SUBSURFACE RECHARGE TO THE TESUQUE AQUIFER SYSTEM FROM SELECTED DRAINAGE BASINS ALONG THE WESTERN SIDE OF THE SANGRE DE CRISTO MOUNTAINS NEAR SANTA FE, NEW MEXICO

By Maryann Wasiolek

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CONVERSION FACTORS AND VERTICAL DATUM

Multiply	By	To obtain
inch	25.4	millimeter
foot	0.3048	meter
mile	1.609	kilometer
acre	4,047	square meter
square mile	2.590	square kilometer
acre-foot	0.001233	cubic hectometer
cubic foot per second	0.02832	cubic meter per second
foot per mile	0.1894	meter per kilometer

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

Water budgets developed for the basins of five streams draining the western side of the Sangre de Cristo Mountains of northern New Mexico indicate that subsurface inflow along the mountain front is recharging the Tesuque aquifer system of the Española Basin. Approximately 14,700 acre-feet of water per year, or about 13 percent of the average annual precipitation over the mountains, is calculated to leave the mountain block and enter the basin as subsurface recharge from the drainage basins of the Rio Nambe, Rio en Medio, Tesuque Creek, Little Tesuque Creek, and Santa Fe River. Seasonal water budgets indicate that most of the subsurface recharge enters the overburden and fractured rock of the mountain block during the winter and spring.

The calculated subsurface recharge values were used to estimate the fluxes permitted to occur from constant-head cells along a constant head boundary defining the mountain front of the Sangre de Cristo Mountains in a numerical computer model of the Tesuque aquifer system near Santa Fe, New Mexico. The fluxes were output from the steady-state model. They were adjusted by modifying model input such as aquifer properties, discharge to the Rio Grande, and recharge from streams over reasonable ranges. For transient model simulations, the constant-head boundary was converted to a specific-flux boundary, and the fluxes simulated during steady state were used as input to the model. Simulated subsurface recharge totaled about 9,600 acre-feet per year, or about 8 percent of average annual precipitation, over the length of the boundary between and including the Rio Nambe and Santa Fe River drainage basins and also including the Rio Chupadero drainage basin, for which no water budget was determined.

INTRODUCTION

Mountain-front recharge is ground-water recharge along the boundary of a regional aquifer system that parallels a mountainous area (Water Resources Research Center, 1980, p. 4-1 to 4-3). Ultimately originating as precipitation over upland areas, mountain-front recharge enters the regional aquifer system of a structural and topographic basin bounding a mountainous area as either near-mountain seepage from streams that drain the mountains or subsurface inflow of water from the rocks of the mountain block.

The subsurface recharge component of mountain-front recharge cannot be directly measured. Nonnumerical methods (methods that do not involve computer-simulation techniques) that indirectly assess the quantity of the subsurface inflow in specific areas include several techniques that are based on climatic, ground-water-level, or chemical data. One of these methods, which is based on climatic data, requires the construction of a water budget for the area under study. A water budget is a tabulation of all known inflows to, changes of storage within, and discharges from an area within a defined period. The volume of water that is unaccounted for in the budget is assumed to represent the quantity of subsurface mountain-front recharge.

Numerical modeling of ground-water flow using computer simulations is another method of estimating subsurface recharge. A computer model of a regional aquifer that is bounded by a mountainous area can be used to calculate subsurface recharge to that aquifer as a flux along the mountain front. The estimates of subsurface recharge in this report were used to estimate the simulated flux permitted to occur along the eastern boundary in a numerical computer model of the Tesuque aquifer system near Santa Fe (McAda and Wasiolek, 1988). The flux used in the model represents the amount of water needed to simulate the necessary amount of discharge from the aquifer and recreate the measured hydraulic heads within the aquifer, given other input to the model.

The assessment of subsurface inflow using water-budget techniques can be a useful tool, particularly in the initial stages of the development of a numerical computer model of regional ground-water movement. Water budgets can be used to determine if subsurface mountain-front recharge to an alluvial-basin aquifer is occurring, and if so, the quantity of the inflow. This estimate of subsurface recharge then can be used to define initial boundary conditions for a numerical computer model of the area. Because aquifer transmissivity and recharge cause proportional changes in discharge calculated using Darcy's law, the range over which the transmissivity of the modeled aquifer can reasonably vary therefore can be restricted. This can be valuable in areas where information concerning the physical nature of the aquifer is limited. A properly constructed and calibrated numerical model then can be used to simulate the effects of well withdrawals within the basin and be a useful tool for prudent development and management of water resources. The water-budget method is used in this study, which was conducted in cooperation with the Santa Fe Metropolitan Water Board and the New Mexico State Engineer Office. Water budgets were developed for the main stream systems draining the western flank of the Sangre de Cristo Mountains near Santa Fe, New Mexico. These include the Rio Nambe, Rio en Medio, Tesuque Creek, Little Tesuque Creek, and Santa Fe River.

Purpose and Scope

This report provides documentation for the initial estimates of subsurface recharge used in the numerical computer model of the Tesuque aquifer system near Santa Fe, New Mexico (McAda and Wasiolek, 1988). Included in this documentation are (1) evidence of subsurface inflow of mountain-front recharge along the western front of the Sangre de Cristo Mountains near Santa Fe; (2) seasonal and annual estimates of subsurface mountain-front recharge from the Rio Nambe, Rio en Medio, Tesuque Creek, Little Tesuque Creek, and Santa Fe River drainage basins to the basin-fill sediments of the Española Basin derived from water budgets developed for those basins; and (3) a comparison of the estimated volumes of subsurface recharge to those simulated by the numerical model of the Tesuque aquifer system (McAda and Wasiolek, 1988).

Description of the Study Area

The study area comprises five mountain-stream drainage basins that drain the western side of the Sangre de Cristo Mountains near the city of Santa Fe in north-central New Mexico (fig. 1). From north to south, these drainage basins are the Rio Nambe, Rio en Medio, Tesuque Creek, Little Tesuque Creek, and Santa Fe River. The southernmost tributary of the Pojoaque River, the Rio Chupadero, was not included in the study because streamflow data were unavailable for this basin. All but the Santa Fe River are tributaries of the Pojoaque River. The Pojoaque River and the Santa Fe River flow through the Española Basin and eventually contribute to the flow of the Rio Grande, the principal stream of the area.

The Sangre de Cristo Mountains are an eastern extension of the southern Rocky Mountains. In the study area, the altitude of the crest of the Sangre de Cristo Mountains is typically between 11,800 and 12,400 feet above sea level. The crest is a topographic divide that separates the drainage areas of the Rio Grande to the west and the Pecos River to the east. The Sangre de Cristo Mountains are the eastern margin of the Española Basin segment of the Rio Grande Rift. The western base of the range is bounded by major faults that mark the contact between the Precambrian metamorphic and intrusive rocks of the mountain block and the younger Tertiary and Quaternary sediments filling the Española Basin (Kelley, 1978). This contact is about 6,600 feet above sea level within the Rio Nambe surface-water drainage basin in the northern part of the study area, and is about 7,200 feet above sea level within the Santa Fe River drainage basin in the southern part of the study area.

The metamorphic and igneous rocks that make up the core of the Sangre de Cristo Mountains consist of a foliated complex of schist and gneiss that have been successively intruded by gray granite, amphibolite, and reddish granite. The gneiss and reddish granite form the majority of the outcropping basement complex (Spiegel and Baldwin, 1963). These rocks have undergone structural deformation and exhibit numerous fractures, joints, and faults. The major regional faults generally trend north, paralleling the mountain front, whereas smaller faults trend north-northeast and are followed by some of the mountain drainages, including the Santa Fe River and Little Tesuque Creek. From the area just north of the Santa Fe River at 8,000 feet in altitude to Tesuque Creek, a thick section of sedimentary strata of the Sandia Formation and Madera Limestone units of the Pennsylvanian Magdalena Group unconformably overlies the Precambrian rocks. Sandstone and limestone of the Sandia Formation and members of the Madera Limestone also crop out in the canyon of Little Tesuque Creek south of Bishops Lodge and along Aztec Springs Creek (fig. 1). Deposits of glacial drift and outwash left by late Pleistocene glaciation are present in the upper watersheds of the study area drainage basins and are widely distributed throughout the Sangre de Cristo Mountains in high, wide valleys greater than 10,200 feet in altitude. The thickness of these deposits is unknown.

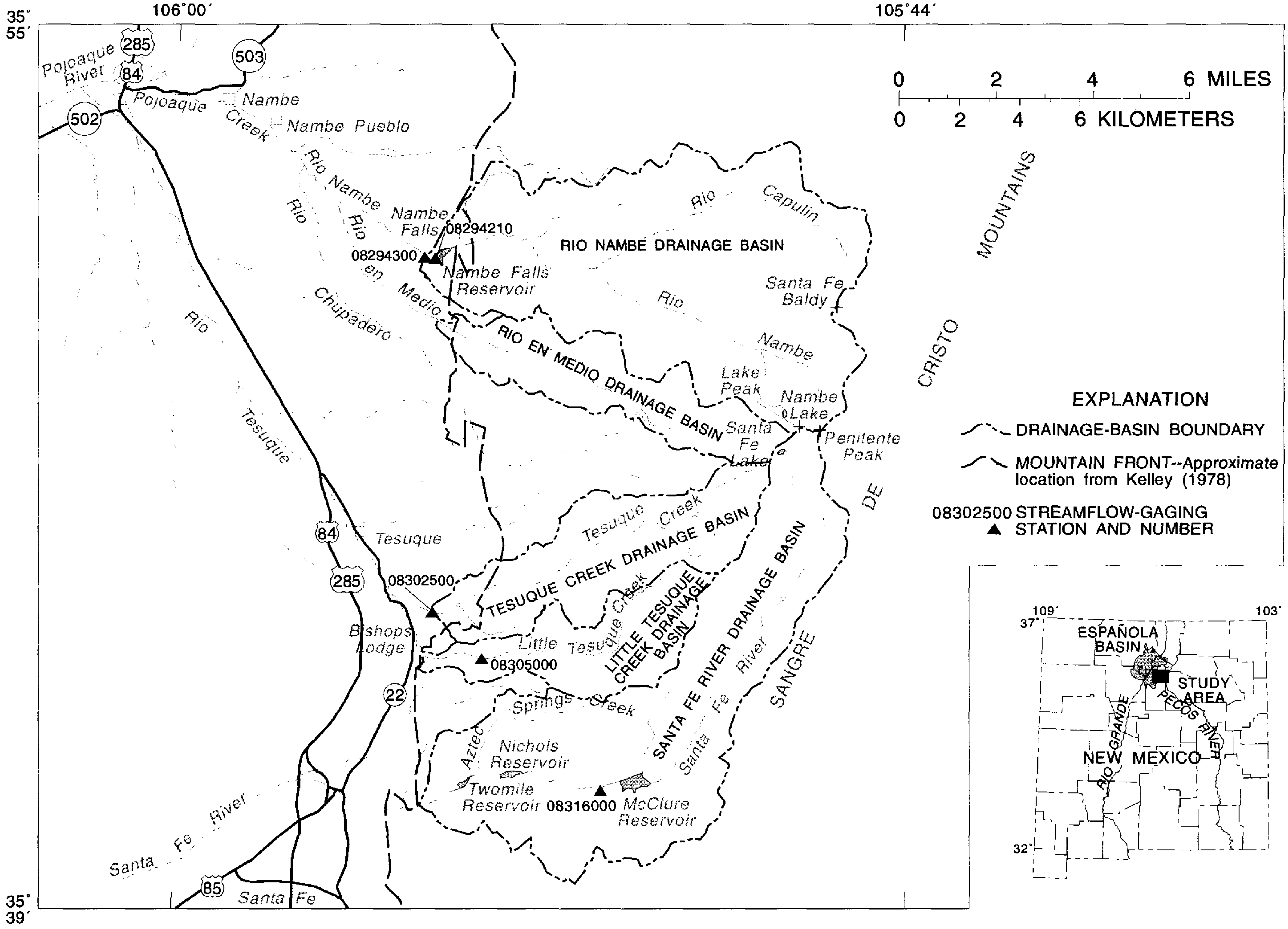


Figure 1.--Location of the study area, drainage basins, and streamflow-gaging stations.

