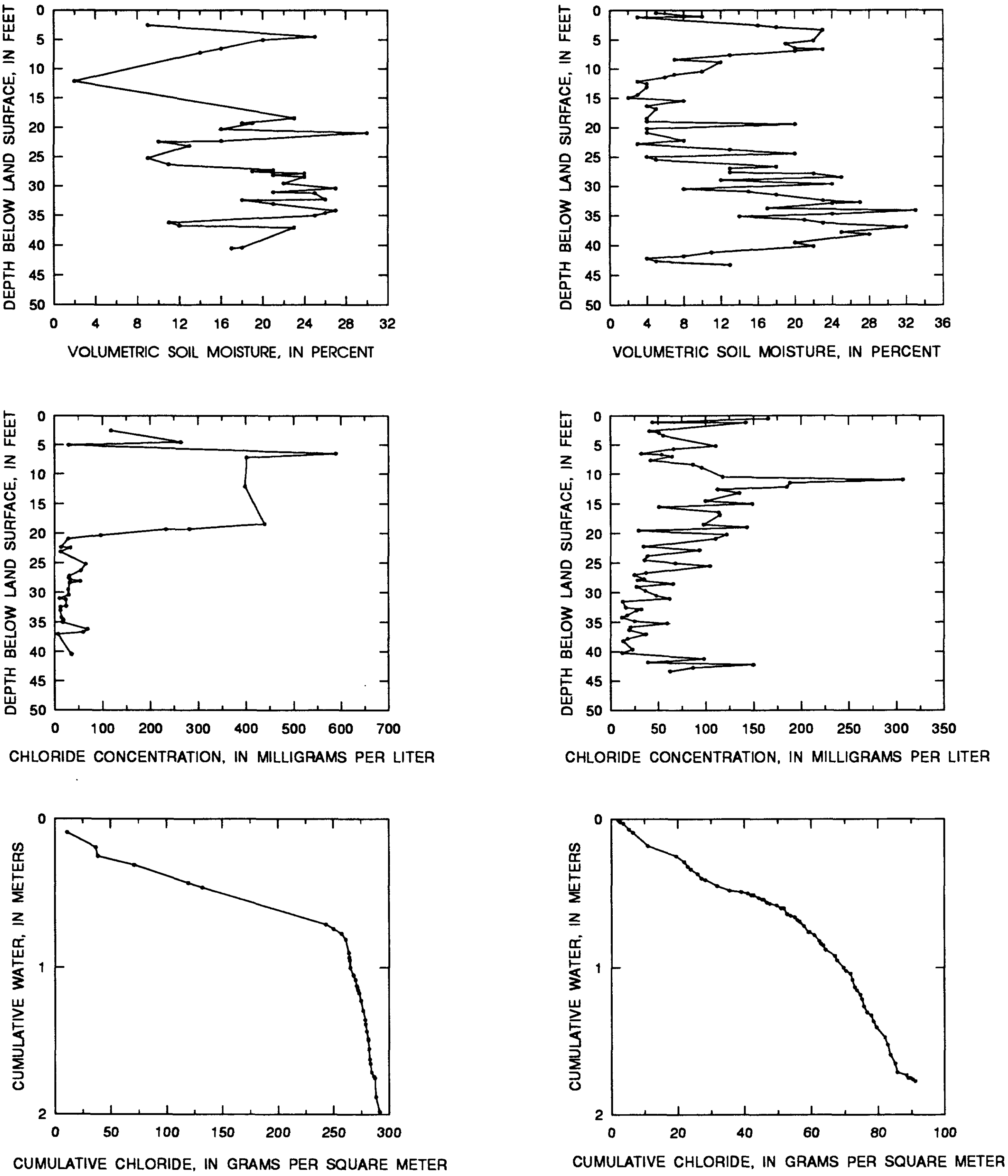
Arroyo Margin Sites

Hole 4 was drilled approximately 50 feet away from and perpendicular to a small arroyo and hole 6 was drilled near Arroyo Calabasas, a relatively large arroyo (fig. 6). Water flowing in the arroyo near hole 4 would not reach hole 4; water flowing in the arroyo near hole 6, however, would occasionally reach hole 6, as evidenced by high-water marks at an altitude higher than that of the hole. The frequency of flooding at hole 6 is not known but, on the basis of the significant amount of grasses and large bushes and trees near the site, probably is infrequent. Caliche zones were penetrated at several depths in both holes, but were much more prevalent in hole 4. Few samples were obtained in the upper 20 feet of hole 4 because of difficult drilling and poor core recovery. However, a sufficient number of samples was obtained to define the soil-water chloride concentration and soil moisture profiles in this part of the hole. Increases in chloride concentration near the bottom of both holes are probably due to the effects of heating and driving water from the cores because of hard drilling. Soil moisture from a particular sample is inversely related to chloride concentration near the bottom of the holes, possibly indicating that soil moisture was driven from the cores.

Chloride-concentration profiles of these two holes are different, indicating differences in recharge (fig. 9). The chloride-concentration profile of hole 4 is similar in shape to those at the mesa sites; however, the maximum chloride concentration is much less in hole 4 than at the mesa sites. The depth at which chloride concentration in soil water significantly decreases in hole 4 is similar to that observed at the mesa holes. However, chloride concentration decreases within a relatively short interval (2 feet), approximately 20 feet below land surface. This decrease is more abrupt than that at the mesa sites. The reason for the abrupt decrease is not known.

The mass of chloride stored in the upper part of this hole would take approximately 2,470 years to accumulate, on the basis of the current chloride mass flux (table 3). This indicates no direct recharge at this site recently. The smaller mass of chloride stored in the upper part of hole 4 compared with that stored in the unsaturated zone at the mesa sites may be due to the shorter length of time that the land surface in the vicinity of hole 4 has been stable and precipitation has been infiltrating at the site. Also, runoff at hole 4 would tend to remove chloride, thus reducing the chloride mass flux to the soil zone. This would decrease the mass of chloride stored in the upper part of the soil zone. Small chloride concentrations measured in the lower part of the hole may represent recharge water that infiltrated during a time when the climate was much wetter and the recharge rate was larger, as was suggested in the discussion of the mesa sites.

The chloride-concentration profile at hole 6 shows a maximum chloride concentration of approximately 306 milligrams per liter at a depth of 11 feet, on the basis of one point (fig. 9). Chloride concentration in soil water gradually decreases below 12.2 feet.



HOLE 4

HOLE 6

Figure 9.--Relation of soil moisture, chloride concentration in soil water, and cumulative chloride in the unsaturated zone at arroyo margin sites.

The chloride-concentration profile for hole 6 can be divided into five generalized intervals on the basis of chloride concentrations and soil moisture (fig. 9). The chloride concentration in soil water ranged from 32 to 165 milligrams per liter in the interval 0 to 10.8 feet, and the mean is approximately 78 milligrams per liter. The chloride concentration in soil water ranged from 29 to 306 milligrams per liter in the interval 10.8 to 26 feet. Chloride concentration was largest at the top of this interval and generally decreased downward. A mean chloride concentration was not calculated for this interval because it would be unduly affected by the single large value. The chloride concentration in soil water ranged from 12 to 59 milligrams per liter in the interval 31 to 40.4 feet (mean 22.7 milligrams per liter). The chloride concentration in soil water ranged from 39 to 150 milligrams per liter in the interval 40.4 to 43.3 feet (mean 87.2 milligrams per liter).

Recharge rates, calculated using equation 1 and mean chloride concentrations for four of the intervals in hole 6, range from 0.05 to 0.19 inch per year (table 3). The wide range in recharge rates calculated for the different intervals in hole 6 are confusing but may reflect that recharge occurs only during flooding at this site. The intervals that have similar chloride concentrations in soil water in this hole may reflect differences in the chloride concentration of water that infiltrates and results in recharge (flood waters). If recharge is not continuous, chloride would build up in the upper part of the hole as the result of evaporation and transpiration of precipitation. This chloride would be transported downward below the influence of evaporation and transpiration by infiltrating flood waters. The chloride concentration in recharge water resulting from a particular flood would be a function of the time since the last flood and the chloride concentration of the infiltrating flood water.

ESTIMATES OF MOUNTAIN-FRONT RECHARGE USING CHLORIDE BALANCE

Areal and temporal variations of chloride concentration in surface water and areal variations of chloride concentration in ground water can be used to investigate recharge processes. Variations of chloride concentration in surface water from different streams that have headwaters in the mountains adjacent to the basin-fill aquifer and that recharge the basin-fill aquifer can be used to estimate how much precipitation falling on the mountains is available for recharge from different streams. Temporal variations of chloride concentration in surface water can be used to investigate how the chloride concentration of potential recharge water changes during the year. Chloride concentration in ground water near areas of mountain-front recharge can be used in chloride-balance calculations to estimate mountain-front recharge (Dettinger, 1989). Changes in chloride concentration in ground water, as ground water moves from areas adjacent to the mountains toward discharge areas, may indicate direct or arroyo-channel recharge.

Samples were collected and analyzed for chloride from selected streams that have headwaters in the mountains adjacent to the basin (fig. 1) during snowmelt runoff and in the late summer when thunderstorms occur. These sampling periods are when streamflows are largest, the time of the greatest potential for recharge.

Historical data and new data collected during this project were used in the interpretation of ground-water chloride concentrations. A large number of chloride analyses of ground water existed prior to the start of this study and many of these analyses were used. Ground-water samples were collected during this study in 1988 for analysis of chloride concentrations in conjunction with sampling of ground water for stable isotopic composition in an attempt to fill in gaps in existing data. In many parts of the study area obtaining ground-water samples was not possible because of the lack of wells.

Approach

The chloride-balance method can be used to estimate natural recharge to an alluvial-basin ground-water system from surrounding mountains (mountain-front recharge) (Dettinger, 1989). In the Santa Fe area, the rate of natural mountain-front recharge estimated using this method represents the rate of water that entered the Tesuque aquifer system prior to significant human effects on the area, such as construction of reservoirs or diversion of water for irrigation. The approach was to estimate mountain-front recharge to the alluvial-basin aquifer system using the following equation:

$$Rmf = Pm\,Cp/Cg, \qquad (11)$$

where Rmf = mountain-front recharge to the alluvial-basin aquifer system, in acre-feet per year;
Pm = average annual precipitation falling on the drainage basin, in acre-feet per year;
Cp = average concentration of chloride in bulk precipitation, in milligrams per liter; and
Cg = concentration of chloride in ground water in the alluvial-basin aquifer system near the mountain front, in milligrams per liter.

Application of this equation assumes that all runoff from the mountains recharges the Tesuque aquifer system. If streams flow out of the area underlain by the Tesuque aquifer or into the Rio Grande this can be accounted for by expanding the equation:

$$Rmf = (PmCp/Cg) - (Q\,Cq/Cg), \qquad (12)$$

where Q = rate of runoff that does not become recharge and leaves the basin as streamflow, in acre-feet per year; and
Cq = chloride concentration in this runoff, in milligrams per liter (fig. 10).