The basin-fill sediments mainly are composed of the laterally and vertically variable unconsolidated and semiconsolidated pinkish-tan arkosic silty sandstone and siltstone of the Tertiary Tesuque Formation of the Santa Fe Group (Spiegel and Baldwin, 1963, p. 131; McAda and Wasiolek, 1988, p. 9). The Tesuque Formation is a regional aquifer in the Santa Fe area.

In the study area, the country is rugged and heavily forested. Juniper and piñon pines are predominant between altitudes of 6,800 and 8,200 feet, and Ponderosa pine is predominant between 8,200 and 8,800 feet. The predominant vegetation between 8,800 and 9,600 feet is a mixed zone of Douglas fir and Ponderosa pine; between 9,600 and 10,000 feet, Douglas fir and Engleman spruce; between 10,000 and 11,000 feet, Engleman spruce and fir; and above 11,000 feet, low plants of the Alpine tundra (Allen Smart, Hydrologist, U.S. Forest Service, written commun., 1984).

Previous Estimates of Subsurface Recharge

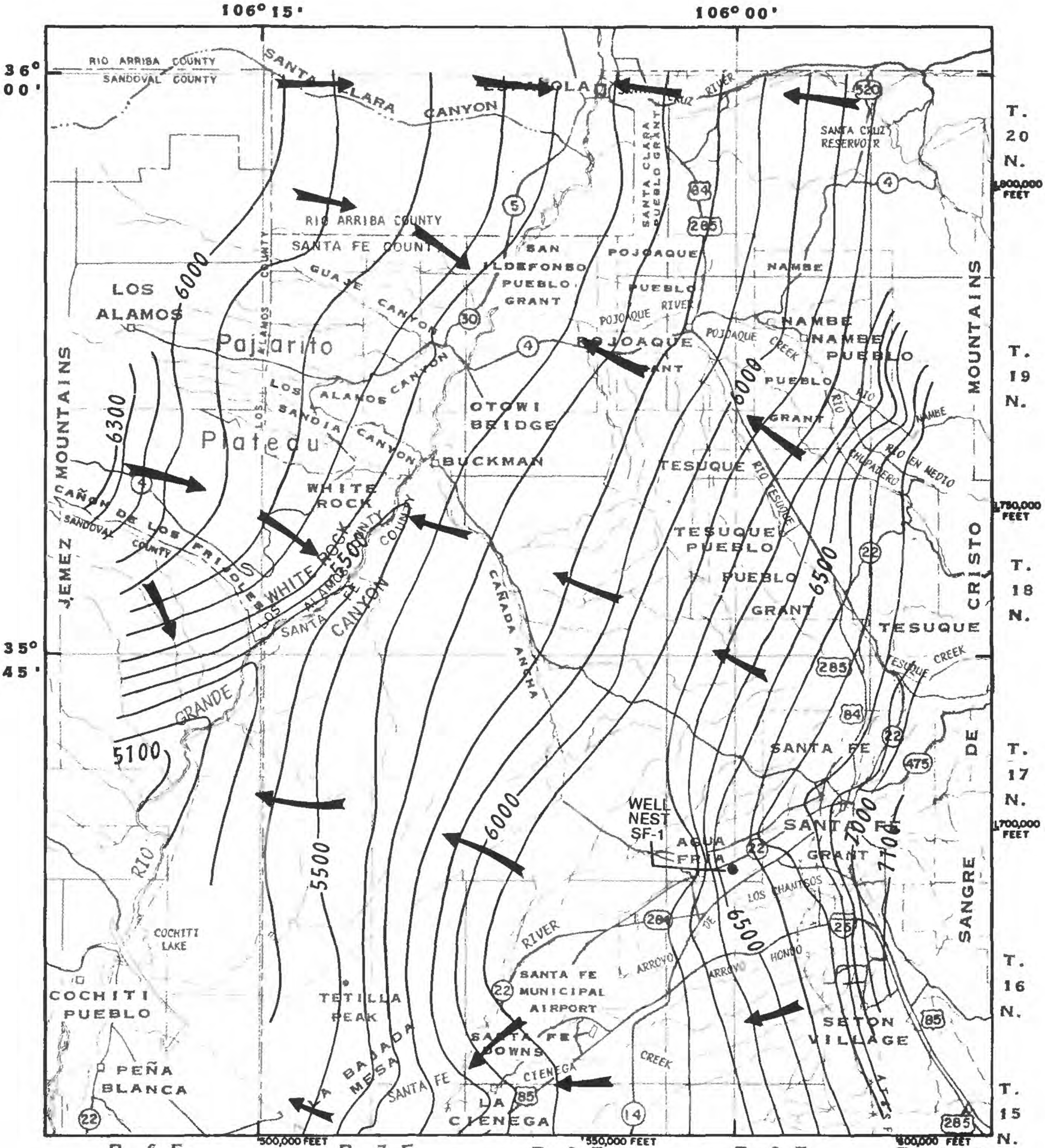
The first investigation that attempted to quantify the subsurface-inflow component of mountain-front recharge in the Santa Fe area was done by McAda and Wasiolek (1988). Earlier studies (Spiegel and Baldwin, 1963; Lee Wilson and Associates, 1978; Hearne, 1985) had calculated only the amount and distribution of streamflow infiltration into sediments of the Tesuque aquifer system. McAda and Wasiolek (1988) made their estimate using a three-dimensional finite-difference numerical model of the Tesuque aquifer system. The western front of the Sangre de Cristo Mountains was defined as the eastern extent of the modeled area. Subsurface inflow from the mountain block into the aquifer initially was simulated by representing the mountain front as a constant-head boundary under steady-state conditions. During transient simulations subsurface inflow was input as specified fluxes. This permitted the simulated recharge to change during initial model calibration.The model was considered calibrated when (1) simulated hydraulic heads were within acceptable limits, (2) simulated discharge from the system was close to calculated discharge, (3) modeled values of aquifer transmissivity were within a reasonable range, and (4) the rate of simulated subsurface inflow from the mountain front was in the range of the rate of subsurface inflow defined by the water-budget calculations discussed in this report (McAda and Wasiolek, 1988, p. 29). The simulated rates of subsurface inflow ranged from 0.4 to 1.4 cubic feet per second per mile along 16 miles of mountain front between the Rio Nambe and Santa Fe River drainage basins (McAda and Wasiolek, 1988, p. 32). A total of 13.3 cubic feet per second or 9,640 acre-feet per year was simulated as subsurface inflow from the rocks of the mountain block into the sediments of the Tesuque aquifer system along this length (McAda and Wasiolek, 1988, p. 20-21, 31-32). A total of 10.7 cubic feet per second or 7,740 acre-feet per year was simulated to enter the basin along that part of the mountain front restricted to the Rio Nambe, Rio en Medio, Tesuque Creek, Little Tesuque Creek, and Santa Fe River drainage basins. The recharge was distributed so that the greater part of it entered the basin near the canyon mouths (McAda and Wasiolek, 1988, p. 20-21, 31-32).

The main evidence for McAda and Wasiolek's (1988) initial assumption of subsurface inflow of water from the mountain block was the configuration of the regional ground-water surface. As can be seen in figure 2, predevelopment water-level contours were parallel to the mountain front. This would not occur unless the mountains are essentially acting as a line source of recharge. Additional evidence included sparse but compelling data showing that water quality in the aquifer deteriorates with distance from the mountain front to the discharge area of the Rio Grande, and information provided by a deep well drilled about 3 miles from the mountain front in 1986 (Hart, 1989). This test well, SF-1 (fig. 2), is a nest of three piezometers that are perforated from 1,917 to 1,922 feet (well SF-1A), 1,025 to 1,030 feet (well SF-1B), and 669 to 674 feet (well SF-1C) (Hart, 1989, p. 4). Water levels measured in these piezometers between September 1986 and June 1987 indicated an upward gradient of 0.07 within the aquifer at this location. This gradient might be due, at least in part, to nearby pumping in the upper part of the aquifer; however, it might also indicate that a significant amount of water enters the lower strata of the regional aquifer upgradient from this location. The hydraulic-head differential and the relatively short distance from the mountain front preclude the concept that this water entered the system as precipitation over the outcropping Tesuque Formation or as stream-channel infiltration. A more tenable concept is that the water in the deeper strata of the aquifer in this area entered the aquifer at depth along the fault zone of the mountain front from the fractured rocks of the mountain block.

The model of the Tesuque aquifer system (McAda and Wasiolek, 1988) provided additional evidence of the existence of subsurface inflow of water from the mountain block. When the model was run assuming only known stream-channel contributions to the aquifer system, the simulated water levels were too low and the estimates of the amount of water discharged to the Rio Grande were too small. The model could not be calibrated without assuming significant inflows of water along the mountain front.

Acknowledgments

For use of the elevation/precipitation equation developed by hydrologists of Carson National Forest, the author expresses appreciation to Pete Stewart and Allen Smart, hydrologists with the U.S. Forest Service. They also offered insights during the original Tesuque aquifer system numerical model study concerning the governing mechanisms of mountain-front recharge in the southern Rocky Mountains.



EXPLANATION

—7100— WATER-LEVEL CONTOUR--Shows altitude of water level. Interval 100 feet. Datum is sea level

APPROXIMATE DIRECTION OF GROUND-WATER FLOW

Figure 2.--Predevelopment potentiometric surface in the upper part of the Tesuque aquifer system (modified from McAda and Wasiolek, 1988, figure 6).

RECHARGE IN MOUNTAINOUS AREAS OF THE SEMIARID SOUTHWEST

A ground-water flow system is defined by the movement of ground water from a source to a sink (Mifflin, 1968). In the semiarid Southwestern United States, the source is usually a recharge area in and along the mountains and the sink is a discharge area in the lowlands of an adjacent structural and topographic alluvial basin (Maxey, 1968). Little recharge to the regional aquifer [defined by the Water Resources Research Center (1980, p. 4-1) to be the largest body of continuous saturation in a ground-water basin] of an alluvial basin occurs over the nonmountainous areas because of the large evaporation potential and low intensity and duration of precipitation over the lowlands. Within the recharge area, water percolates through an unsaturated zone to the saturated zone and then continues to move through the rocks of the mountain block. Under predevelopment conditions, water that is not intercepted by local topography or structure and forced to issue as spring flow or contribute to base flow of a stream will eventually flow into the regional aquifer of the adjacent basin as subsurface recharge. After moving laterally through the basin-fill sediments for some distance, water that does not leave the basin as interbasin flow begins to move upward until it discharges as surface water or is evapotranspired (fig. 3). In the recharge area of the mountains, ground water will have a downward component of vertical gradient, whereas in the discharge area, ground water will have an upward component of vertical gradient. Water within the regional aquifer between the two areas might have little or no vertical gradient (Mifflin, 1968, figs. 4-5).

Mountain-front recharge is water that enters the regional aquifer system in the sediments that fill an alluvial basin along the boundary of that system with a mountainous area. Mountain-front recharge can take the form of either infiltration from streams that drain the mountains or subsurface inflow from the mountain block to the basin-fill sediments.

Within the study area, the streamflow-infiltration component of mountain-front recharge has been gaged or reasonably estimated by a number of investigators (Spiegel and Baldwin, 1963; Reiland, 1975; Reiland and Koopman, 1975). Therefore it will not be discussed further except how that quantity affects calculations of the subsurface-inflow component.

Subsurface Recharge from the Mountain Block

The subsurface-inflow component of mountain-front recharge only recently has been recognized as an important component of recharge to basin-fill aquifers in the semiarid Southwest. Since Feth (1964, p. 14-17) presented a convincing case for "hidden recharge," as he termed it, he and subsequent investigators have gathered evidence of the subsurface inflow of significant quantities of water from consolidated rocks of the mountain blocks bordering alluvial basins into the regional aquifers of those basins. Feth (1964) and Feth and others (1966) stated that proof of a significant volume of subsurface recharge from the Wasatch Mountains of north-central Utah was provided by (1) ground-water contours that paralleled the mountains, (2) the chemical similarity of ground water from wells penetrating the regional aquifer of that area to spring water of the mountains, (3) the seasonal fluctuations of water discharging from a tunnel drilled in the Wasatch Mountains that were closely analogous to the seasonal fluctuations of water levels in wells in the area, and (4) the results of water-budget calculations for the Weber Delta area. Using a water-budget method, they calculated that ground-water inflow from the mountain front contributes 30,000 acre-feet of water annually to the regional aquifer of the Weber Delta district (Feth and others, 1966, p. 33, 39, 41-42). This quantity is 20.8 percent of the annual precipitation over the Wasatch Mountains within their study area.

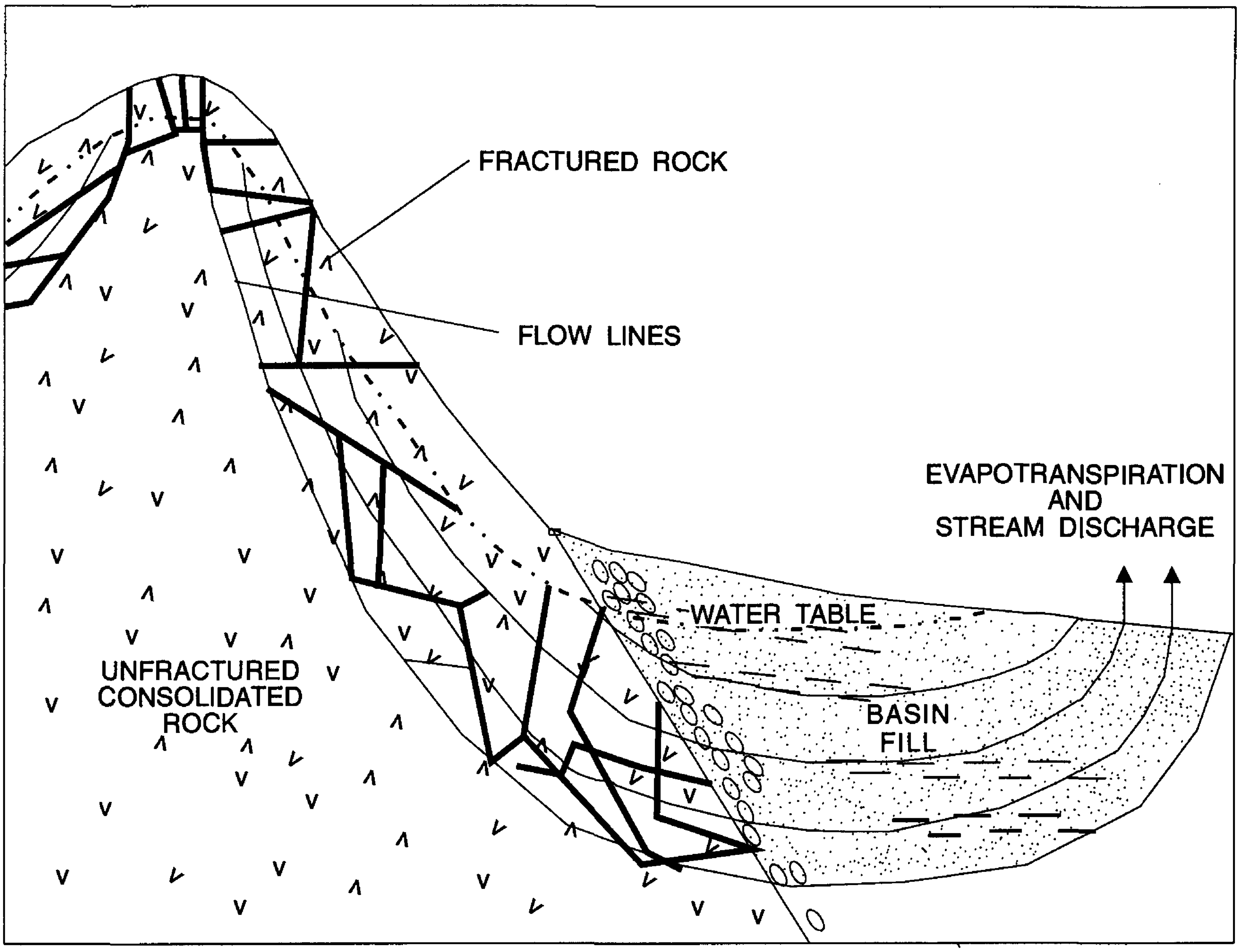


Figure 3.--Paths by which subsurface inflow may recharge the aquifer of an alluvial basin (modified from Feth, 1964; and Mifflin, 1968).

Similar evidence for the subsurface-inflow recharge component has been found in numerous other mountain ranges and associated basins in the Southwestern United States. One of the most compelling investigations was conducted by Huntley (1979) in an area very similar to that under investigation in the present study. Huntley studied recharge to the aquifer of the northern San Luis Valley of southern Colorado. This valley is bounded on the west and northwest by the volcanic San Juan Mountains, and on the east and northeast by the igneous and metamorphic Sangre de Cristo Mountains. A complex graben related to the Rio Grande Rift Zone, the San Luis Valley is filled with Pliocene and Miocene sediments derived from the surrounding highlands. The basin-fill strata have been correlated with the Santa Fe Group strata of New Mexico (Hawley, 1978; Huntley, 1979, p. 1213-1214; Hearne and Dewey, 1988, p. 65-67). Using a water-budget approach, Huntley calculated the amounts of recharge entering the San Luis Valley from the two mountain ranges as remainders in the water balances. He found that 37.5 percent of the precipitation over the San Juan Mountains and 14.1 percent of the precipitation over the Sangre de Cristo Mountains become ground water (Huntley, 1979, p. 1199-1200). He attributed the difference in percentages to the difference in the geology of the two ranges.

Hearne and Dewey (1988) also developed water budgets for the San Juan and Sangre de Cristo Mountains of southern Colorado. Their estimate of ground-water inflow from the San Juan Mountains to the aquifers of the northern San Luis Valley is 40 percent less than that calculated by Huntley (Hearne and Dewey, 1988, p. 30). Hearne and Dewey (1988, p. 33) made no estimate of ground-water inflow from the Sangre de Cristo Mountains.

Factors Affecting Subsurface Recharge

The quantity of subsurface recharge that is available to enter a nearby regional aquifer is related to the amount of precipitation that falls on the mountainous area bordering the boundary of that aquifer. Subsurface recharge also is related to the permeability of the soils and bedrock of the mountain block, which affect infiltration.

Precipitation

In the Southwestern United States, precipitation is a function of altitude due to orogenic and atmospheric influences. Mifflin's (1968) studies in southern Nevada basins indicate that the principal source areas of recharge to the desert basin are above 6,500 feet in altitude, although studies conducted in other areas indicate that lower altitude areas also contribute to recharge (Anderson, 1972; Belan, 1972). Relief also influences precipitation: a differential heating of land and air on a rugged mountain slope having steep canyons will induce instability in airmasses rising along that slope. On a larger scale, the physical orientation of the mountain range affects the amount of precipitation that falls on the range and the length of time that the snowpack is retained the following spring. Mountain ranges oriented perpendicular to the direction from which moisture arrives may receive more precipitation on their windward sides than if they had been otherwise oriented. The leeward side of such ranges are within the rain shadow and receive less precipitation. Snow lingers longer on north-facing slopes than on slopes oriented in other directions (Mifflin, 1968).

The actual quantity of precipitation does not appear to be as important to the quantity of subsurface recharge as the time of year in which it occurs. Results from a number of studies indicate that winter season precipitation is primarily responsible for subsurface mountain-front recharge because of the increased likelihood that winter precipitation will be in the form of snow; the long duration, low intensity, and great areal coverage of winter precipitation; and the small rate of evapotranspiration in the winter (Mifflin, 1968; Simpson and others, 1970; Ben-Asher, 1978; Kafri and Ben-Asher, 1978; Gallaher, 1979; Keith, 1980; Water Resources Research Center, 1980).

Infiltration

The permeability of the soils and bedrock of the mountain block affects how mountain-front recharge will occur and the rate and volume of that recharge. Low-permeability soils and bedrock in the mountains usually result in large runoff, causing recharge in the form of streamflow infiltration at the mountain front. High-permeability soils and bedrock tend to permit more infiltration directly into the mountain block and result in more recharge moving into the basin as subsurface inflow. Under certain conditions, however, areas of fractured, indurated terrain may be favored as recharge areas. If soil cover is thin or absent and surface area per unit volume of material represented by the fracture planes is small, large amounts of moisture are not needed to satisfy field-capacity and lateral-flow requirements. Under these conditions, recharge to the mountain block might be significant if a prolonged supply of moisture is available at or near land surface (Mifflin, 1968). The flow capacity of the terrain, which is the maximum amount of water a particular hydrogeologic environment can accept and transmit in the subsurface (Mifflin, 1968), can be large.

The distribution, intensity, and size of the fractures also affect the amount of water that can enter the mountain block. In igneous or metamorphic terrain, streams often follow zones of structural weakness such as faults or folds. Because such zones also tend to have a greater intensity of associated fracturing and greater permeability, a large proportion of water infiltrating into the mountain block might be expected to enter along these zones. However, it is also possible that deeply incised canyons that formed along fault zones intersect saturated ground-water mounds and induce local discharge to streams (Mifflin, 1968; Huntley, 1979). The fault zone itself might be sealed with gouge. The intensity and depth of the smaller fractures associated with the main zone of deformation and the degree to which the fractured rocks have been resealed with clay or secondary mineralization determine which of these scenarios will dominate the movement of water in a particular canyon.

The permeability of the geologic formations that fill the basin affects the amount of available subsurface recharge present in the rocks of the mountain block that actually enters the regional aquifer at the mountain front. Low-permeability strata inhibit the movement of subsurface inflow and/or restrict it to limited zones of high permeability, such as buried stream channels. Where the fault boundary of the mountain block is relatively impermeable, water can be forced upward to emerge as springs along the base of the mountain, rather than move into the aquifer. Where the fault zone is permeable, it can act as a conduit and permit recharging water to move vertically and enter the aquifer of the basin at depth.