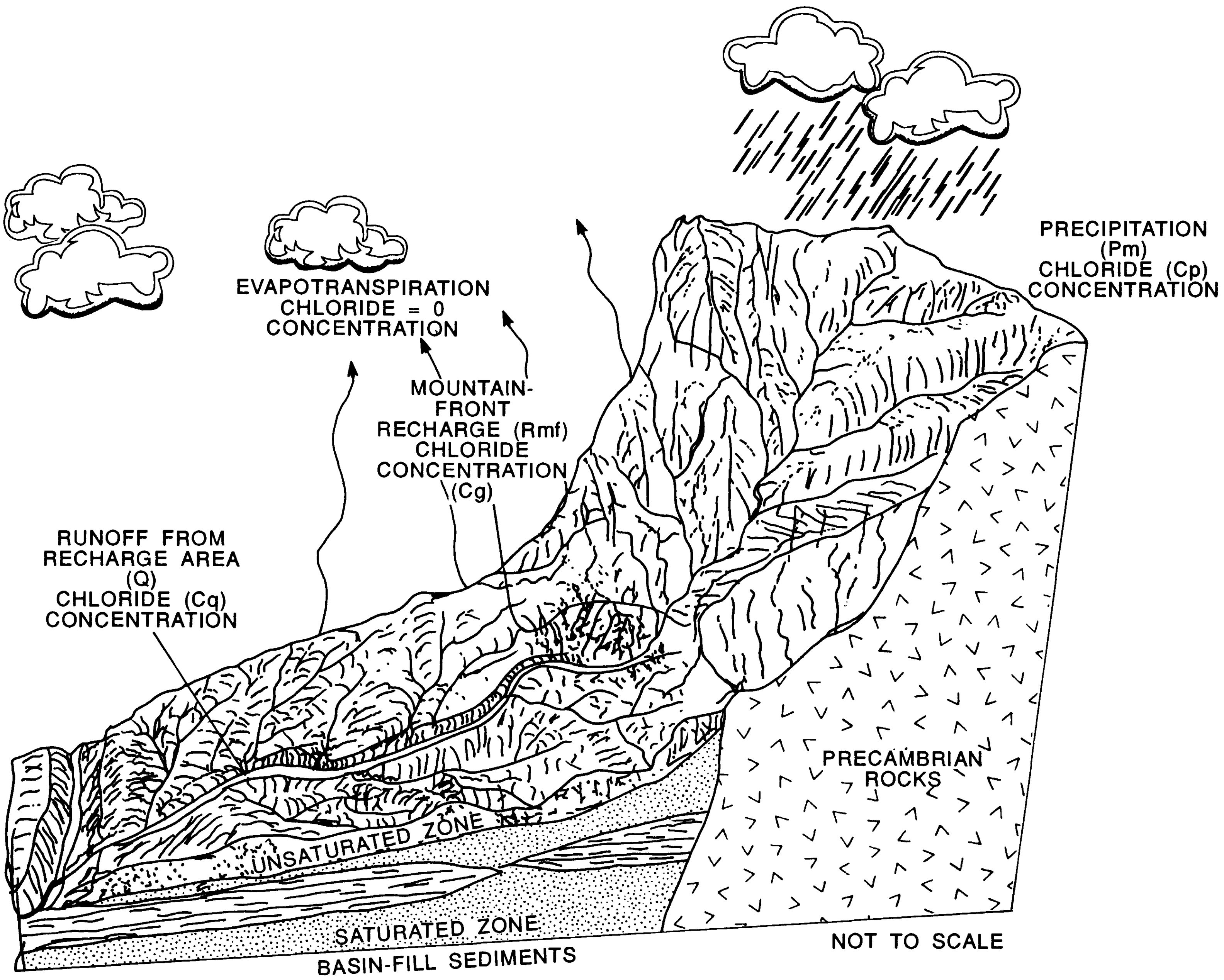


Figure 10.--Schematic diagram of mountain-front recharge and chloride balance.

The assumptions necessary to apply this equation are: (1) the only source of chloride in ground water is from precipitation, (2) the chloride concentration in precipitation and rate of precipitation have not changed with respect to time; (3) direct recharge and arroyo-channel recharge have not affected chloride concentrations in ground water, and (4) chloride is conservative (chemically nonreactive) and there is no change in the storage of chloride in the system. The assumption that the only source of chloride in ground water is from precipitation is important in the Santa Fe area because development in the mountains has resulted in sources of chloride other than precipitation. Salting of roads in the winter and subsequent runoff from the roads to streams have affected chloride concentrations in streams (Gosz, 1975) and possibly ground water in some areas along the mountain front. Infiltration of septic tank effluent and weathering and dissolution of chloride minerals also could increase chloride concentrations in ground water. Chloride concentrations in septic tank effluents are increased relative to supply water by 30 to 100 milligrams per liter (Metcalf and Eddy, Inc., 1972, p. 231). A large density of septic tanks in a small area can result in increases in chloride concentrations in ground water due to infiltration (recharge) of septic tank effluent. Nitrate concentrations also generally increase in ground water as the result of recharge of septic tank effluent. Weathering of minerals that would result in increases in chloride concentrations probably is negligible in the Santa Fe area because the majority of rocks in the mountainous area east of Santa Fe are igneous and metamorphic rocks that generally contain very little chloride (Feth, 1981, p. 12). Feth (1981, p. 17) stated that "Rocks and minerals, other than evaporites, are not sources of readily available Cl [chloride], although areas undergoing hydrothermal alteration and areas rich in scapolite may be exceptions."

The assumption that the rate of precipitation and the chloride concentration in precipitation have not changed with respect to time is difficult to evaluate. The rate of precipitation varies from year to year and probably has varied considerably in the last 20,000 years (Phillips and others, 1986). The rate of precipitation is estimated from long-term averages (1931-60). The chloride concentrations in ground water used in the calculations are from sites relatively close to the mountain front in an attempt to sample water that has recharged relatively recently (10-1,000 years ago). Precipitation rates may be different presently (1989) than when the ground water sampled was recharged. The rate of precipitation and the chloride concentration in precipitation used in the calculations are assumed to be accurate because without a significant amount of data collection it is not possible to evaluate errors. Errors in rates of precipitation and in concentration of chloride in precipitation would cause recharge estimates to be in error by the same proportion that the values used are in error.

Direct and arroyo-channel recharge would affect the chloride concentration in ground water if the chloride concentration in recharge water resulting from these processes is different from that in recharge water resulting from mountain-front recharge. To minimize this effect, ground-water samples were collected close to the mountain front where mountain-front recharge is dominant. The effect of direct and arroyo channel recharge on chloride concentrations in ground water would be the smallest near the mountain front.

The assumption that chloride is conservative and that the storage of chloride in the system has not changed probably is reasonable in the mountainous area east of Santa Fe because of the large amount of precipitation in the area and because chloride salts are highly soluble and chloride ions are nonreactive and mobile. In a short time frame (several months) chloride may accumulate as a precipitate in the soil or as increases in chloride concentrations in the shallow ground water, but in a longer time frame (several years) the storage of chloride in the area probably would not change.

Recharge estimates using the chloride-balance method are only as accurate as the data used in the calculations and the validity of the underlying assumptions. This is a useful technique because the approach is independent of other techniques used to calculate mountain-front recharge in the Santa Fe area (Spiegel and Baldwin, 1963; Hearne, 1985; and McAda and Wasiolek, 1988).

Chloride Concentration in Surface Water

Chloride concentration in surface water varies areally and temporally (table 4). Water from the Santa Fe River generally had the smallest chloride concentrations and water from Little Tesuque Creek generally had the largest. The lack of significant human impacts in the Santa Fe River drainage upstream from the three reservoirs is probably the main reason that the smallest chloride concentrations were measured in this drainage. The increase in chloride concentrations downstream, from upstream from McClure Reservoir (1) to downstream from Two Mile Reservoir (4), in spring 1987 (table 4 and fig. 1) probably is due to evaporation in the reservoirs as water is routed downstream from reservoir to reservoir. Large chloride concentrations in water in Little Tesuque Creek probably are in part due to human activities such as salting of roads in the winter and residential development of land in the drainage. The chloride concentrations in samples from other streams probably also are affected by human activities and are not representive of chloride concentrations in these streams prior to development. Differences in chloride concentrations in water from different streams are also a function of the volume of precipitation and evapotranspiration in the drainage basin of a particular stream. Evapotranspiration is a greater proportion of precipitation at lower altitudes; thus, chloride concentrations in streams that have drainage basins in lower altitudes would be larger than chloride concentrations in streams that have drainage basins in higher altitudes.

The chloride concentration of samples from streams along the mountain front (all but Rio Tesuque at State Highway 4 (11) was largest prior to and at the beginning of snowmelt (April 1988) and smallest near the end of snowmelt (May-June 1987) (table 4). Although these data are for different years, these largest chloride concentrations prior to or at the beginning of snowmelt are not surprising; they are the result of vegetation concentrating chloride in water in the unsaturated zone and the shallow alluvial aquifer in the mountains by transpiration during the previous summer and fall. This water is flushed from the unsaturated zone and the shallow alluvial aquifer in the mountains by the large amount of recharge during snowmelt. The chloride concentration in streamflow decreases later during snowmelt as the water stored in the unsaturated zone and shallow alluvial aquifer in the mountains through the winter is flushed and the proportion of snowmelt in streamflow increases. After snowmelt the shallow alluvial aquifer in the mountains would contain relatively dilute snowmelt water that would be concentrated during the summer by evapotranspiration.

The relatively large chloride concentrations in surface water prior to and at the beginning of snowmelt also could be due to the solution of road salt. Many roads where road salt is applied during the winter are located near streams, and runoff from these roads would affect chloride concentrations in the water in these streams prior to the main snowmelt runoff.

Summer thunderstorms result in no recharge to the shallow alluvial aquifers in the mountains, and increases in stream discharge during summer thunderstorms is due to surface runoff (Graustein, 1981, p. 234). The chloride concentration in surface runoff would be similar to that in precipitation. Mixing of surface runoff and water discharged to the streams from the aquifer would result in decreases in chloride concentration in streamflow during summer thunderstorms.

On the basis of relatively few chloride analyses of surface water, it is obvious that chloride concentration changes throughout the year in a particular stream in the mountains; thus, estimating chloride concentration in recharge water from these streams is difficult. Chloride concentration in snowmelt runoff is smallest after solution of road salt and the initial flushing of the unsaturated zone and shallow alluvial aquifer in the mountains. Chloride concentration in streams during the late summer to late winter (prior to snowmelt) probably is largest.

Streamflow is also largest during the snowmelt period. The potential for mountain-stream-channel recharge probably is greatest during snowmelt because of the increase in streamflow and small evapotranspiration rates in the early spring. The chloride concentration in water from the Santa Fe River in the spring of 1988 probably is most representative of the chloride concentration of snowmelt under natural (predevelopment) conditions, although the chloride concentration in water from other streams in the area prior to development probably was slightly different because of differences in the amount of evapotranspiration in the different drainage basins. Smaller chloride concentrations in water in the Santa Fe River relative to other streams indicate that human activities have probably resulted in changes to the composition of recharge water from these other streams.

Chloride Concentration in Ground Water

Although chloride concentration in ground water (based on samples from wells and springs) in the Santa Fe area varies substantially, several areas of similar chloride concentration can be delineated (tables 5 and 6 and pl. 1). Data collected from 1943 to 1988 were available; however, when samples were collected from the same well during different years, the most recent analysis was plotted on plate 1. The large variation in chloride concentration may in part be due to changes with time in the chloride concentration in ground water at a particular location. Areal variations in chloride concentration need to be examined prior to application of the chloride-balance method to ensure that the chloride concentration in ground water used in the calculation has not been affected by chloride introduced to the ground water as the result of human activities. Areal variations in chloride concentration also can be used to investigate changes in chloride concentration of recharge water due to human activities. In general, the smallest chloride concentration in the basin probably is more representative of ground water unaffected by chloride contamination. Small chloride concentrations in ground water also indicate that rock/water interaction has not been a significant process in introducing dissolved chloride to ground water.

Several areas having ground-water chloride concentrations generally less than 5 milligrams per liter (zones 1, 2, 3, and 5) are downgradient from areas having much larger concentrations (fig. 3 and pl. 1). The large chloride concentrations upgradient from relatively small chloride concentrations indicate that the chloride concentration in recharge water has increased through time, or that human activities upgradient have resulted in local changes in the composition of ground water. Movement of septic tank effluent or irrigation water to the ground water would elevate chloride concentrations in the ground water. In some of the upgradient areas where chloride concentrations are large, nitrate concentrations are larger than 1 milligram per liter, which may indicate that septic tank effluent has recharged the ground water (table 5). For example, chloride concentrations in ground water in a large area southwest of Santa Fe (zone 1, pl. 1) are generally less than 5 milligrams per liter, but in an area east (upgradient) from this zone generally exceed 15 milligrams per liter. Ground water in zone 1 probably is representative of recharge water that infiltrated along the mountain front prior to significant development of the area. West or downgradient from zone 1, Longmire (1985) found anomalously large chloride and nitrate concentrations, which he attributed to infiltration of sewage effluent from the Santa Fe Municipal Waste Treatment Plant through the streambed of the Santa Fe River.

Ground water in an area northwest of Santa Fe (zone 2, pl. 1) also has chloride concentrations less than 5 milligrams per liter. This zone is similar to zone 1 in that chloride concentrations in ground water upgradient from this zone generally are large.

Ground water in zone 3, located along the Rio Tesuque, also has chloride concentrations less than 5 milligrams per liter (pl. 1). No samples were collected upgradient (east) from this zone, although ground water upstream (southeast) along the Rio Tesuque near Tesuque has chloride concentrations much larger than 5 milligrams per liter. Ground water upstream along the Rio Tesuque may be affected by septic tank effluent or a change in the composition of recharge water from the streams in the area.

Chloride concentrations in ground water in the area along the Pojoaque River generally are greater than 10 milligrams per liter (zone 4, pl. 1). In this area of the Pojoaque River, Hearne (1985, p. 22-24) indicated that the potentiometric surface is approximately at the altitude of the riverbed and there is a large amount of evapotranspiration. Evapotranspiration would tend to increase the chloride concentration in ground water. Nitrate concentrations in this area also are relatively large, suggesting that septic tank effluent also may be affecting ground-water chemistry (table 5).

Ground-water chloride concentrations in the Buckman area (zone 5, pl. 1) also generally are less than 5 milligrams per liter and similar to those near the recharge area nearer the mountain front (zones 1, 2, and 3, pl. 1). The ground-water flow system (McAda and Wasiolek, 1988, p. 13) discharges to the Rio Grande in the Buckman area. Because this area is approximately 14 miles from the mountain front (recharge area), ground water in this area probably was recharged a relatively long time ago. If there has been little or no change of chloride concentration in recharge water along the mountain front, the small chloride concentrations in ground water near Buckman (assuming they are representative of the discharge area for the flow system) indicate that little or no rock/water interaction results in increases in the ground-water chloride concentration and that arroyo-channel recharge is not significant.