HYDROLOGY OF THE DRAINAGE BASINS IN THE STUDY AREA

The five mountain drainage basins of the study area are between altitudes of about 7,000 to 12,000 feet above sea level. They drain the western flanks of the Sangre de Cristo Mountains from the crest of the range to the mountain-front contact between the mountain block and the adjoining alluvial basin (fig. 1). Substantial rain and snow fall over these mountain drainages, particularly over their upper watersheds. Snow covers parts of the drainage basins typically from November through late June. Water entering the basin as streamflow or direct runoff infiltrates into the basin sediments within a few miles of the mountain front. Some of this water possibly reaches the main zone of saturation in the aquifer.

The drainage basins are underlain by fractured, indurated igneous and metamorphic rocks covered to an unknown depth by locally derived soil and regolith. Graustein (1981, p. 199) suggested that within the Tesuque Creek drainage basin the regolith is between 3 and 10 meters in thickness. However, the frequency and distribution of bedrock outcrops indicate extensive areas where the materials covering the bedrock are much thinner. Because the regolith is derived primarily from the physical weathering of granitic rock, it is composed mainly of poorly sorted sand and gravel and contains little silt or clay. The presence of the soil and regolith undoubtedly facilitates the transmission of precipitation to fractured rocks by providing a permeable overburden that prevents rapid runoff and stores water as it slowly percolates downward. Graustein (1981, p. 200) reported that the overburden readily transmits precipitation, even during heavy rainfall. The permeability of the underlying bedrock is unknown. Although Graustein (1981, p. 199) speculated that the permeability is "very low," the bedrock of the drainage basins is highly faulted and potentially could transmit significant quantities of water through fractured zones in higher altitude areas where the extensive, slowly melting snowpack provides a prolonged supply of moisture. Huntley (1979, table 1) concluded that in southern Colorado the fractured metamorphic and igneous rocks of the northern part of the Sangre de Cristo Mountains collect and transmit recharge to the San Luis Basin. The courses of the main streams in the drainage basins of the study area likely are fault controlled to a large degree. Associated fracturing likely is most intense along and perpendicular to the axes of the drainage basins, although the main faults themselves possibly are sealed with gouge.

Graustein (1981, p. 200-201) observed that within the Tesuque Creek drainage basin, the thickness of the unsaturated zone fluctuates but averages at least 2 meters. The water table generally lies below the region of rooting and other biological activity. He reported that during summer, evapotranspiration from the forests intercepts almost all of the moisture falling as rain before it can reach the water table, and speculated that principal ground-water recharge takes place during snowmelt in April, May, and June. Graustein (1981, p. 202) estimated a 4-month residence time for ground water, although he conceded that it possibly could be much longer.

Precipitation falling on the part of the Sangre de Cristo Mountains within the study area that neither contributes to streamflow of the Rio Nambe, Rio en Medio, Tesuque Creek, Little Tesuque Creek, or Santa Fe River nor is transpired by vegetation may move downward through the unsaturated zone in the regolith covering the bedrock of the mountain block or in the bedrock itself until it reaches the saturated zone. Water that does not discharge from this zone into the local streams or springs will continue to move downward through the fractured bedrock, recharging the ground-water system of the mountains and eventually entering the regional Tesuque aquifer system of the adjacent Española Basin at an unknown depth. Possibly not all water entering the fractured rocks of the mountain block actually recharges the basin aquifer. Some of this water may travel along fault zones and discharge at another location or, if the hydrologic system of the mountains is not in equilibrium, may be retained in storage in the rocks. The approach taken in the present study is predicated on the assumptions that the surface-water drainage basin corresponds to the ground-water basin and that ground-water storage does not change in the mountain bedrock and regolith cover.

CALCULATION OF SUBSURFACE RECHARGE

Although the stream-channel infiltration component of mountain-front recharge can be measured directly, the subsurface-inflow component can be calculated only indirectly. Methods that have been used by previous investigators include (1) comparing the chemistry, in particular the amounts of chloride and sulfate, of water from springs and wells in the mountains with water from wells penetrating the basin aquifer (Feth and others, 1966; Huntley, 1979); (2) analyzing waters from the basin aquifer for radon in areas of igneous or volcanic terrains (Rogers, 1958; reported in Feth and others, 1966); (3) using Darcy's law to determine the amount of water that needs to enter the regional basin aquifer from the mountain block to maintain measured hydraulic heads in that aquifer (Belan, 1972; Belan and Matlock, 1973; Besbes and others, 1978); (4) calculating a water budget for the mountain area using known or estimated values of precipitation, evapotranspiration, and streamflow, whereby the residual, or unaccounted for, water is assumed to be recharge (Gates, 1963; 1965; Feth and others, 1966; Ben-Asher, 1978; Huntley, 1979; McAda and Wasiolek, 1988); (5) constructing a calibrated, multidimensional, numerical model of the regional basin aquifer to calculate the amount of water needed at the mountain front to simulate discharge and hydraulic heads in the aquifer (Anderson, 1972; McAda and Wasiolek, 1988); (6) estimating recharge by trial and error while assuming that recharge is directly related to precipitation that increases with altitude (Maxey and Eakin, 1949; Eakin, 1966; Rantz and Eakin, 1971); (7) numerically simulating recharge through individual pockets of soil in mountainous areas (Kafri and Ben-Asher, 1976; 1978); (8) using oxygen-18 and environmental tritium to determine the altitude and seasonal distribution of ground-water recharge (Gross and others, 1976; Gallaher, 1979); and (9) relating measured stream baseflow to average annual precipitation on areas receiving more than 12 inches of water per year (Cordova and others, 1972). A summary of these studies as well as an overview of mountain-front recharge was given by Water Resources Research Center (1980, chap. 4). Most synopses of methods presented here are taken from that report.

As the Water Resources Research Center discussed (1980, p. 4-34 to 4-39), the methods outlined above are of two general types: those using climatic data and those using ground-water-level data (methods that use chemical and isotope data rely on climatic data). Climatic models calculate potential recharge; however, they tend to overestimate the amount of actual recharge by ignoring the limiting influences of geology. Models using ground-water-level data calculate the amount of recharge that theoretically has occurred. If properly used and if sufficient information is available concerning the permeability of the basin aquifer, those models using hydraulic-head data probably provide more accurate estimates of subsurface inflow than the climatic methods (Water Resources Research Center, 1980, p. 4-34 to 4-39).

Method of Calculation

A water-budget method was used in this investigation to calculate the potential amount of subsurface mountain-front recharge. This method is based on the assumption that over a defined period of time (a year in the present study), the amount of water entering an area is equal to the amount of water leaving that area once accounting for change in storage; that is, the total volume of annual precipitation received by a stream drainage basin having no ground-water inflow from outside the basin is equivalent to the sum of the annual volumes of streamflow discharge, evapotranspiration, and recharge to the ground-water system plus any change in storage in either the saturated or unsaturated zones. Because change in soil and aquifer storage over a long period of time usually can be considered to be zero, the water budget can be written as follows:

$$R = P - RO - ET \tag{1}$$

where R = recharge to ground-water system;
P = precipitation;
RO = runoff or stream discharge; and
ET = evapotranspiration.

The recharge component represents the amount of water available for the subsurface-inflow component of mountain-front recharge.

Description of Water-Budget Components

Precipitation

Much of the precipitation over the study area is produced either during the winter by the interaction of polar, tropical Pacific, and tropical continental airmasses and extratropical storms in the vicinity of the Sangre De Cristo Mountains; or during late summer by frequent violent thunderstorms that develop from moist tropical airmasses from the Gulf of Mexico (Spiegel and Baldwin, 1963, p. 146-147). Winter precipitation falls mainly as snow over the study area. The snowpack tends to linger in the high mountains through the spring, often not disappearing entirely until late June. A period of dry weather often occurs during late spring and early summer. Summer storms produce rain and occasional hail.

Few precipitation data are available for various altitudes of the high-mountain surface-water drainage basins included in this study. A long period of record is available only for the Santa Fe area, where stations have been maintained since 1852 at various locations that have altitudes ranging from 6,312 to 7,013 feet above sea level. The longest period of record is for the city of Santa Fe at an altitude of 7,013 feet, where precipitation has been recorded almost continuously. Other stations in the southern Rocky Mountains (outside the study area) that have fairly long periods of record, are located at high altitudes, and seem to be affected by weather patterns similar to those affecting the study area include the following stations: Red River, in Taos County, altitude 7,323 feet, period of record from 1931 to 1983; Taos Canyon, in Taos County, altitude 8,225 feet, period of record from 1909 to 1943; Ancor Mine, in Taos County, altitude 10,200 feet, period of record from 1911 to 1920; Bateman Ranch, in Rio Arriba County, altitude

8,900 feet, period of record from 1909 to 1930; Santa Fe Canyon, in Santa Fe County, altitude 8,000 feet, period of record from 1910 to 1916 and 1923 to 1928; and Rea Ranch, in Torrance County, altitude 9,200 feet, period of record from 1912 to 1919 (Spiegel and Baldwin, 1963, table 9; Gabin and Lesperance, 1977; Kunkel, 1984). These stations were selected by Spiegel and Baldwin (1963, p. 146-149) in their study of the hydrology and geology of the Santa Fe area as having distributions and amounts of precipitation representative of those received in the Sangre de Cristo Mountains around the city of Santa Fe at various altitudes. No new stations fitting those criteria have been established since that time, although temporary stations were set up at several locations within the Tesuque Creek watershed by researchers at the University of New Mexico (Gosz, 1975; Graustein, 1981).

Spiegel and Baldwin (1963) used these available precipitation data to develop relations between altitude and precipitation on the basis of season. They concluded that extrapolation of the annual curve indicated that about 58 inches of precipitation would fall each year in the higher areas of the Sangre de Cristo Mountains (p. 149-150). This figure may be too high; the Soil Conservation Service (1972b) map of precipitation in New Mexico (fig. 4) indicates that the amount of precipitation expected to fall over the high peaks north of Santa Fe is between 35 and 40 inches per year.

Using the available data for most of the same stations used by Spiegel and Baldwin (1963), the hydrologists of Carson National Forest developed a regression equation relating precipitation to altitude for the southern Rocky Mountains of southern Colorado and northern New Mexico. The equation,

$$y = 0.0048(x) - 19.16 \text{ inches,} \qquad (2)$$

where x = one-third of local topographic relief[1] + lowest altitude, in feet, for altitudes above 9,600 feet; and
x = one-half of local topographic relief + lowest altitude, in feet, for altitudes below 9,600 feet;

determines annual precipitation (y) in inches (Pete Stewart, U.S. Forest Service, written commun., 1984) and provides an estimate of precipitation for high altitudes that is reasonably consistent with Soil Conservation Service maps (1972b) for New Mexico. Equation 2 was used in the present study to calculate seasonal and annual precipitation at different altitude ranges in the study area. Seasonal distribution of this precipitation at different altitudes was estimated by (1) calculating the seasonal distribution of precipitation using available data at the stations discussed above, (2) plotting the percentages of the annual total (which each seasonal value composes) versus altitude, and (3) using the resulting graph to estimate the calculated annual precipitation that can be expected to fall each season. In keeping with the method of dividing the year into seasons within the Rocky Mountain/Inland Intermountain hydrologic region used by Troendle and Leaf (1980), winter is considered to extend from October through February, spring from March through June, and summer/fall from July through September.