If the volume of arroyo-channel recharge water were large, chloride concentrations in ground water near Buckman would be larger than those measured, assuming that chloride concentrations in arroyo-channel recharge water are 40 to 60 milligrams per liter as indicated by the two sites sampled and that the aquifer is well mixed. For example, if chloride concentration in mountain-front recharge water were 4 milligrams per liter and the volume of arroyo-channel recharge water (chloride concentration 50 milligrams per liter) were one-half the total recharge, the resulting water would have a chloride concentration of 27 milligrams per liter (0.5 x 50 plus 0.5 x 4). As can be seen, large volumes of arroyo-channel recharge water would significantly increase chloride concentrations in ground water.

The chloride concentration in ground water near a particular stream is similar to that measured in water from that stream; however, there are differences in the chloride concentrations in water from the different surface-water drainages. Chloride concentration in ground water near the Rio Chupadero, Arroyo Hondo, Tesuque Creek, Little Tesuque Creek, and Pojoaque Creek is in the same range as that in surface water. Chloride concentration in surface water from Arroyo Hondo was slightly larger than that in surface water from the Rio Chupadero and Pojoaque Creek. Chloride concentration in ground water along the Santa Fe River, near the mountain front, is much larger than that measured in water from the Santa Fe River in that area. Several zones were delineated downgradient from the mountain front where ground-water chloride concentration was similar to that measured in nearby reaches of the Santa Fe River, possibly indicating that ground-water chemistry near the mountain front has been affected by human activities.

Application of the Chloride-Balance Method

The chloride-balance method was used to estimate mountain-front recharge (mountain-stream-channel recharge plus subsurface inflow from mountains) in the Santa Fe River, Rio Tesuque, and Arroyo Hondo drainages (table 7). The drainage areas of the individual mountain basins were delineated on 1:100,000-scale maps, and the rate of precipitation (Pm, eq. 12) was estimated by overlaying contour maps of mean annual precipitation (U.S. Weather Bureau, 1961) and the drainage areas. The drainage areas were delineated upstream from streamflow-gaging stations to enable making calculations using precipitation values estimated by Spiegel and Baldwin (1963) (table 7). Calculations were also made using the precipitation values estimated by Wasiolek (in press) (table 7). The difference in drainage basin area between this study and that of Wasiolek is because Wasiolek (in press) calculated precipitation for the drainage basin upstream from the mountain front, not upstream from a particular stream gage. The average dissolved-chloride concentration in precipitation (Cp, eq. 12) used in the calculations was 0.29 milligram per liter. The value for dissolved-chloride concentration in ground water used in the method (Cg, eq. 12) was based on the distribution of dissolved chloride measured in ground water near each drainage (pl. 1). The chloride concentration in ground water was estimated to be 4.0 milligrams per liter in the Rio Tesuque drainage and 3.0 milligrams per liter in the Santa Fe River and Arroyo Hondo drainages. For the Arroyo Hondo drainage basin, all runoff from the mountains adjacent to the basin-fill aquifer was assumed to recharge the ground-water system. Recharge was estimated for the Santa Fe River and Rio Tesuque drainages in two ways: assuming no runoff and corrected for runoff. Runoff that does not result in recharge was estimated to be 580 acre-feet per year in the Santa Fe River drainage and 890 acre-feet per year in the Rio Tesuque drainage based on the results of Hearne (1985). The dissolved-chloride concentration in runoff (Cq, eq. 12) from the Santa Fe River and Rio Tesuque drainages was assumed to be the same as that in recharge or ground water, 3.0 and 4.0 milligrams per liter, respectively. The equation used to calculate recharge (eq. 12) can then be simplified to:

$$Rmf = \frac{Pm\,Cp}{Cg} - Q, \tag{13}$$

where Rmf = mountain-front recharge to the alluvial-basin aquifer system, in acre-feet per year;
Pm = average annual precipitation falling on the drainage basin, in acre-feet per year;
Cp = average concentration of chloride in bulk precipitation, in milligrams per liter; and
Cg = concentration of chloride in ground water in the alluvial-basin aquifer system near the mountain front, in milligrams per liter; and
Q = rate of runoff that does not become recharge and leaves the basin as streamflow, in acre-feet per year.

Annual mountain-front recharge estimated for the Santa Fe River drainage is approximately 2,900 acre-feet per year (table 7) assuming no runoff, or 2,320 acre-feet per year assuming runoff of 580 acre-feet per year out of the basin. By using the mean annual basin precipitation (combination of two subbasins) estimated by Spiegel and Baldwin (1963), annual mountain-front recharge is estimated to be approximately 3,200 acre-feet per year (table 7) assuming no runoff and 2,620 acre-feet per year assuming runoff out of the basin. Chloride concentration in streamflow at the mountain front can be estimated if subsurface inflow from the mountain is assumed to be zero. This value can be compared to measured chloride concentrations in streamflow to determine if subsurface inflow from the mountains is a significant source of recharge or if chloride concentrations in streamflow are significantly affected by human activities. Mean annual dissolved-chloride concentration in surface water at the mountain front was estimated to be 1.5 milligrams per liter, derived by dividing the average annual mass of chloride intercepting the basin by the measured or estimated annual streamflow (table 7). This estimated value is consistent with the concentration of 1.4 milligrams per liter measured upstream from McClure Reservoir in spring 1987 (tables 4 and 7). This indicates that subsurface inflow from the mountains as a source of recharge is negligible in the Santa Fe River drainage. In watersheds not affected by human activities this method could be used to estimate annual streamflow if no ground water discharges out of the watershed and if the chloride concentration of the streamflow were known.

The mountain-front recharge estimate for the Rio Tesuque drainage was divided between Little Tesuque Creek and Tesuque Creek because of the separate streamflow gages on these drainages. Mountain-front recharge was estimated to be approximately 630 acre-feet per year for the Little Tesuque Creek drainage and approximately 950 acre-feet per year for the Tesuque Creek drainage (table 7), assuming no runoff (total of 1,580 acre-feet per year). The total mountain-front recharge estimate for the Rio Tesuque assuming runoff (890 acre-feet per year) is approximately 690 acre-feet per year (1,580 - 890). Total mountain-front recharge for the Rio Tesuque drainage using the average basin precipitation estimates of Spiegel and Baldwin (1963) is approximately 590 acre-feet per year ((580 + 900) - 890) (table 7), assuming runoff (890 acre-feet per year). The average annual dissolved-chloride concentration in Little Tesuque Creek was estimated to be 6.3 milligrams per liter and in Tesuque Creek was estimated to be 1.7 milligrams per liter (table 7). These values are much smaller than those measured during this study (table 4). This is consistent with the suggestion that there has been a change in chloride concentration in water in these drainages due to human activities as was discussed in the "Chloride concentration in surface water" section of this report.

Mountain-front recharge estimated for the Arroyo Hondo drainage is 830 acre-feet per year, assuming no runoff. Mountain-front recharge estimated for the Arroyo Hondo drainage using the average basin precipitation estimates of Spiegel and Baldwin (1963) is 590 acre-feet per year; however, the drainage basin area used by Spiegel and Baldwin (1963) was approximately 80 percent of the drainage basin area used for the mountain-front recharge estimate in this report. The average annual dissolved-chloride concentration in water from Arroyo Hondo was estimated to be 4.7 milligrams per liter, which also is smaller than that measured in Arroyo Hondo during this study, possibly indicating a change in the chloride concentration in water in this drainage resulting from human activities.

Estimates for the Santa Fe River drainage are smaller than those of Hearne (1985), McAda and Wasiolek (1988), and Wasiolek (in press) (table 8). Mountain-front recharge (mountain-stream-channel recharge plus subsurface inflow from the mountains) estimates for the Rio Tesuque drainage obtained using the chloride-balance method are similar to those of Spiegel and Baldwin (1963), Lee Wilson and Associates (1978), and Hearne (1985) (table 8). Estimates for the Arroyo Hondo drainage are larger than those estimated by Spiegel and Baldwin (1963) and smaller than those estimated by McAda and Wasiolek (1988). Underestimation of mountain-front recharge by the use of equation 12 would result if the chloride concentration in precipitation were too small, if the precipitation volume were too small, if the chloride concentration in ground water were too large, or if there were a natural source of chloride in the mountains. The chloride concentration in precipitation and the volume of precipitation used in the estimates are, however, similar to values measured or used by other investigators (Spiegel and Baldwin, 1963; and Graustein, 1981). The chloride concentration of ground water used in the calculations generally was the smallest measured in ground water in the Tesuque aquifer system near the particular drainage. The most probable reason for error in the calculations would be a natural source of chloride in the mountains other than precipitation, such as weathering of minerals. Collection of more ground-water samples near the mountain front and streamflow samples for analysis of chloride concentration would be useful in proving that there is no source of chloride in the mountains other than precipitation.

RECHARGE BASED ON STABLE-ISOTOPE COMPOSITION

Stable isotopes of hydrogen and oxygen have been used to determine sources of ground-water recharge to an aquifer (Fontes, 1980; Yapp, 1985). Deuterium, oxygen-18, naturally occurring stable isotopes of hydrogen, and oxygen are part of the water molecule and thus are ideal tracers of water movement. The hydrogen and oxygen isotopic composition of water changes as a result of physical (evaporation and condensation), chemical, and biological processes (Gat, 1980). Changes in isotopic composition of water due to physical processes are important in this study. The isotopic composition of precipitation, the ultimate source of recharge, varies as a function of geographic considerations such as latitude, altitude, distance from the coast, and volume of precipitation (Dansgaard, 1964). The isotopic composition of precipitation at a particular point also varies seasonally (Gat, 1980, p. 30).

The approach used was to measure the hydrogen and oxygen isotopic composition of different possible sources of recharge to the Tesuque aquifer system, measure the hydrogen and oxygen isotopic composition of ground water from selected wells distributed throughout the basin, and then compare the areal distribution of the isotopic composition of ground water with the composition of various sources of recharge. If there are differences in the isotopic composition of different sources of recharge, the areas of mixing of these different recharge waters in the aquifer should be evident in the areal distribution of the isotopic composition of ground water, and the relative contribution of the various sources of recharge can be estimated.

Precipitation, snowmelt runoff, and summer thunderstorm runoff were possible sources of recharge that were sampled. Precipitation was sampled for hydrogen and oxygen isotopic composition on approximately a biweekly basis at the Sangre de Cristo Water Treatment Plant atmospheric-deposition station, which is approximately 7,400 feet above sea level (fig. 1). Samples were collected in an open bucket containing mineral oil to prevent evaporation, which would increase the isotopic composition of the sample.

Samples of snowmelt runoff and summer thunderstorm runoff were collected from the Pojoaque River, Rio Chupadero, Rio Tesuque, Tesuque Creek, Little Tesuque Creek, Santa Fe River, Arroyo de los Chamisos, and Arroyo Hondo (fig. 1). Samples of snowmelt runoff were collected in May and June 1987 and in late April 1988 from most of these streams. Samples of summer thunderstorm runoff were collected from most of these streams in late August and early September 1987. Most of these streams are perennial near the mountains, but because of streamflow lost to evaporation, infiltration, and diversion for irrigation, the streams are intermittent west of the mountain front. Streamflow is largest in the spring due to snowmelt runoff: approximately one-half of the annual flow is in April, May, and June (Spiegel and Baldwin, 1963, p. 156-157). Flow can also be large in August and September due to runoff from summer thunderstorms. Minimum flow in these streams is usually in January, February, or December (Spiegel and Baldwin, 1963, p. 157).

The isotopic composition of a sample is reported in delta units (δ) as parts per thousand (permil) relative difference in the ratio of the rare isotope to the common isotope with reference to the same ratio of a standard (Gat, 1980, p. 21):

$$\delta D^0/_{00} = \left[\frac{(D/H)\text{ sample}}{D/H\text{ standard}} - 1\right] 1{,}000$$

$$\delta^{18}O^0/_{00} = \left[\frac{\dfrac{^{18}O}{^{16}O}\text{ sample}}{\dfrac{^{18}O}{^{16}O}\text{ standard}} - 1\right] 1{,}000, \tag{14}$$

where D = deuterium (rare isotope);
H = hydrogen (common isotope);
^{18}O = oxygen-18 (rare isotope); and
^{16}O = oxygen-16 (common isotope).

The standard used is Vienna standard mean ocean water (V-SMOW). Samples were analyzed by two laboratories that have different analytical precision. The stated analytical precision for one laboratory was plus or minus 1 permil for δD and plus or minus 0.1 permil for $\delta^{18}O$. The stated analytical precision for the other laboratory was plus or minus 0.5 permil for δD and plus or minus 0.05 permil for $\delta^{18}O$. Five samples were sent to both laboratories to determine if the results from each laboratory were comparable; the results from the laboratories agreed within the stated analytical precision for the individual samples.

Hydrogen and Oxygen Isotopic Composition of Precipitation

The isotopic composition of precipitation at the Sangre de Cristo Water Treatment Plant varies widely (table 9 and fig. 11). The δD ranged from -179 to -30 permil and the $\delta^{18}O$ ranged from -23.3 to -4.5 permil. The meteoric water line was defined by Craig (1961) to be a line that describes the relation between δD and $\delta^{18}O$ in worldwide precipitation ($\delta D = 8\ \delta^{18}O + 10^{0}/_{00}$). The relation between δD and $\delta^{18}O$ for precipitation for a particular region varies from the global equation; the equation for local precipitation is called the local meteoric water line. A local meteoric water line was determined by doing a linear regression of the data collected. The equation for the local meteoric water line at the Sangre de Cristo Water Treatment Plant was:

$$\delta D = 8.0\ \delta^{18}O + 11.1\ ^{0}/_{00}. \qquad (15)$$

This is similar to the local meteoric water line determined by Vuataz and Goff (1986, p. 1843) for the Jemez Mountains west of the study area ($\delta D = 8.0\ \delta^{18}O + 12$). The local meteoric water line calculated for the Santa Fe area has a coefficient of determination (R^2) value of 0.985 and both the slope and intercept of the equation are significantly different than 0 at the 95-percent confidence level.

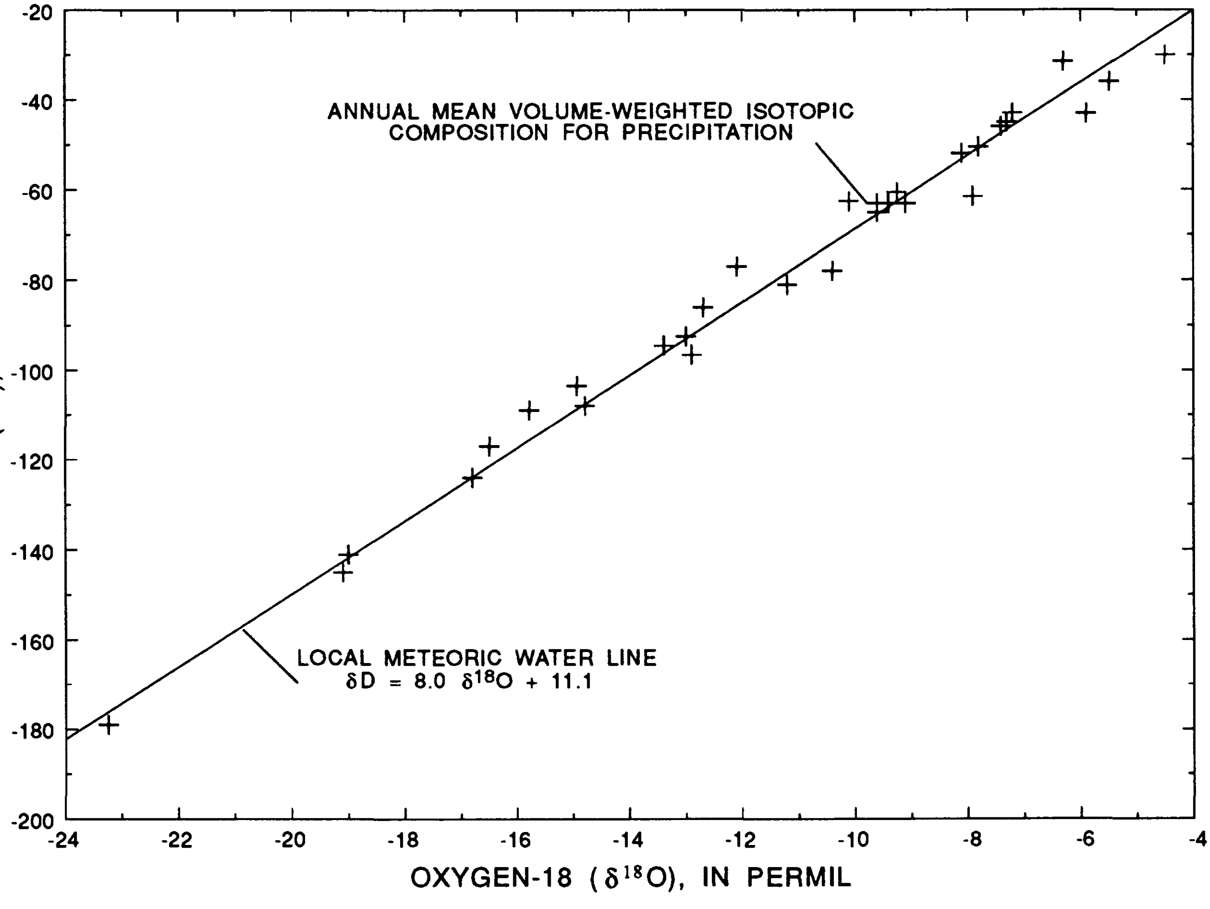


Figure 11.--Relation between δ oxygen-18 and δ deuterium for precipitation in the Santa Fe area.

The hydrogen isotopic composition of precipitation generally is isotopically enriched in deuterium (more positive) in the spring and summer months (April through October) and least enriched in deuterium (more negative) in the fall and winter months (November through March) (fig. 12). An annual mean volume-weighted δD composition of -65.2 permil was calculated for August 26, 1987, through August 25, 1988. This value may be less negative compared to normal, long-term precipitation conditions because during the sampling period there was more summer precipitation than the mean annual summer precipitation and winter precipitation generally was less than its mean; thus, the estimate was biased by a larger amount of precipitation during the summer months relative to the long-term mean.

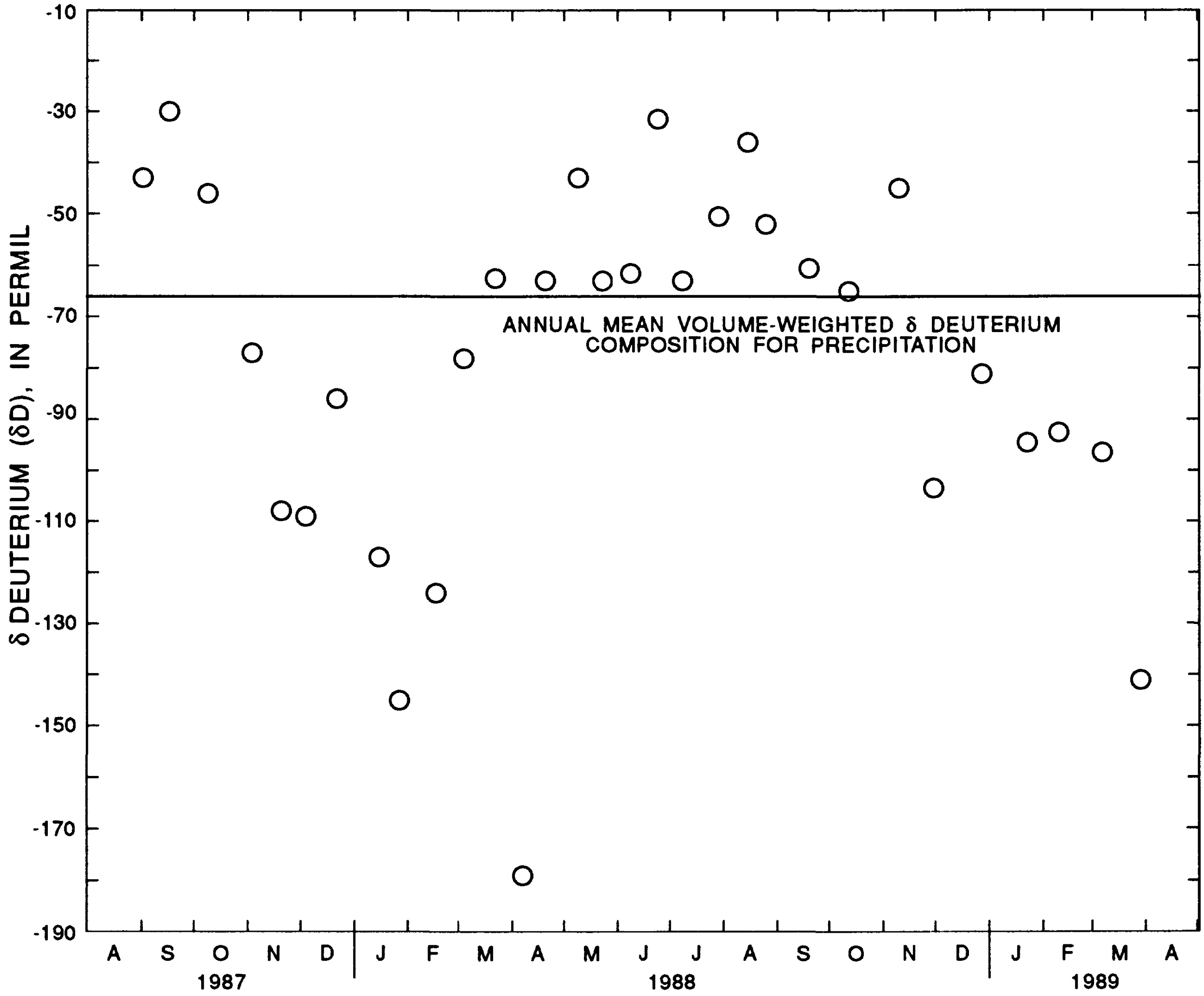


Figure 12.--Relation between sample collection date and δ deuterium for precipitation in the Santa Fe area, September 1987 to March 1989.

Hydrogen and Oxygen Isotopic Composition of Surface Water

The δD composition of surface water collected from the streams having headwaters in the mountains ranges from -91.5 to -68.0 permil and the δ^{18}O composition ranges from -13.2 to -10.0 permil (table 4 and pl. 2). A linear regression of surface-water data resulted in the following equation:

$$\delta D = 5.4\, \delta^{18}O - 19.5\ ^{0}/_{00} \qquad (R^2 = 0.84). \tag{16}$$

This equation has a much different slope and intercept than the local meteoric water line that was determined using precipitation data (fig. 13). Points that plot below the calculated local meteoric water line may represent water from areas where evaporation has occurred. Evaporation enriches the water in deuterium and oxygen-18 such that the $\delta D/\delta^{18}O$ slope is less than 8 (Gat, 1980). All of the points fall below the annual mean volume-weighted hydrogen and oxygen isotopic composition of precipitation collected at the Sangre de Cristo Water Treatment Plant (fig. 13). This could be because the altitude of the drainage basins is higher than the altitude of the precipitation collection site or because most runoff from the mountainous drainage basins is the result of winter precipitation.

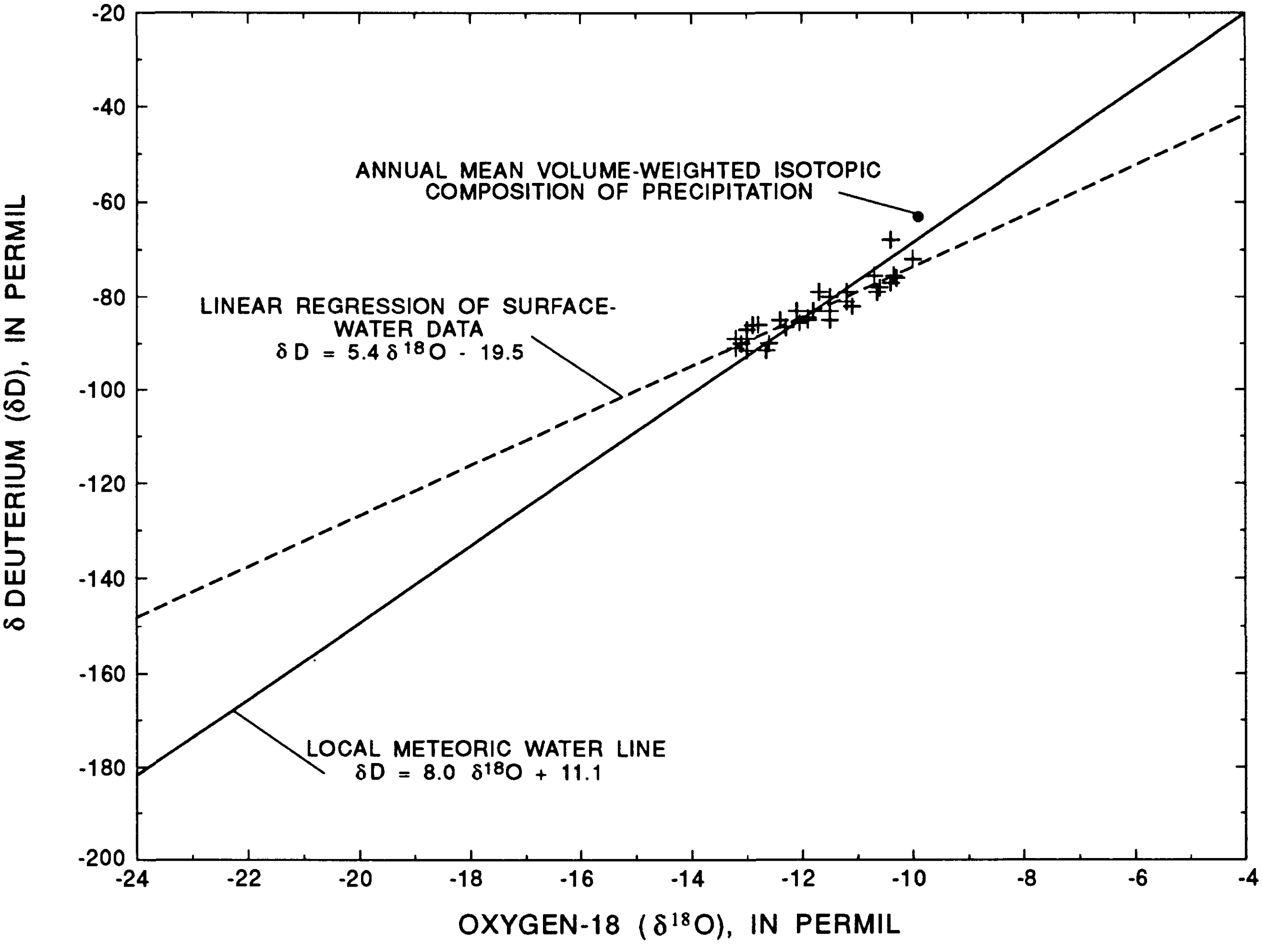


Figure 13.--Relation between δ oxygen-18 and δ deuterium for surface water in the Santa Fe area.