[1]Local topographic relief is the difference between the highest and lowest attitudes within an area.

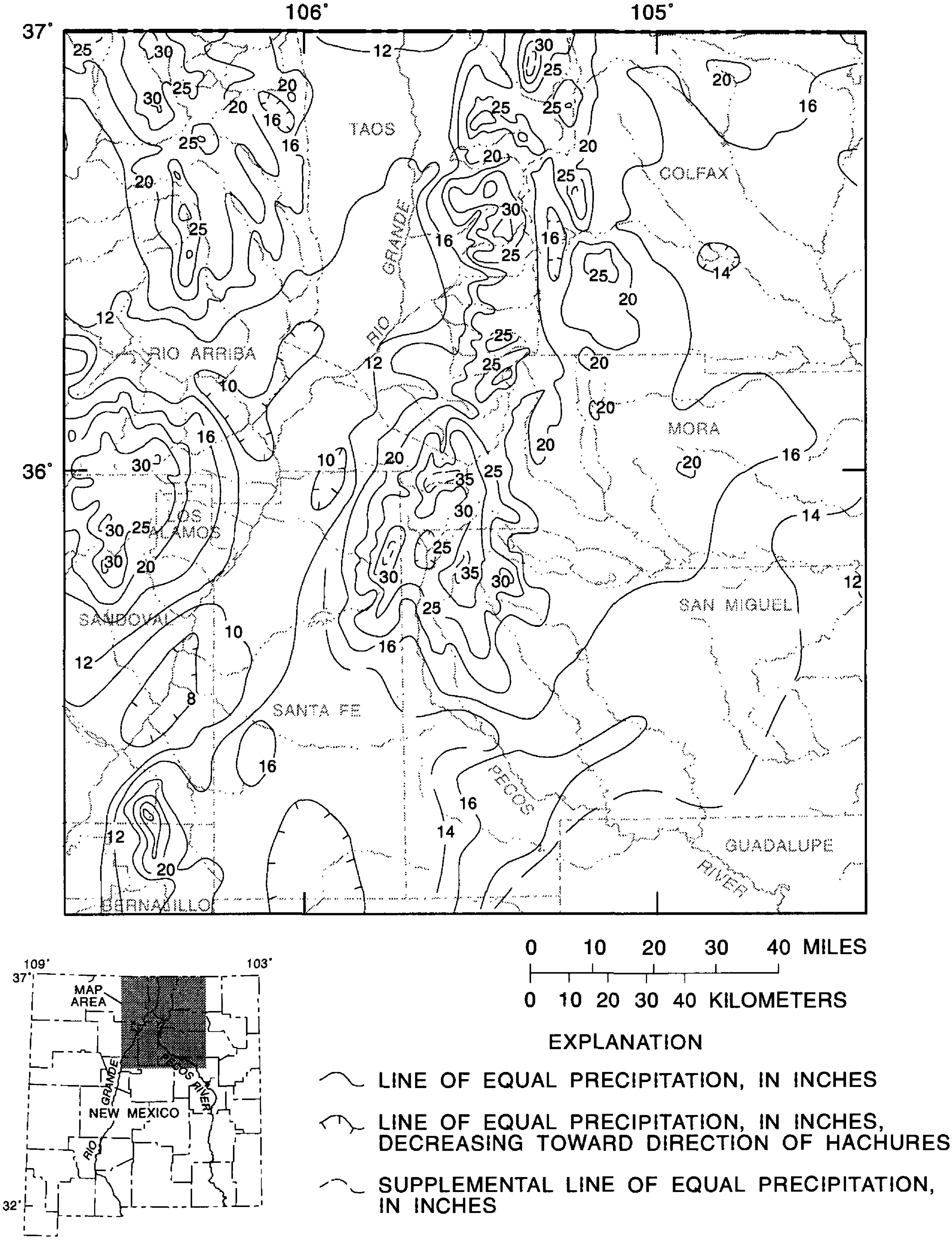


Figure 4.--Average annual precipitation for north-central New Mexico (modified from Soil Conservation Service, 1972b).

The amount of winter and spring precipitation that falls as snow in the Rocky Mountains is decreased by snow evaporation and sublimation of the snowpack. This snow evaporation and sublimation occur at all altitudes, although they appear to be most pronounced within large, treeless areas on ridgelines where snow is unprotected by forest canopy and can be redistributed by wind. The methodology of Troendle and Leaf (1980) includes consideration of snow evaporation and sublimation in the winter and spring season evapotranspiration graphs. The winter graph is entirely reflective of these factors because little evapotranspiration occurs during winter months. The volume of snow that falls is reduced over treeless areas according to figure 5 (fig. III.6 of Troendle and Leaf, 1980). "H" in this figure is the height of surrounding trees. When the diameter of a treeless area exceeds the height of the trees by a factor of 13, less than the total amount of snow that fell will be retained in the treeless area. When the diameter of a treeless area equals or exceeds the height of the surrounding trees by a factor of 30, only 50 percent of the snow that fell will be retained within the area.

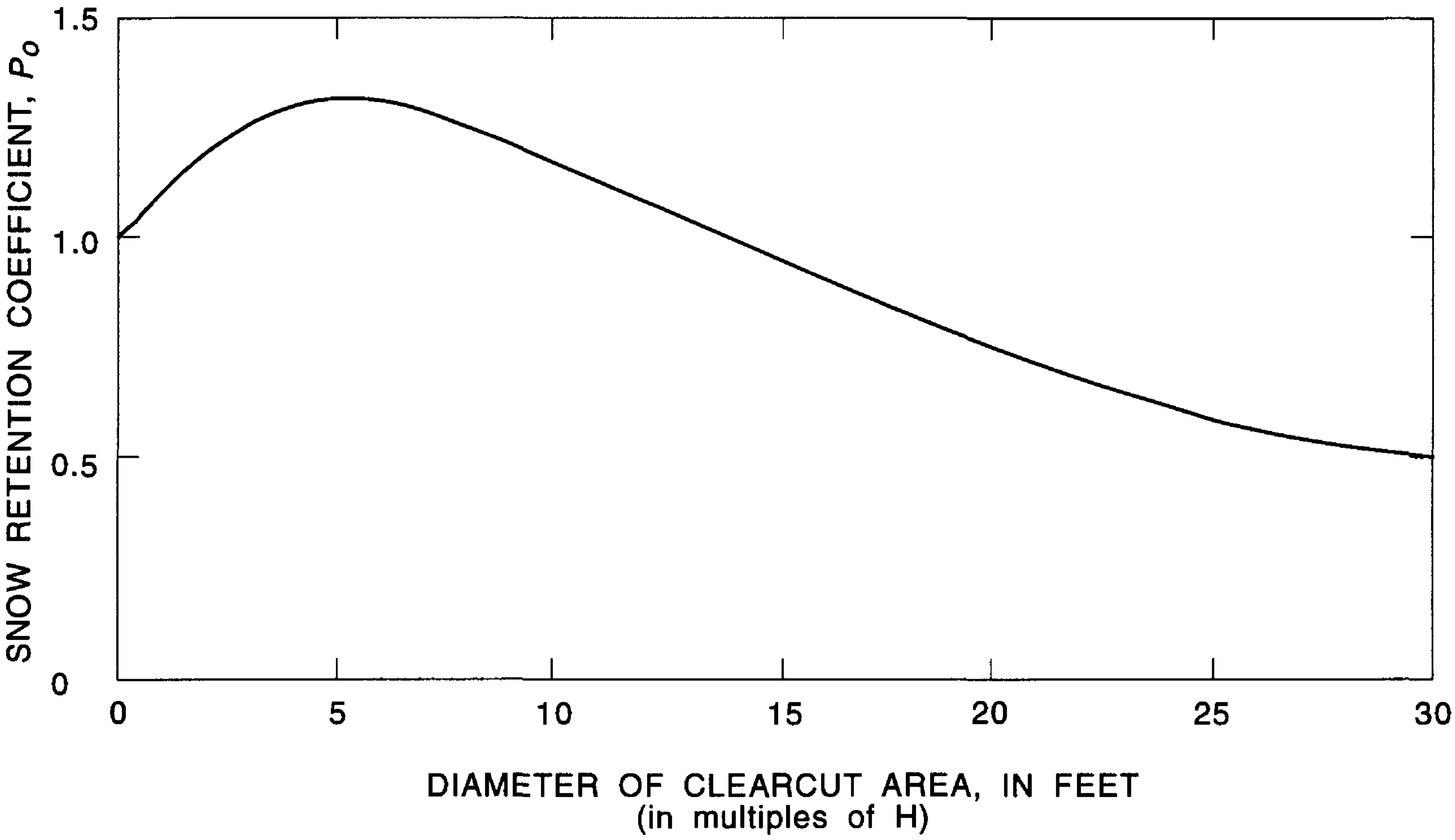


Figure 5.--Snow retention as a function of size of clearcut area. H is the height of surrounding trees (from Troendle and Leaf, 1980, fig. III.6).

In the present study, the locations and areal extents of the treeless parts of the watershed were obtained from U.S. Geological Survey topographic maps. The effective precipitation was considered to be 50 percent of actual precipitation in treeless areas and 100 percent of actual precipitation in forested areas. This resulted in variable reductions in precipitation for particular altitude ranges within some of the watersheds during spring and winter as follows:

Watershed	Precipitation reduction (percent)	Altitude range (feet)
Rio Nambe	33	11,200-12,600
Rio Nambe	22	10,600-11,200
Rio Nambe	5	10,000-10,600
Rio Nambe	5	8,200-8,800
Rio en Medio	39	11,000-12,280
Rio en Medio	14	10,200-11,000
Tesuque Creek	35	10,800-12,000
Santa Fe River	16	11,100-12,000

Annual and seasonal rates of precipitation over each of the study area basins were calculated by dividing each surface-water basin into altitude zones, measuring the areas of each of those zones and calculating the relative proportion of the total basin area each covers, then multiplying the precipitation rates for the corresponding altitude ranges (calculated using eq. 2 and then dividing into seasonal rates as described above) by the proportional areas and summing the results. All high-altitude zones with significant amounts of open area were adjusted for sublimation. All but one of the drainage basins, that of Little Tesuque Creek, have significant areas of tundra and other unforested areas in their upper drainage areas. Snow falling on such bare areas lies on frozen ground and is exposed to the sun and wind for approximately 4 months of the year. During that time sublimation takes place, reducing the amount of water available from precipitation. Studies indicate that most sublimation occurs over open areas rather than heavily forested areas. The rate of sublimation was estimated (Garstka, 1964, p. 10-30) to be 0.5 inch of water for each month of exposure. Estimated precipitation was adjusted for the amount of sublimation expected to occur during November through March.

Evapotranspiration

Evapotranspiration was calculated using techniques outlined in Troendle and Leaf (1980). Their report provides a methodology to estimate evapotranspiration and potential streamflow for hydrologic regions similar to that of the study area. The computer code WATBAL (Subalpine Water Balance Model) was calibrated with observed data from representative and experimental drainage basins in the Rocky Mountain area, then used to develop relations between seasonal precipitation and seasonal evapotranspiration. Precipitation/evapotranspiration relations for the Rocky Mountain/Inland Intermountain region (defined as covering all or parts of South Dakota, Wyoming, Montana, Colorado, New Mexico, Arizona, Utah, and Idaho) are presented in figures 6-8 for various seasons by different energy aspects (Troendle and Leaf, 1980, figs. III-24, III-25, and III-26) and were used to calculate seasonal and annual evapotranspiration in the study area drainage basins.