Water from the Rio Chupadero (15) and Tesuque Creek near the ski area (8) generally was more negative (with respect to deuterium), and water from Arroyo Hondo (14) generally was more positive (fig. 14). For a particular site, samples collected in the spring generally are more negative than samples collected during the summer, a trend similar to that observed in precipitation (winter precipitation isotopically more negative than summer precipitation). Water collected from Little Tesuque Creek at State Highway 22 (7) in August 1987 is isotopically the most positive surface water collected (fig. 14). This sample was collected during a thunderstorm, while the streamflow was significantly increased due to local runoff. This surface water is isotopically similar to precipitation collected in August 1987 but much different than the surface-water sample collected on the same day but prior to the thunderstorm at Little Tesuque Creek at the first crossing with Hyde Park Road (6), which is upstream. This indicates that the isotopic composition of water in Little Tesuque Creek becomes more positive as the result of runoff from intense summer thunderstorms. However, the isotopic composition of water in most of the streams sampled in August 1987 was more negative than most summer precipitation, indicating that most flow in the streams sampled during this time of the year is the result of winter precipitation. There would be mixing during summer thunderstorms of local surface runoff and snowmelt water (winter precipitation) discharging from the shallow alluvial aquifers in the mountains; however, most water in the streams having headwaters in the mountains probably is the result of winter precipitation. This agrees with the findings of Graustein (1981) as discussed earlier.

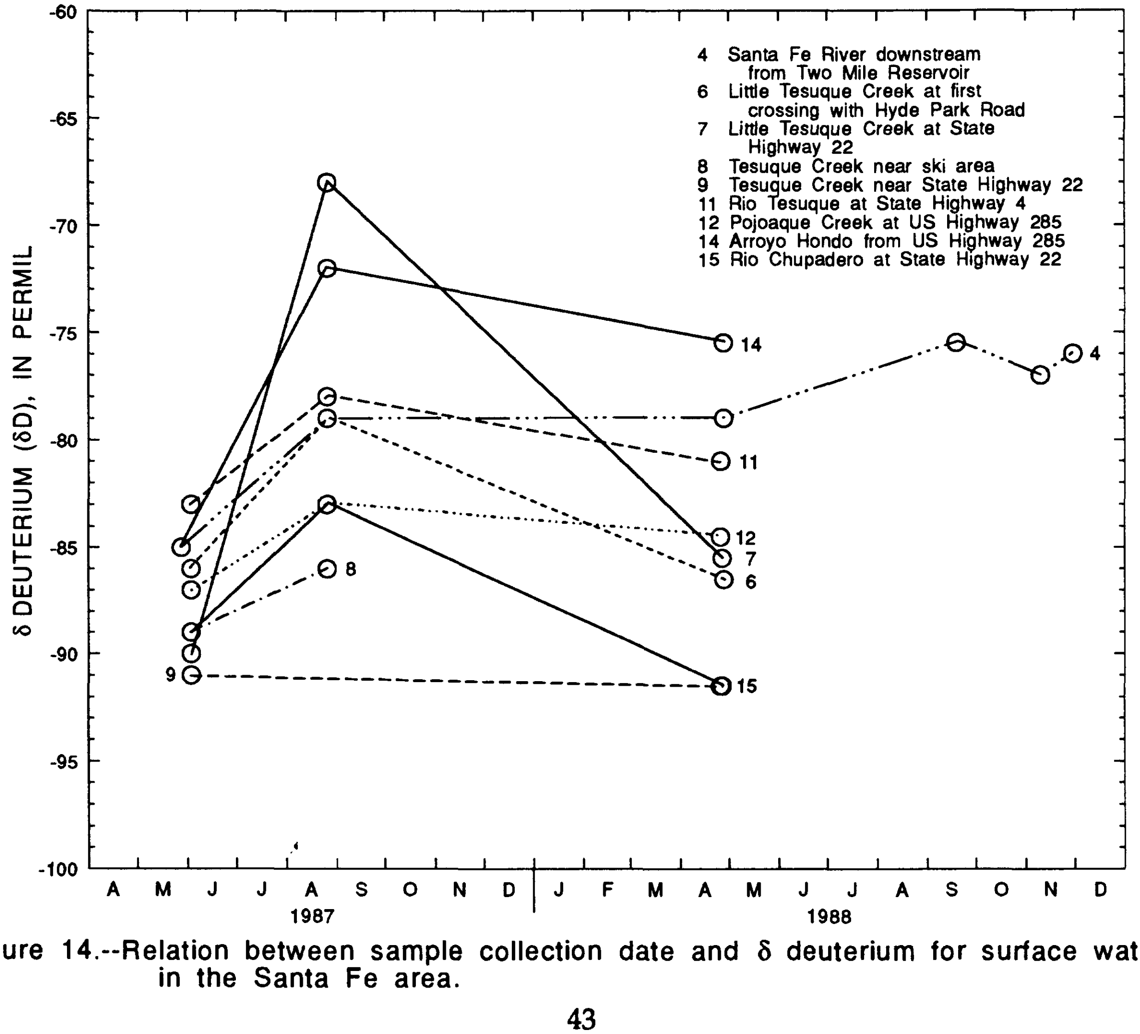


Figure 14.--Relation between sample collection date and δ deuterium for surface water in the Santa Fe area.

Hydrogen and Oxygen Isotopic Composition of Ground Water

The δD composition of ground water ranges from -116 to -61 permil and the $\delta^{18}O$ composition ranges from -15.8 to -9.3 permil (table 6 and fig. 15). Most ground water sampled has a δD composition range of -85 to -70 permil and a $\delta^{18}O$ composition range of -12 to -10 permil (fig. 15). The linear regression equation calculated from the ground-water samples is:

$$\delta D = 7.8\ \delta^{18}O + 9.4\ {}^{0}/_{00} \qquad (R^2 = 0.87). \qquad (17)$$

This equation is similar to the equation (eq. 15) calculated using precipitation data ($\delta D = 8.0\ \delta^{18}O + 11.1{}^{0}/_{00}$) (local meteoric water line). The isotopic composition of most of the ground water does not seem to be significantly affected by evaporation because most samples that plot below the local meteoric water line are not far below the line. Evaporation could be occurring and not affect the isotopic composition of the recharge water if, during certain times of the year, a large part of the recharge water is evaporated, leaving a relatively small amount of isotopically positive water, which mixes with a large amount of unevaporated water. The resulting mixed water would have chloride concentrations larger than the unevaporated water because of the large amount of salts that would be concentrated in the evaporated water. The isotopic composition of the mixed water would not be substantially affected by the small amount of isotopically positive evaporated water. Transpiration that does not affect the isotopic composition of water (Zimmerman and others, 1967) also may be a major process that concentrates dissolved solids (chloride) in recharge water and ground water.

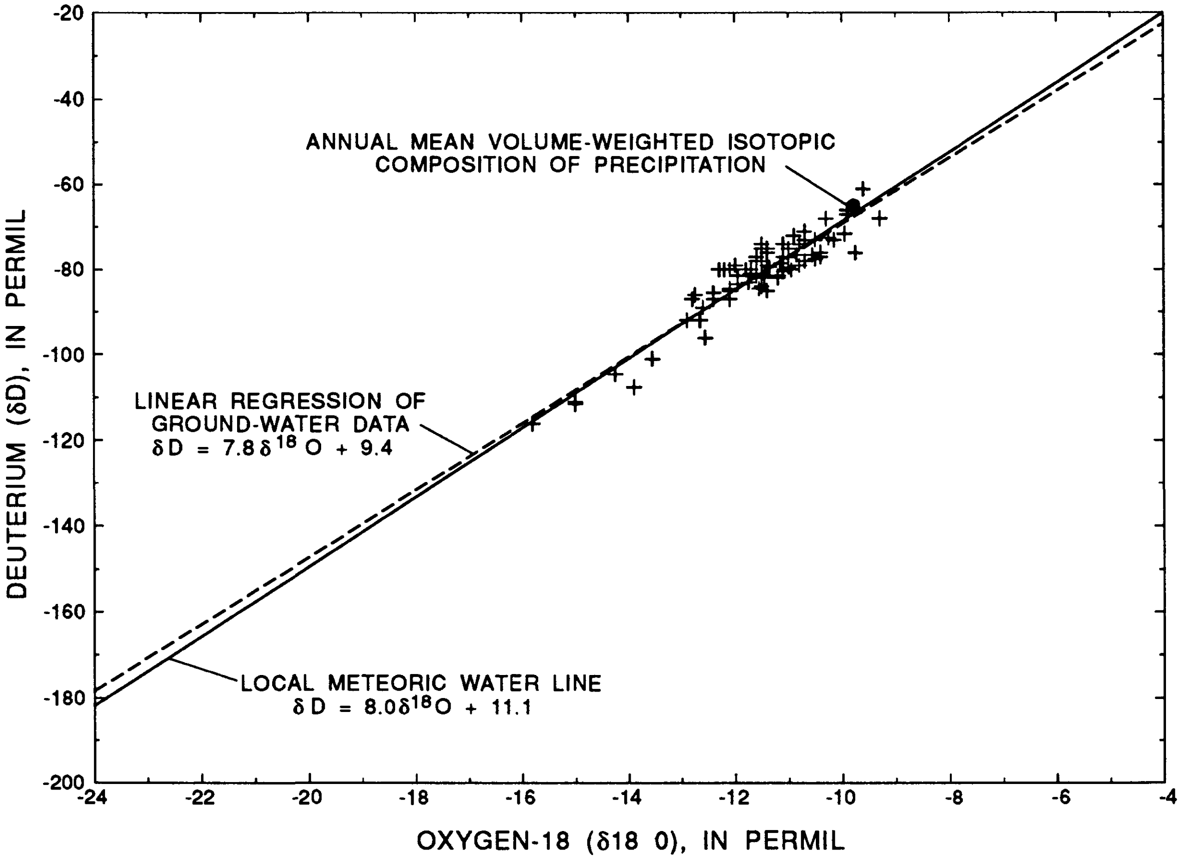


Figure 15.--Relation between δ oxygen-18 and δ deuterium for ground water in the Santa Fe area.

Most ground-water samples plot below the annual mean volume-weighted hydrogen and oxygen isotopic composition of precipitation (fig. 15). This suggests that most water that recharges the aquifer results from winter precipitation, which generally is isotopically more negative. The range in isotopic composition of ground water is similar to the range measured in surface waters. The similarity in the isotopic composition of ground water and surface water (derived from the mountainous areas) and the lack of ground-water samples that are isotopically similar to summer precipitation indicate that mountain-front recharge is the most significant type of recharge and that arroyo-channel recharge, which generally occurs in the summer, is relatively insignificant.