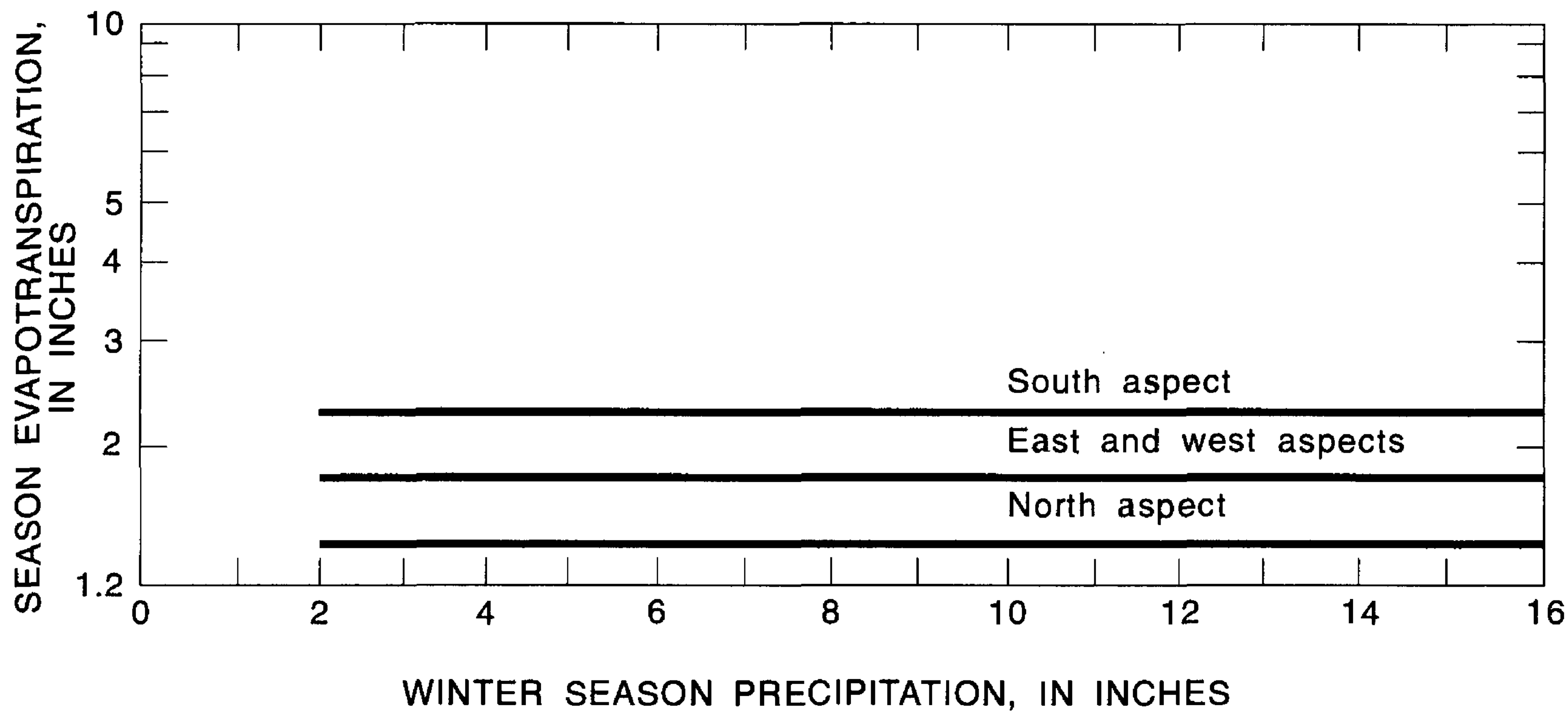


Figure 6.--Precipitation-evapotranspiration relations for the Rocky Mountain/Inland Intermountain hydrologic region 4 for the winter season, by energy aspect (from Troendle and Leaf, 1980, fig. III-24).

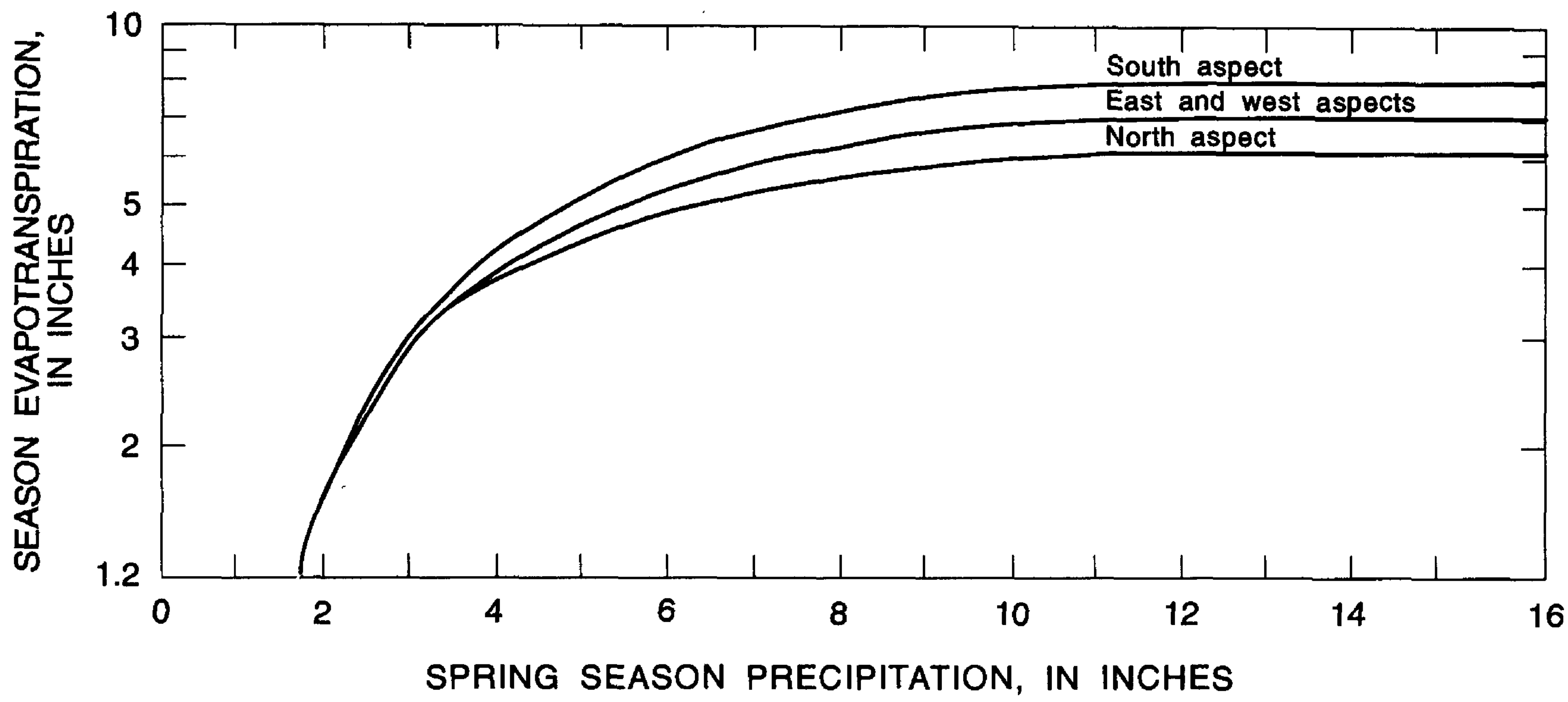


Figure 7.--Precipitation-evapotranspiration relations for the Rocky Mountain/Inland Intermountain hydrologic region 4 for the spring season, by energy aspect (modified from Troendle and Leaf, 1980, fig. III-25).

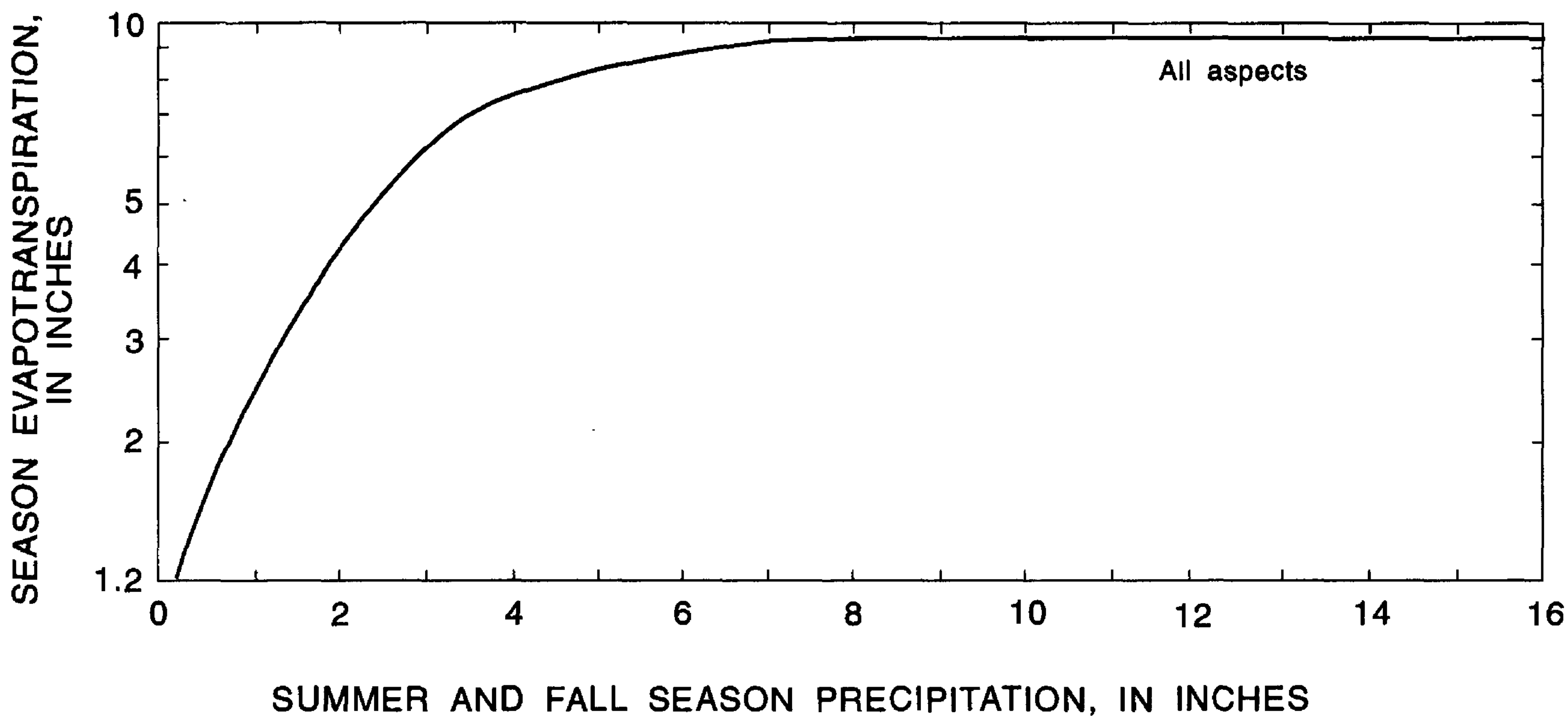


Figure 8.--Precipitation-evapotranspiration relations for the Rocky Mountain/Inland Intermountain hydrologic region 4 for the summer/fall season, by energy aspect (modified from Troendle and Leaf, 1980, fig. III-26).