With the exception of the samples collected along the Pojoaque River, the deuterium composition of ground water generally gets lighter to the north (pl. 2). This is similar to the trend recognized in surface-water samples (fig. 14). The δD composition of most ground water near Arroyo Hondo and the Santa Fe River is generally between -80 and -70 permil (pl. 2). The δD composition of water from several wells north of Arroyo Hondo and south of the Santa Fe River is greater than -70 permil, which may indicate that summer precipitation results in some recharge to the aquifer in this area. The δD composition of ground water near the Rio Tesuque generally is less than -80 permil. The δD composition of water along the Rio Chupadero varies over a large range, but generally is more negative than other water sampled in the study area. Along the Pojoaque River, the δD composition of ground water ranges from -79.5 to -76 permil and plots below the regression line of ground waters. The isotopic composition of water in this area is probably affected by evaporation, which would tend to make the water isotopically more positive than its original composition prior to evaporation; thus the waters are more positive than other waters in the area. Evaporation also would cause the water to plot below the regression line of ground water if most ground waters were not affected by evaporation.

The δD composition of several waters sampled in the Buckman area generally are more negative (-104.5 to -111.5 permil) than most ground water sampled in the study area. This area is a discharge area for the flow system (McAda and Wasiolek, 1988) and is located relatively far (approximately 14 miles) from the recharge areas along the mountain front and could represent water that recharged the aquifer a long time ago. Phillips and others (1986, p. 183) indicated that the δD composition of ground water that was recharged 8,000 to 17,000 years ago in the San Juan Basin in northwestern New Mexico was approximately 25 permil more negative than ground-water recharge presently occurring. Phillips and others (1986, p. 184) indicated that the mean annual temperature has been the major control of the stable isotopic composition of recharge to the San Juan Basin. They estimated that 8,000 to 17,000 years ago, the mean annual temperature in the San Juan Basin was approximately 7 degrees Celsius less than the present temperature. The relatively more negative ground water in the Buckman area probably represents water that was recharged during this time.

The isotopic composition of ground water near a particular drainage was similar to that of surface water in the drainage, but the isotopic composition of surface water was different among particular drainages (pl. 2). It was not possible, however, to trace ground water from a particular drainage or recharge source through the flow system. This was in part due to the large variation in isotopic composition of ground water in small areas and the lack of sampling sites in areas downgradient from the recharge areas.

SUMMARY

Chloride-balance methods were used in the unsaturated zone and in ground water to estimate direct and mountain-front recharge to the basin-fill aquifer in the Santa Fe area. Results of the chloride-balance determinations in the unsaturated zone indicate that no recharge has occurred in the recent past at sites having little or no runoff or flooding. Recharge does occur in arroyo channels, and the chloride concentration of recharge water ranges from 40 to 60 milligrams per liter at the sites sampled. Recharge rates in arroyos were not calculated because the volume of water infiltrating through arroyo channels and the chloride concentration in this water are difficult to measure. On the basis of chloride concentrations in ground water, arroyo-channel recharge is not a significant source of recharge.

Chloride concentrations in surface water and ground water were used to investigate recharge processes along drainages having headwaters in the mountains adjacent to the Tesuque aquifer system. Chloride concentrations in water from these streams were smallest in the spring during the end of the snowmelt period and were largest in the late winter to early spring at the beginning of the snowmelt period. Chloride concentration was intermediate in the late summer during summer thunderstorm runoff. The measured chloride concentration generally was smallest in the Santa Fe River and largest in Little Tesuque Creek. The large chloride concentrations in Little Tesuque Creek probably are in part from runoff containing dissolved road salt and from ground-water inflow that contains septic tank effluent to the stream. Chloride concentrations in ground water had large areal variations. In several areas, ground-water chloride concentrations are less than 5 milligrams per liter. Chloride concentrations generally are larger in areas upgradient from areas having relatively small ground-water chloride concentrations. The larger chloride concentrations upgradient indicate that the chloride concentration in recharge water has changed or that the sources of recharge have changed. Possible changes in the sources of recharge would be the infiltration of septic tank effluent or infiltration of irrigation water, as opposed to infiltration of streamflow alone before these effects of development. In the Buckman area, which is in part of the discharge area for the flow system, ground-water chloride concentrations generally are less than 5 milligrams per liter. This indicates that arroyo-channel recharge and rock/water interaction do not significantly affect chloride concentrations in ground water. If arroyo-channel recharge were a significant source of recharge and water in the aquifer is well mixed, chloride concentration in the Buckman area would be larger than that observed because the chloride concentration of arroyo-channel recharge ranged from 40 to 60 milligrams per liter and the chloride concentration in ground water near the mountain front (recharge area) was similar to that in ground water near Buckman (discharge area). Estimates of natural recharge, using the chloride-balance method and assuming runoff out of the recharge area, are approximately 2,320 acre-feet per year in the Santa Fe River drainage, 690 acre-feet per year in the Rio Tesuque drainage, and 830 acre-feet per year in the Arroyo Hondo drainage.

Stable isotopes of hydrogen and oxygen were used to investigate sources of recharge to the basin-fill aquifer. A local meteoric water line of $\delta D = 8.0\ \delta^{18}O + 11.1$ was determined from precipitation data collected in the study area. Ground water generally plotted along this meteoric water line, indicating that evaporation does not significantly affect recharge water. Summer precipitation generally is isotopically more positive than winter precipitation. On the basis of the isotopic composition of ground water, winter precipitation results in relatively more recharge than summer precipitation and arroyo-channel recharge is relatively insignificant. The isotopic composition of ground water near a particular drainage was similar to that of surface water in the drainages, but there were differences in the isotopic composition of surface water from particular drainages; however, it was not possible to trace ground water from a particular drainage or recharge source through the flow system. This was in part due to substantial variation in the isotopic composition of ground water in small areas and the lack of sampling sites in some areas in the flow system downgradient from the recharge areas. The isotopic composition of surface water and ground water generally gets more negative to the north. The isotopic composition of ground water in the Buckman area was much more negative than that of most ground water in other parts of the study area. The isotopically more negative ground water in the Buckman area probably was recharged to the aquifer during a time (possibly 8,000 to 17,000 years ago) when mean annual temperatures were less than at present.

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Table 1.--Natural flow in and summary of estimated or calculated recharge to and discharge from the Tesuque aquifer system in selected drainages near Santa Fe

[All values are in acre-feet per year; --, no data]

	Natural flow		Stream-channel recharge				Discharge	
Drainage	Spiegel and Baldwin, 1963	Reiland, 1975	Spiegel and Baldwin, 1963	Lee Wilson and Associates, 1978	Hearne 1985	McAda and Wasiolek, 1988	Hearne, 1985	McAda and Wasiolek, 1988
Santa Fe River	6,700 (1) 5,820 (3) 680 (5)	-- --	5,800 (2) 2,900 (4)	3,500	5,220	5,430	3,150	4,700
Arroyo Hondo	535 (6)	--	535	--	--	510	--	--
Arroyo de los Chamisos	--	--	--	--	--	1,010	--	--
Little Tesuque Creek	900 (6)	400 (7)	--	--	400	--	--	--
Tesuque Creek	2,800 (6)	2,300 (7)			303	--	--	--
Rio Tesuque	--	--	1,450	1,500	1,090	3,400	250	670
Rio Chupadero	--	300 (8)	--	--	390	290	--	--
Rio en Medio	--	1,800 (8)	--	--	890	2,460	--	510
Rio Nambe	--	8,000 (9)	--	--	--	--	950	--
Pojoaque Creek	--	--	--	--	--	--	330	--
Pojoaque River Basin (total)	--	--	--	2,700(10)	3,080	5,900	3,050	5,300

(1) Annual water yield, upstream from gaging station, downstream from McClure Dam.
(2) Maximum in a 4-mile reach from mountain front.
(3) Median runoff below McClure Dam.
(4) "Optimum" in a 4-mile reach from mountain front.
(5) Downstream from gaging station downstream from McClure Dam to Two Mile Reservoir.
(6) Annual average water yield, upstream from present (1960) or most recent gaging station.
(7) Upstream from diversions.
(8) At Nambe Pueblo boundary.
(9) At Nambe Falls.
(10) Excluding the Rio Tesuque drainage.

Table 2.--Dissolved-chloride concentration and precipitation amount collected at the Sangre de Cristo Water Treatment Plant

[--, no data; sample volumes in parentheses were not measured, but were calculated from the wedge rain gage assuming no evaporation of sample]

Date	Chloride, dissolved (milligrams per liter as Cl)	Sample volume collected (milliliters)	Precipitation amount (inches)		Mass of chloride (milligrams)
			Tipping bucket	Wedge	
Nov. 20-Dec. 22, 1987	0.850	350	--	0.45	0.298
Dec. 22, 1987-Jan. 15, 1988	.880	240	--	.45	.211
Jan. 15-27, 1988	.140	1,215	--	.58	.170
Jan. 27-Feb. 16, 1988	1.400	104	--	--	.146
Feb. 16-Mar. 4, 1988	2.000	104	--	[1].52	.208
Mar. 4-Apr. 20, 1988	.880	729	1.02	1.27	.642
Apr. 20, 1988-May 23, 1988	.400	1,218	1.25	1.13	.487
May 23-July 8, 1988	1.700	969	3.71	3.55	1.647
July 8-29, 1988	.230	(3,164)	1.98	1.94	.728
July 29-Aug. 15, 1988	3.000	202	1.40	1.32	.606
Aug. 15-25, 1988	.170	(3,794)	2.39	2.30	.645
Aug. 25-Sept. 19, 1988	.270	(4,569)	2.71	2.95	1.234
Sept. 19-Oct. 12, 1988	.660	1,329	2.02	2.05	.877
Oct. 12-Nov. 10, 1988	.950	270	.18	.15	.257
Nov. 10-30, 1988	.650	1,015	.54	.15	.660
Dec. 5, 1988-Jan. 23, 1989	5.600	105	.41	.70	.588
Jan. 23-Feb. 10, 1989	.110	3,790	1.46	1.55	.417
Feb. 13-Mar. 7, 1989	.950	244	.23	.20	.232
Mar. 7-29, 1989	.990	264	.43	.60	.261

[1] Sampling period January 27, 1988, through March 4, 1988.

Table 3.--Recharge and cumulative chloride estimates

[--, value not calculated. *, minimum amount of recharge occurring at these sites]

Drill hole	Interval (feet)	Cumulative chloride (grams per square meter)	Average chloride concentration in soil water (milligrams per liter)	Recharge rate (inches per year)	Time required for accumulation of chloride (years)
			Mesa sites		
1	0-20	925	--	--	8,800
1	25.7-49	--	134	--	--
2	0-32	850	--	--	8,090
2	32.5-49	--	70.9	--	--
7	0-30	700	--	--	6,660
7	15.1-29	--	321	--	--
7	30.6-49.7	--	43	--	--
			Arroyo channel sites		
3	0-47.2	--	45.5	0.09*	--
5	0-49	--	62.7	0.07*	--
			Arroyo margin sites		
4	0-20	260	--	--	2,470
6	0-10.8	--	77.7	0.06	--
6	26-31	--	40.4	0.11	--
6	31.5-40.2	--	22.7	0.19	--
6	41.2-43.3	--	87.2	0.05	--

Table 4.--Dissolved-chloride concentration and δ deuterium and δ oxygen-18 composition of surface water from selected drainages near Santa Fe

[See figure 1 for location of sites. --, no data]

Station reference number	Sampling site	Date	Chloride concentration (milligrams per liter)	δ deuterium (permil)	δ oxygen-18 (permil)
1	Santa Fe River upstream from McClure Reservoir	5-28-87	1.4	--	--
2	Santa Fe River downstream from McClure Reservoir	5-28-87	1.8	--	--
3	Santa Fe River downstream from Nichols Reservoir	5-28-87	1.9	--	--
4	Santa Fe River downstream from Two Mile Reservoir	5-28-87	2.1	-85	-12.4
		8-26-87	4.6	-79	-11.2
		4-28-88	6.5	-79.0	-10.65
		8-25-88	6.2	--	--
		9-19-88	5.5	-75.5	-10.7
		11-10-88	--	-77.0	-10.4
		11-30-88	--	-76.0	-10.3
5	Little Tesuque Creek at Hyde Park Headquarters	6-03-87	6.6	--	--
		8-26-87	10.7	--	--
6	Little Tesuque Creek at first crossing with Hyde Park Road	6-03-87	11.7	-86	-12.8
		8-26-87	26.8	-79	-11.7
		4-28-88	34.8	-86.5	-12.30
7	Little Tesuque Creek at State Highway 22	6-03-87	10.7	-90	-12.6
		8-26-87	23.8	-68	-10.4
		4-27-88	37.0	-85.5	-12.05
8	Tesuque Creek near ski area	6-03-87	1.2	-89	-13.2
		8-26-87	1.3	-86	-12.9

Table 4.--Dissolved-chloride concentration and δ deuterium and δ oxygen-18 composition of surface water from selected drainages near Santa Fe--Concluded

Station reference number	Sampling site	Date	Chloride concentration (milligrams per liter)	δ deuterium (permil)	δ oxygen-18 (permil)
9	Tesuque Creek near State Highway 22	6-03-87	4.9	-91	-13.2
		4-27-88	13.2	-91.5	-13.00
10	Rio Tesuque at State Highway 22	6-03-87	7.0	-90.0	-13.1
11	Rio Tesuque at State Highway 4	6-03-87	17.3	-83	-11.5
		8-26-87	22.0	-78	-10.6
		4-26-88	19.9	-81.0	-11.20
12	Pojoaque Creek at U.S. Highway 285	6-03-87	3.3	-87	-13.0
		8-26-87	7.1	-83	-11.8
		4-26-88	10.7	-84.5	-11.90
13	Arroyo Hondo at U.S. Highway 285	5-28-87	8.4	-85	-11.5
		8-26-87	--	-72.0	-10.0
		8-28-88	16.9	-75.5	-10.35
14	Arroyo Hondo upstream from U.S. Highway 285	5-28-87	5.5	-85.0	-11.9
15	Rio Chupadero at State Highway 22	6-03-87	8.1	-89	-13.0
		8-26-87	11.7	-83	-12.1
		4-26-88	14.2	-91.5	-12.65
	Arroyo de los Chamisos				
16	Site 1	5-28-87	11.8	-80.0	-11.5
17	Site 2	5-28-87	4.9	-82.0	-11.1

Table 5.--Dissolved-chloride and dissolved-nitrogen concentrations in ground water near Santa Fe

[Well location number: first six digits are latitude, next seven digits are longitude, and last two digits are sequence number; mg/L, milligrams per liter; --, no data; <, less than]

Well location number	Date of sample	Chloride, dissolved (mg/L as Cl)	Nitrogen, nitrate, dissolved (mg/L as N)	Nitrogen, NO_2+NO_3, dissolved (mg/L as N)	Depth of well, total (feet)	Water level (feet below land surface)
353012106033301	8-22-86	13.0	--	1.30	--	--
353104105510801	9-15-70	44.0	0.30	--	--	--
353108106042001	8-22-86	11.0	--	1.20	96	--
353205105571001	8-14-86	7.4	--	1.60	--	--
353222106071001	8-22-86	5.1	--	0.55	--	--
353229106081001	7-14-76	25.0	--	0.07	272	--
353229106081001	3-25-85	15.0	--	<0.10	272	--
353243106084101	8-13-86	10.0	--	0.86	--	--
353251106073101	8-06-86	6.8	--	0.44	--	--
353255106023001	8-01-86	6.2	--	0.69	--	--
353306105542001	3-21-74	37.0	--	2.40	--	--
353339105581501	1-16-52	30.0	2.30	--	80	--
353343106072201	8-01-51	13.0	0.14	--	--	--
353355106033101	2-14-77	6.5	--	0.85	794	--
353406106071101	2-14-77	5.4	--	0.08	163	--
353439105532801	6-25-85	48.0	--	1.70	--	--
353501106033101	6-14-77	2.9	--	0.83	--	--
353504106031501	3-13-73	5.0	0.29	--	260	--
353508106025701	7-24-86	1.6	--	0.64	--	--
353518105551301	3-22-74	20.0	--	4.00	--	--
353522105513301	3-22-74	21.0	--	2.20	--	--
353526106054101	10-10-51	--	2.20	--	--	--
353533106045301	8-27-86	10.0	--	1.90	--	--
353541106043201	5-20-85	3.0	--	0.95	--	--
353544106030801	8-01-51	5.0	2.50	--	225	176.0

Table 5.--Dissolved-chloride and dissolved-nitrogen concentrations in ground water near Santa Fe--Continued

Well location number	Date of sample	Chloride, dissolved (mg/L as Cl)	Nitrogen, nitrate, dissolved (mg/L as N)	Nitrogen, NO_2+NO_3, dissolved (mg/L as N)	Depth of well, total (feet)	Water level (feet below land surface)
353556106071901	4-18-77	3.3	–	1.50	–	–
353605106071701	10-10-51	3.5	1.20	--	–	–
353607106071701	10-10-51	3.5	1.20	--	–	–
353608106015701	8-09-86	2.3	–	0.44	–	–
353608106070201	8-28-86	6.3	--	3.10	–	–
353631106024101	7-08-87	6.3	–	0.26	255	–
353655105541801	8-14-86	61.0	–	0.23	–	–
353658106022401	7-09-87	3.6	–	5.40	368	–
353703106050201	7-11-86	3.1	–	0.70	–	–
353711106023401	7-12-85	2.0	–	0.30	–	–
353722106013901	7-25-86	1.4	–	0.47	–	–
353723106064301	8-28-86	4.8	–	1.70	–	–
353733106005701	8-14-86	1.6	–	0.21	–	–
353738106005301	8-13-86	4.2	–	0.95	–	–
353738106030201	6-13-85	5.2	–	1.30	–	–
353739105564601	7-11-85	25.0	–	1.80	–	–
353742106041801	7-03-86	6.7	–	0.93	–	–
353743106042501	6-13-85	2.1	–	0.36	–	–
353747106024001	6-21-85	5.1	–	1.30	495	–
353749106030201	11-21-52	4.0	0.36	--	384	212.0
353749106030201	4-30-85	6.2	–	1.30	340	–
353750106042201	8-13-51	2.2	0.27	--	248	–
353753106050901	6-27-85	10.0	–	3.50	–	–
353808106031001	8-07-86	1.4	0.24	0.25	–	–
353808106031801	8-08-86	1.3	–	0.18	–	–
353811105544201	7-11-85	27.0	–	1.60	270	–
353812106042001	6-28-85	2.8	–	0.27	500	–
353814106031701	8-27-86	1.1	–	0.14	–	–
353815106032601	6-12-85	1.7	–	0.58	–	–
353817106012401	3-01-85	2.5	–	0.47	–	–

Table 5.--Dissolved-chloride and dissolved-nitrogen concentrations in ground water near Santa Fe--Continued

Well location number	Date of sample	Chloride, dissolved (mg/L as Cl)	Nitrogen, nitrate, dissolved (mg/L as N)	Nitrogen, NO_2+NO_3, dissolved (mg/L as N)	Depth of well, total (feet)	Water level (feet below land surface)
353817106015601	11-21-52	0.5	0.18	--	410	--
353818106020202	4-16-74	2.0	--	0.37	--	--
353819105563501	4-11-74	19.0	--	3.10	--	--
353829105561201	9-12-51	18.0	0.77	--	300	60.0
353843106025001	7-24-51	44.0	6.80	--	380	179.0
353845105564401	6-26-85	10.0	--	4.50	210	--
353850105584301	1-02-52	10.0	1.20	--	220	--
353931106003701	7-14-87	21.0	--	1.10	69	--
353933106004101	3-08-77	9.5	--	4.40	110	--
353945105574501	9-16-86	8.8	--	<0.10	1,952	--
353945105574503	9-16-86	86.0	--	0.46	780	--
353953105540201	8-27-86	14.0	--	<0.10	--	--
354012105540201	8-27-86	15.0	--	<0.10	--	--
354013105590501	7-18-86	16.0	--	3.70	--	--
354019105590801	7-24-51	9.0	3.20	--	58	6.0
354019106024001	4-26-77	2.6	--	5.90	440	369.13
354020105591501	1-15-53	10.0	2.50	--	--	--
354028106010801	6-25-85	4.4	--	1.40	438	--
354029105563401	6-26-85	6.6	--	3.90	--	--
354032105574801	12-16-64	9.4	3.60	--	700	--
354033105583701	9-11-51	8.0	6.10	--	20	18.0
354034105574301	6-07-51	11.0	3.40	--	725	--
354038105572101	8-09-68	8.3	--	--	316	137.4
354041105581301	0-00-56	8.0	5.00	--	740	192.0
354052105570201	6-07-51	16.0	--	--	255	40.0
354052105582101	8-03-51	10.0	6.30	--	197	58.0
354059105591501	7-24-86	13.0	--	2.70	--	--
354103105574401	11-26-46	17.0	1.60	--	347	64.0
354105105580401	6-07-51	12.0	6.80	--	616	--
354117105574701	6-07-51	8.5	--	--	492	--

Table 5.--Dissolved-chloride and dissolved-nitrogen concentrations in ground water near Santa Fe--Continued

Well location number	Date of sample	Chloride, dissolved (mg/L as Cl)	Nitrogen, nitrate, dissolved (mg/L as N)	Nitrogen, NO_2+NO_3, dissolved (mg/L as N)	Depth of well, total (feet)	Water level (feet below land surface)
354119105590501	7-25-86	3.5	--	1.80	--	--
354132105571901	7-09-85	61.0	--	15.00	--	--
354135105561701	9-11-51	8.0	0.56	--	100	100.0
354135105561702	9-12-51	12.0	4.10	--	180	80.0
354135105562401	8-20-51	--	2.70	--	150	82.38
354143105561701	8-20-51	--	0.61	--	157	--
354256105550801	8-15-86	23.0	--	0.38	--	--
354300105530502	7-06-77	16.0	--	0.30	560	--
354352106071401	7-18-77	4.2	--	2.60	--	--
354354105543001	8-15-86	8.0	--	0.43	--	--
354419106022601	9-19-51	10.0	--	--	1,500	--
354419106022601	12-20-73	8.2	--	13.00	1,500	--
354427106060601	8-28-86	14.0	--	13.00	400	--
354442105550701	8-01-51	8.0	0.86	--	400	75.0
354501106014001	5-28-75	18.0	--	--	841	--
354503106014701	7-18-77	7.1	--	6.00	651	--
354553105555401	8-28-86	34.0	--	11.00	--	--
354555105554901	4-11-74	13.0	--	4.30	--	--
354608105561801	11-02-51	4.0	--	--	--	--
354609105561701	11-02-51	4.0	0.36	--	--	--
354623105561001	12-15-64	2.5	0.41	--	100	--
354623106025701	8-28-86	9.6	--	4.40	350	--
354652105565301	3-05-54	2.0	0.34	--	100	--
354747106021701	8-27-86	6.6	--	1.00	--	--
354805105582501	6-07-74	15.0	--	0.05	--	--
354812105583001	1-18-65	6.7	0.02	--	72	--
354832105540401	4-29-77	20.0	--	--	130	--
354832105544901	7-28-77	6.0	--	0.76	--	--
354844106083301	12-28-50	5.0	--	--	--	--
354844106083301	9-19-51	4.0	--	--	--	0.0

PAGE 61 FOLLOWS

Table 5.--Dissolved-chloride and dissolved-nitrogen concentrations in ground water near Santa Fe--Continued

Well location number	Date of sample	Chloride, dissolved (mg/L as Cl)	Nitrogen, nitrate, dissolved (mg/L as N)	Nitrogen, NO_2+NO_3, dissolved (mg/L as N)	Depth of well, total (feet)	Water level (feet below land surface)
355300106092301	1-15-61	16.0	--	--	1,750	--
355300106092301	1-15-61	16.0	0.27	--	1,750	--
355300106092301	1-19-61	16.0	0.27	--	1,750	--
355300106092301	2-08-61	15.0	--	--	1,750	--
355300106092301	6-09-61	16.0	--	--	1,750	--
355301106092201	3-20-51	20.0	--	--	--	--
355301106092201	3-20-51	23.0	--	--	--	--
355301106092201	4-18-57	--	--	--	--	--
355301106092201	10-09-57	24.0	--	--	--	--
355301106092201	4-18-58	27.0	--	--	--	--
355301106092201	9-07-58	18.0	--	--	--	--
355301106092201	9-17-58	18.0	--	--	--	--
355301106092201	2-17-59	27.0	--	--	--	--
355301106092201	8-03-59	20.0	--	--	--	--
355301106092201	5-20-60	7.0	--	--	--	--
355304106092201	10-09-57	3.0	0.07	--	--	--
355304106092201	3-21-58	5.2	0.05	--	--	--
355304106092201	10-10-58	3.0	0.00	--	--	--
355304106092201	4-21-59	3.0	0.02	--	--	--
355304106092201	10-26-59	5.0	0.02	--	--	--
355304106092201	4-26-60	3.1	0.00	--	--	--
355304106092201	11-22-60	3.4	0.02	--	--	--
355304106092201	4-22-61	3.0	0.02	--	--	--
355312105574301	7-20-54	22.0	--	--	347	60.0
355312105574302	2-09-54	6.0	3.40	--	70	--
355317105575701	2-09-54	7.0	5.40	--	--	--
355324106024801	12-28-50	7.0	0.43	--	80	--
355326106065901	12-10-64	19.0	2.90	--	160	--
355326106065901	12-17-69	20.0	2.70	--	--	--
355331106050201	12-27-50	21.0	3.80	--	63	--

Table 5.--Dissolved-chloride and dissolved-nitrogen concentrations in ground water near Santa Fe--Concluded