Determining the energy aspect of the individual basins was necessary to use these figures. Energy aspect is essentially a term that describes the degree to which the basin is oriented so that the energy of the sun will melt the snow and permit evapotranspiration to occur. Low-altitude, south-facing basins have high-energy/south aspects; low- to mid-altitude, north-, east-, and west-facing basins and high-altitude, south-facing basins have intermediate-energy/east-west aspects; and high-altitude, north-, east-, and west-facing basins have low-energy/north aspects. All study area basins are located at "high" altitudes using Troendle and Leaf's (1980) criteria. No part of any basin, therefore, has a high-energy/south aspect. Those portions of each basin that face east, west, or north were identified and considered to have low-energy/high-altitude aspects ("north aspect" in figs. 6 and 7). Those portions of each drainage basin that face south were identified and considered to have an intermediate-energy/east-west aspect. These determinations have possibility for error.

Runoff

Surface-water yields from the four mountain drainages of the Rio Nambe, Tesuque Creek, Little Tesuque Creek, and Santa Fe River (fig. 1) were calculated by averaging monthly streamflow data derived from daily measurements recorded at U.S. Geological Survey streamflow-gaging stations (table 1; all tables are at back of report) near the mountain front (U.S. Geological Survey, 1950-60; 1962-88). Surface-water yields for the Rio en Medio drainage basin (tables 2 and 3) were derived from previous estimates of Reiland (1975) and Reiland and Koopman (1975). When the streamflow gage is not located at the contact between the basin sediments and the Precambrian rocks, as is the case with the Little Tesuque Creek, Tesuque Creek, and Santa Fe River drainages, calculated yields were adjusted. When upstream reservoirs control the flow of a stream, as is the case with the Rio Nambe and the Santa Fe River, monthly streamflow was adjusted to account for the change of storage in the reservoirs and for evaporation from the surfaces of the reservoirs.

Limitations of Water-Budget Calculations

Limitations are inherent in using an annually averaged water budget to determine the amount of subsurface inflow from the mountain block into an alluvial basin aquifer. A water budget is essentially a lumped-parameter model that assumes that all inputs to and outputs from the model can be described by a limited number of parameters. Such an approach assumes that the complexities of the processes involved and their interactions are incorporated within the defined inputs and outputs. The validity of this assumption is affected by the nature and degree of the interrelations among the parameters. For the present study, all inputs to the model were assumed to be included in precipitation, and all outputs from the model were assumed to be included in evapotranspiration, streamflow discharge, sublimation and snow evaporation, and subsurface recharge.

The accuracy of the calculations is directly dependent on the accuracy of the measurements or estimates of the "known" parameters of precipitation, evapotranspiration, and streamflow. Due to the imperfect nature of scientific measurement and the paucity of site-specific data, however, values for these parameters often are only rough estimates made either from equations developed for generalized conditions over regional areas or from calculations based on data gathered over a limited period of time over a limited local area. For the present study, precipitation within various altitude zones was estimated by applying an equation that was developed from precipitation measurements taken at a limited number of stations in southern Colorado and northern New Mexico for a limited number of years (Pete Stewart, written commun., 1984) over the entire southern Rocky Mountains. Evapotranspiration and snow evaporation were estimated using graphs also developed for the entire Rocky Mountains (Troendle and Leaf, 1980) using the computer code WATBAL. Streamflow runoff was calculated from local data that were limited by the number of streamflow-gaging stations and the period of record available. A large range of error can be expected for each of these components, in particular because, with the exception of streamflow data, they are not derived from site-specific information. The evapotranspiration estimates derived from Troendle and Leaf (1980) are probably most subject to error, if only because the graphs developed for seasonal evapotranspiration were developed for a region that encompasses six States. The region varies greatly in humidity, tree type, soil type, and numerous other factors. Because detailed analysis of the topography of each of the drainage basins was not done, the proportioning of basin aspect between low-energy/north aspect and intermediate-energy/east-west aspect is subject to considerable error. An accurate evaluation of aspect by altitude for each basin might change the evapotranspiration estimates.

An average annual water budget that includes only precipitation, evapotranspiration, streamflow runoff, and subsurface recharge in the input-output equation treats the hydrologic cycle as a steady-state system over the period of a year. All inputs that enter the system in the course of a year are assumed to leave the system in that same year with no net changes in soil moisture or storage of water in the aquifer. In actuality, no given year will respond exactly like an "average" year. The "average" rates of the water-budget components represent the averages of many years of data; the water budget is itself an idealization that probably never represents a "real" individual year.

Because the use of water budgets dictates that precipitation, evapotranspiration, snow evaporation, and streamflow be treated as averages over each of the seasonal subdivisions of a year and that these averages be derived over the period of record available, the impact of individual events will be masked. For example, prolonged, individual summer thunderstorms might provide sufficient moisture to overcome the soil-moisture deficit and recharge rocks of the mountain block, although a calculated seasonal average water budget will not reflect that event.

The water-budget method assumes that ground-water divides coincide with surface-water divides. The validity of that assumption in an area may be important to the applicability of the water-budget method to that area because it defines the extent of each basin system.

Water budgets can be misused because of a lack of understanding about their application. One of the most common misconceptions about water budgets is that they provide, through quantification of recharge, an assessment of the amount of water that can be withdrawn from wells without a lowering of water levels within an aquifer. Theis (1940) and Bredehoeft and others (1982) explained why this idea is invalid. The estimates of subsurface recharge from the Sangre de Cristo Mountains into the Tesuque aquifer system of the Española Basin provided in this report do not quantify the amount of water that can be withdrawn from the Tesuque aquifer without adverse effects, nor do the computer-simulated rates of subsurface mountain-front recharge reported in McAda and Wasiolek (1988).

RESULTS OF WATER-BUDGET CALCULATIONS

Rio Nambe Drainage Basin

The Rio Nambe drainage basin (figs. 1, 9) encompasses 34.24 square miles of heavily forested, mountainous terrain on the western face of the central Sangre de Cristo Mountains. Trending basically east-west, it extends from an altitude of 12,600 feet above sea level around Santa Fe Baldy and Lake Peak down to an altitude of only 6,500 feet above sea level at the streamflow-gaging station downstream from Nambe Falls Dam. About 9 miles wide and 4 miles long at midlength, the eastern limit of this leaf-shaped watershed is defined by the crest of the Sangre de Cristo Mountains. In the upper half of the watershed of the Rio Nambe, two streams drain the area: the Rio Capulin flows through the country north of Santa Fe Baldy, and the Rio Nambe flows from Nambe Lake at an altitude of 11,400 feet and drains the country south of Santa Fe Baldy. The two streams join to form the main stem of the Rio Nambe in the steep valley downstream from Puerto Nambe about 4 miles upstream from Nambe Falls Dam at an altitude of about 7,680 feet. The gradient of the stream channels exceeds 600 feet per mile in the upper watershed, but flattens considerably downstream.

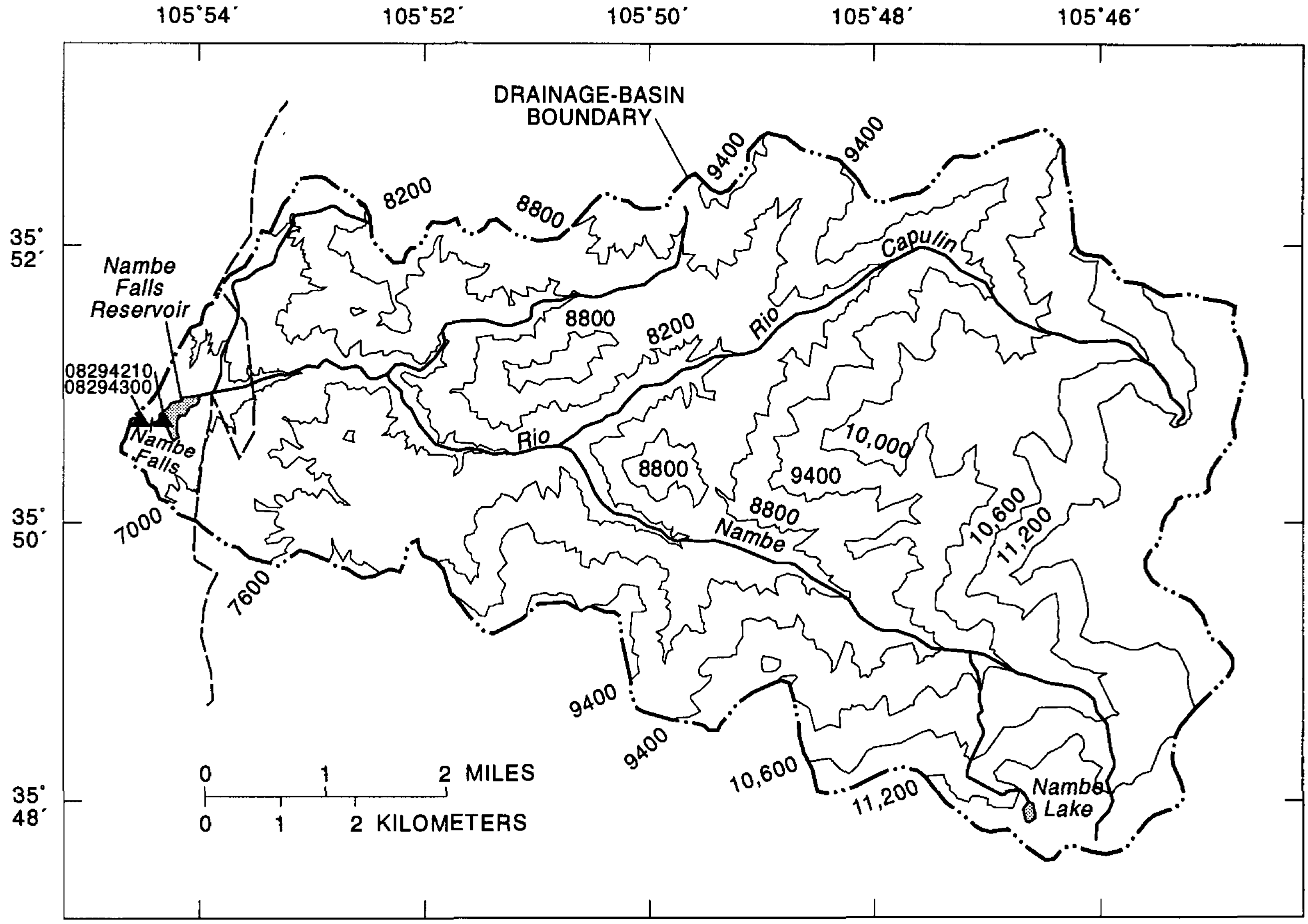
Precipitation

Calculated seasonal and annual precipitation for the Rio Nambe surface-water drainage basin is presented in tables 4-7. An average of 24.78 inches of effective precipitation will be produced in the basin in a year when the effect of snow evaporation during the winter and spring is considered (table 7). About 2.31 square miles of this watershed is unforested and retains large, continuous amounts of snow from November through mid-June. An estimated 8.00 inches of precipitation falls during the winter, 8.75 inches during the spring, and 8.03 inches during the summer/fall.