Well location number	Date of sample	Chloride, dissolved (mg/L as Cl)	Nitrogen, nitrate, dissolved (mg/L as N)	Nitrogen, NO_2+NO_3, dissolved (mg/L as N)	Depth of well, total (feet)	Water level (feet below land surface)
355333106085901	10-10-58	5.0	0.05	--	--	--
355333106085901	4-21-59	2.8	0.20	--	--	--
355333106085901	10-26-59	4.5	0.18	--	--	--
355333106085901	4-26-60	2.2	0.18	--	--	--
355333106085901	11-22-60	2.8	0.20	--	--	--
355333106085901	4-26-61	3.0	0.20	--	--	--
355335106010102	6-12-74	22.0	--	0.18	--	--
355337106063701	3-10-59	16.0	3.20	--	70	16.0
355340106061001	12-17-69	7.2	0.30	--	--	--
355404106070001	6-03-74	6.9	--	0.21	--	--
355411106074001	12-27-50	66.0	0.20	--	40	--

Table 6.--δ deuterium and δ oxygen-18 composition of and dissolved-chloride concentration in ground water near Santa Fe

[Well location number: first six digits are latitude, next seven digits are longitude, and last two digits are sequence number; µS/cm, microsiemens per centimeter at 25 degrees Celsius; --, no data. All data were collected in 1988]

Well location number	Well depth (feet)	Specific conductance (µS/cm)	δ deuterium (permil)	δ oxygen-18 (permil)	Chloride concentration (milligrams per liter)
353817106002701	70	550	-67	-9.9	25.3
354746106022101	700	333	-116	-15.8	5.7
353745105595601	320	195	-80	-11.8	1.5
353843105583801	120	650	-80	-11.7	--
353752105580301	200	600	-80	-12.2	27.8
353737105563701	550	470	-66	-9.9	20.0
353821105570001	225	360	-61	-9.6	8.3
353754105553401	250	1,800	-68	-9.3	--
354457106060601	300	375	-77	-11.1	13.2
354258106034501	350	300	-87	-12.4	3.1
354934105553001	80	600	-85	-12.1	--
354712105531901	15	160	-89	-12.6	14.8
354834105540401	120	175	-92	-12.9	14.4
354840105535701	--	480	-74	-10.8	16.3
353832106003901	750	250	-79	-12.0	12.1
353942106005801	130	398	-74	-11.5	13.5
354006106004101	260	180	-80	-12.3	2.5
353959106003901	300	245	-79	-11.4	7.7
354040106001801	285	215	-72	-10.9	3.0
353913106011801	200	210	-77	-11.6	6.0
353843106011001	700	248	-81	-11.7	13.7
353853106000701	200	445	-78	-11.6	20.0
353840105594201	116	400	-75	-11.4	25.0
353934106002101	180	315	-68	-10.3	12.6
353947105595201	200	305	-76	-11.4	12.3

Table 6.--δ deuterium and δ oxygen-18 composition of and dissolved-chloride concentration in ground water near Santa Fe--Continued

Well location number	Well depth (feet)	Specific conductance (μS/cm)	δ deuterium (permil)	δ oxygen-18 (permil)	Chloride concentration (milligrams per liter)
353959105592701	200	350	-77	-10.4	13.8
354012105590801	75	650	-73	-10.7	65.2
354034105590501	120	285	-71	-10.7	15.8
354052105583501	--	340	-74	-11.1	11.3
354134105575101	--	433	-75	-11.5	18.8
354119105553301	--	520	-77	-11.0	--
354013105540401	420	455	-77	-11.0	18.1
354049105545401	155	455	-79	-12.0	28.3
354105105541601	80	1,050	-78	-11.5	65.0
353923105591201	229	350	-80	-12.1	26.1
353641106012401	360	197	-81.0	-11.60	2.3
353508106025701	350	232	-75.0	-11.00	1.6
353655105541801	300	710	-71.5	-9.95	54.2
353737105554901	150	468	--	--	15.7
353736105552601	250	466	-72.5	-10.25	15.5
353758105552601	220	550	-76.0	-9.75	15.6
353714105564201	350	398	-73.0	-10.15	9.2
353700105572201	286	218	-77.5	-10.50	5.2
353623105555501	350	422	-78.5	-11.15	16.1
353552105543101	20	700	--	--	33.2
353555105543301	350	1,880	-73.0	-10.50	67.0
353456106020701	250	298	-81.0	-11.50	2.3
353515106021801	350	243	--	--	3.3
353528106021101	320	236	-77.0	-11.10	2.3
353620106010201	375	272	-76.5	-10.85	2.9
353650106002701	330	238	--	--	3.4
353643106001201	350	228	-79.5	-11.35	2.7
353618105584201	380	000	-81.5	-11.60	10.7
353809105555501	320	670	-85.0	-11.40	36.5
354542105554301	200	363	-84.5	-11.55	5.6

Table 6.--δ deuterium and δ oxygen-18 composition of and dissolved-chloride concentration in ground water near Santa Fe--Concluded

Well location number	Well depth (feet)	Specific conductance (µS/cm)	δ deuterium (permil)	δ oxygen-18 (permil)	Chloride concentration (milligrams per liter)
354530105554301	90	000	-86.0	-12.75	16.2
354523105553901	175	305	-84.5	-12.10	4.0
354521105553401	175	324	--	--	13.8
354320105544501	535	530	-80.0	-10.95	23.2
354336105543301	400	502	-78.0	-10.70	16.4
354408105545201	150	570	-81.5	-11.45	41.9
354504105552401	120	404	-85.5	-12.40	16.8
354439105544701	130	406	-87.0	-12.80	11.3
354811105545801	350	438	-107.5	-13.90	9.1
354756105551201	500	371	-96.0	-12.55	6.9
355333106021901	50	580	-76.5	-10.55	16.5
355312106041401	110	592	-76.0	-10.40	15.6
355315106041801	100	640	-79.5	-11.00	17.6
355320106032101	67	660	-79.0	-10.8	21.4
355104105592901	180	355	-87.0	-12.10	5.6
354208105585101	450	272	-92.0	-12.65	4.1
354801105551401	725	387	-101.0	-13.55	11.4
354353105543401	85	326	-81.5	-11.20	9.3
354423105540801	0	272	-82.0	-11.45	--
355039105591701	160	408	-84.0	-11.50	4.9
355148106000601	73	780	-82.0	-11.20	31.4
354346105570801	740	262	-80.5	-11.10	4.1
354433105571701	580	232	-81.5	-11.70	7.4
355000106092801	2,000	1,080	-111.5	-15.00	27.3
355006106094801	--	--	-83.5	-11.95	2.8
355006106094802	--	--	-81.5	-11.95	3.4
355006106094803	--	--	-83.0	-11.75	2.8
354935106085301	--	--	-111.0	-15.00	--
354944106091801	--	--	-104.5	-14.25	--

Table 7.--Mountain-front recharge estimates based on the chloride-balance method

[(1), this study; (2), Spiegel and Baldwin, 1963; (3), Wasiolek, in press, (4), Reiland, 1975]

Drainage basin (square miles)	Average annual precipitation in basin (inches)	Pm Average annual volume of precipitation intercepting basin (acre-feet)	PmCp Average annual mass of chloride intercepting basin (acre-feet milligrams per liter)	Rmf Estimated annual mountain-front recharge (acre-feet)	Rmf Estimated annual mountain-front recharge assuming runoff (acre-feet)	Measured or estimated annual streamflow (acre-feet)	Estimated chloride concentration in drainage at mountain front (milligrams per liter)
Santa Fe River (downstream point of drainage basin; latitude 35°41'12", longitude 105°38'40")							
26.95(1)	20.91(1)	30,060	8,700	2,900	2,320	5,800 (2)	1.5
18.2 (2)	26.0 (2)	25,000					
8.8 (2)	18.0 (2)	8,400					
		33,000	9,600	3,200	2,620	5,800 (2)	1.7
28.70(3)	23.62(3)	36,200	10,500	3,500	2,920	5,800 (2)	1.8
Little Tesuque Creek (downstream point of drainage basin; latitude 35°43'30", longitude 105°53'15")							
7.34(1)	21.90(1)	8,573	2,500	630		400 (4)	6.3
7.2 (2)	21.0 (2)	8,100	2,300	580		400 (4)	5.8
7.66(3)	22.96(3)	9,380	2,700	670		400 (4)	6.8
Tesuque Creek (downstream point of drainage basin; latitude 35°44'20", longitude 105°54'20")							
11.84(1)	20.77(1)	13,120	3,800	950		2,300 (4)	1.7
11.2 (2)	21.0 (2)	12,500	3,600	900		2,300 (4)	1.6
11.22(3)	24.18(3)	14,470	4,200	1,050		2,300 (4)	1.8
Rio Tesuque (sum of Little Tesuque Creek and Tesuque Creek)							
				1,580(1)	690		
				1,480(2)	590		
				1,720(3)	830		
Arroyo Hondo (downstream point of drainage basin; latitude 35°37'03", longitude 105°54'17")							
8.38(1)	19.15(1)	8,560	2,500	830		535 (2)	4.7
6.7 (2)	17.0 (2)	6,100	1,800	590		535 (2)	3.4

Table 8.--Estimates of stream-channel recharge and subsurface inflow from the mountains for selected drainage basins near Santa Fe

[All values are in acre-feet per year. --, no data]

Investigator	Arroyo Hondo drainage		Santa Fe River drainage		Rio Tesuque drainage	
	Mountain-stream-channel recharge	Subsurface inflow from mountains	Mountain-stream-channel recharge	Subsurface inflow from mountains	Mountain-stream-channel recharge	Subsurface inflow from mountains
Speigel and Baldwin (1963)	535	--	2,900 (1)	--	1,450	--
Lee Wilson and Associates (1978)	--	--	3,500	--	1,500	--
Hearne (1985)	0	0	5,220	0	1,800	--
McAda and Wasiolek (1988)	510	360 (2)	5,430	3,190 (3)	3,400 (4)	1,500 (5)
Wasiolek (in press)	--	--	--	4,170	--	3,320
This study (6)	830		2,900		1,580	

(1) "Optimum" recharge in 4-mile reach from mountain front.
(2) Includes node 28,24 (row 28, column 24).
(3) Includes nodes 21,24; 22,24; 23,24; 24,24.
(4) Includes all inflow to aquifer along the Rio Tesuque drainage.
(5) Includes nodes 17,25; 18,25; 19,25; 20,25.
(6) Estimate of stream-channel recharge plus subsurface inflow from the mountains.

Table 9.--Precipitation amount and δ deuterium and δ oxygen-18 composition of precipitation collected at the Sangre de Cristo Water Treatment Plant

[--, no data]

Sampling period	Precipitation amount (inches)		δ deuterium (permil)	δ oxygen-18 (permil)
	Tipping-bucket rain gage	Wedge rain gage		
8/26/87 - 9/02/87	--	0.33	-43	-7.2
9/02/87 - 9/17/87	--	0.10	-30	-4.5
9/17/87 - 10/09/87	--	0.08	-46	-7.4
10/09/87 - 11/03/87	--	1.34	-77	-12.1
11/03/87 - 11/20/87	--	0.80	-108	-14.8
11/20/87 - 12/04/87	--	0.10	-109	-15.8
12/04/87 - 12/22/87	--	0.35	-86	-12.7
12/22/87 - 1/15/88	--	0.45	-117	-16.5
1/15/88 - 1/27/88	0.14	0.58	-145	-19.1
1/27/88 - 2/17/88	0.21	--	-124	-16.8
2/17/88 - 3/04/88	0.06	--	-78	-10.4
3/04/88 - 3/22/88	0.08	0.18	-63.0	-10.10
3/22/88 - 4/07/88	0.08	0.22	-179.0	-23.3
4/07/88 - 4/20/88	0.86	0.87	-63.0	-9.40
4/20/88 - 5/09/88	0.09	0.07	-43.0	-5.90
5/09/88 - 5/23/88	1.16	1.06	-63.0	-9.60
5/23/88 - 6/08/88	0.37	0.36	-62.0	-7.90
6/08/88 - 6/24/88	1.47	1.44	-32.0	-6.30
6/24/88 - 7/08/88	1.87	1.75	-63.0	-9.10
7/08/88 - 7/29/88	1.98	1.94	-51.0	-7.80
7/29/88 - 8/15/88	1.40	1.32	-36.0	-5.50
8/15/88 - 8/25/88	2.39	2.30	-52.0	-8.10
8/25/88 - 9/19/88	2.71	2.95	-61.0	-9.3
9/19/88 - 10/12/88	2.02	2.05	-65.0	-9.60
10/12/88 - 11/10/88	0.18	0.15	-45.0	-7.30
11/10/88 - 11/30/88	0.54	0.15	-104.0	-15.0
12/05/88 - 12/28/88	0.08	0.20	-81.0	-11.20
12/28/88 - 1/23/89	0.33	0.50	-95.0	-13.40
1/23/89 - 2/10/89	1.46	1.55	-93.0	-13.00
2/10/89 - 3/07/89	0.23	0.20	-97.0	-12.90
3/07/89 - 3/29/89	0.43	0.60	-141.0	-19.00