Evapotranspiration

Tables 4-6 present the calculation of evapotranspiration over the Rio Nambe surface-water drainage basin, which is based on techniques outlined in Troendle and Leaf (1980). The estimates of seasonal precipitation calculated previously were used with figures 6-8 to obtain seasonal rates of evapotranspiration. All of the Rio Nambe drainage basin above the altitude of 10,600 feet and below 7,000 feet has a north aspect. The percentages of the Rio Nambe drainage basin that have an intermediate-energy/east-west aspect (as applied to figs. 6-8) are as follows:

Range in altitude (feet)	Percentage
10,000-10,600	25
9,400-10,000	33
8,800-9,400	66
8,200-8,800	87
7,600-8,200	44
7,000-7,600	5



Base compiled from the following sources: hydrography from U.S. Geological Survey digital data, 1:100,000, 1983; topographic contours and drainage basin and subbasin boundaries digitized from U.S. Geological Survey, 1:24,000, 1953, 1977. Universal Transverse Mercator projection, zone 13

EXPLANATION

MOUNTAIN FRONT--Approximate location from Kelley (1978)

9400 LAND-SURFACE CONTOUR--Interval, in feet, is variable. Datum is sea level

08294300 ▲ STREAMFLOW-GAGING STATION AND NUMBER

Figure 9.--Rio Nambe drainage basin, New Mexico.

An estimated 1.51 inches of precipitation is evapotranspired during the winter, 5.82 inches during the spring, and 9.33 inches during the summer/fall. A total of 16.66 inches of water, or 67 percent of the estimated annual adjusted precipitation, was calculated by this method to be lost to evapotranspiration (table 7).

Runoff

Prior to 1979, daily streamflow of the Rio Nambe was measured at gaging station 08294300 (figs. 1, 9). In February 1976, the Nambe Falls Dam and Reservoir were completed about 1,000 feet upstream from this site. A new streamflow-gaging station, 08294210, was established downstream from the dam, and the old station was discontinued, after December 1978. Measurements made at the old station between February 1976 and December 1978 were affected by the presence of the dam. The new station is located in the outlet conduits of Nambe Falls Dam 300 feet upstream from Nambe Falls (figs. 1, 9). Daily measurements of flow of the Rio Nambe discharged from the reservoir commenced in January 1979 (table 1).

Nambe Falls Reservoir has a capacity of 2,020 acre-feet and a surface area of 59 acres at the crest of the spillway. Area and capacity tables from the Bureau of Reclamation (1976) and month-end reservoir contents from the annual reports of the Rio Grande Compact Commission (1976-87) were used to adjust recorded streamflow measurements by accounting for evaporation from the surface of the reservoir and change in reservoir storage. An evaporation rate of 70 percent of the measured monthly pan evaporation rate was used.

These computed mean monthly natural flows for the Rio Nambe, presented in table 2, were calculated by adjusting the measured monthly streamflow values at gaging station 08294210 for changes in the volume of water in storage in Nambe Falls Reservoir and for evaporation from the surface of that reservoir, then averaging the resulting monthly discharges with streamflow measured at gaging station 08294300 prior to construction of the dam. An annual stream discharge of 9,280 acre-feet of water was calculated to leave the Rio Nambe drainage basin and be measured at the mountain front. This volume is equivalent to 5.09 inches of water averaged over the basin. Of this volume, 1,390 acre-feet was discharged during the winter, 5,360 acre-feet during the spring, and 2,530 acre-feet during the summer/fall (table 3).

Estimated Subsurface Recharge

By using the calculated values for precipitation, evapotranspiration, and runoff, mountain-front recharge is estimated as follows:

$$24.78 \text{ inches} - 16.66 \text{ inches} - 5.09 \text{ inches} = 3.03 \text{ inches}$$

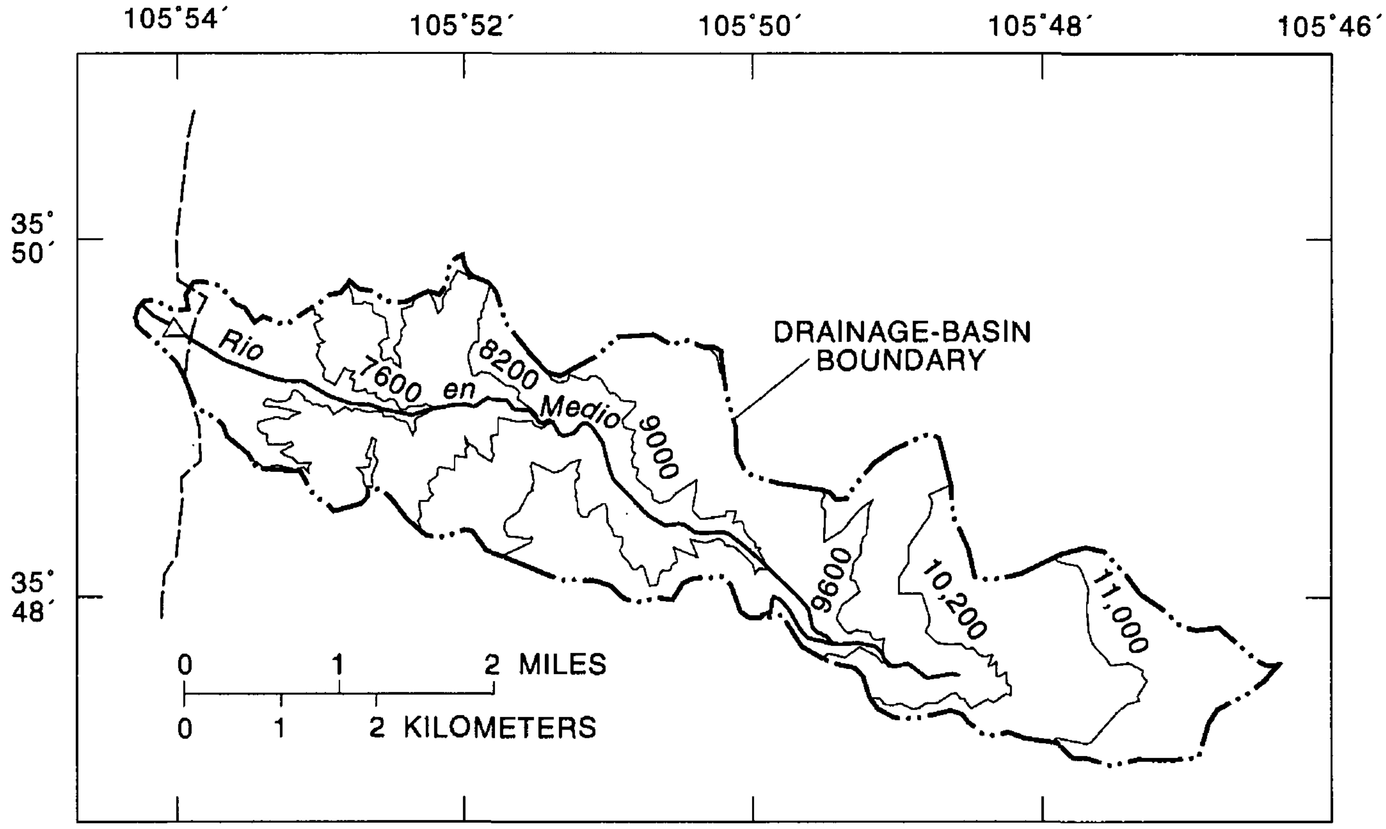
The estimated amount of water that could recharge the Española Basin at the mountain front was calculated to average 3.03 inches per year over the Rio Nambe drainage basin (table 7). During summer months the high rate of evapotranspiration depletes soil moisture, preventing recharge and causing a soil moisture deficit, which appears in table 7 as a negative recharge number. A total of 5,520 acre-feet of water per year or 7.62 cubic feet per second may be available to enter the basin as subsurface inflow (tables 7 and 24). Because the length of mountain front receiving recharge from the Rio Nambe drainage basin is about 3.5 miles, recharge would enter the basin at a rate of about 2.2 cubic feet per second per mile of mountain front.

Rio en Medio Drainage Basin

The Rio en Medio drainage basin (figs. 1 and 10) is a long, narrow watershed that extends along the southern border of the Rio Nambe drainage basin and encompasses 8.66 square miles (table 8). About 7 miles from west to east and 1 mile from north to south, the Rio en Medio drainage basin trends west-northwest from an altitude of more than 12,000 feet on the east to 7,000 feet on the west. One stream, the Rio en Medio, literally "river in the middle" in Spanish, drains the area.

Precipitation

Calculated seasonal and annual precipitation for the Rio en Medio surface-water drainage basin is presented in tables 8-11. In the course of a year, 24.06 inches of effective precipitation will be produced in the Rio en Medio drainage basin when snow evaporation is considered. About 0.50 square mile of the upper Rio en Medio watershed is tundra or unforested areas over which fallen snow is exposed to the elements. An estimated 7.67 inches of precipitation falls during the winter, 8.40 inches during the spring, and 7.99 inches during the summer/fall.



Base compiled from the following sources: hydrography from U.S. Geological Survey digital data, 1:100,000, 1983; topographic contours and drainage basin and subbasin boundaries digitized from U.S. Geological Survey, 1:24,000, 1953, 1977. Universal Transverse Mercator projection, zone 13

EXPLANATION

MOUNTAIN FRONT--Approximate location from Kelley (1978)

9600 LAND-SURFACE CONTOUR--Interval, in feet, is variable. Datum is sea level

△ GENERAL LOCATION OF STREAMFLOW ESTIMATES BY REILAND AND KOOPMAN (1975)

Figure 10.--Rio en Medio drainage basin, New Mexico.

Evapotranspiration

Tables 8-10 present the calculation of evapotranspiration over the Rio en Medio surface-water drainage basin, which is based on techniques outlined in Troendle and Leaf (1980). The percentages of the Rio en Medio drainage basin that have an intermediate-energy/east-west aspect (as applied to figs. 6-8) are as follows:

Range in altitude (feet)	Percentage
Above 11,000	32
10,200-11,000	50
9,600-10,200	16
9,000-9,600	33
8,200-9,000	25
7,600-8,200	22
7,000-7,600	9

From these figures, an estimated 1.50 inches of precipitation is evapotranspired during the winter, 5.83 inches during the spring, and 9.23 inches during the summer/fall. A total of 16.56 inches of water, or 69 percent of the estimated annual precipitation, was calculated to be lost by this method to evapotranspiration (table 11).

Runoff

No streamflow-gage records are available for the Rio en Medio at the mountain front. Available data are limited to 10 years of measurement from October 1963 to October 1974 for a small area high in the watershed. Estimates of monthly streamflow at the mountain front for this stream were generated by Reiland and Koopman (1975) using a runoff-altitude relation that they developed for the Rio Nambe drainage basin to the north. They assumed that yields per unit area were the same for the two drainages and that monthly values for the Rio en Medio could be computed to be 22.5 percent of those of the Rio Nambe at Nambe, which was the ratio of the drainage areas as calculated by them. Reiland and Koopman (1975, p. 14-15) provided monthly estimates of streamflow for the Rio en Medio from 1935 to 1972 (table 2). A mean annual runoff of 1,740 acre-feet, or a yield of 3.77 inches of water over the 8.66-square-mile drainage basin, was calculated from these estimates (tables 3 and 11).

Estimated Subsurface Recharge

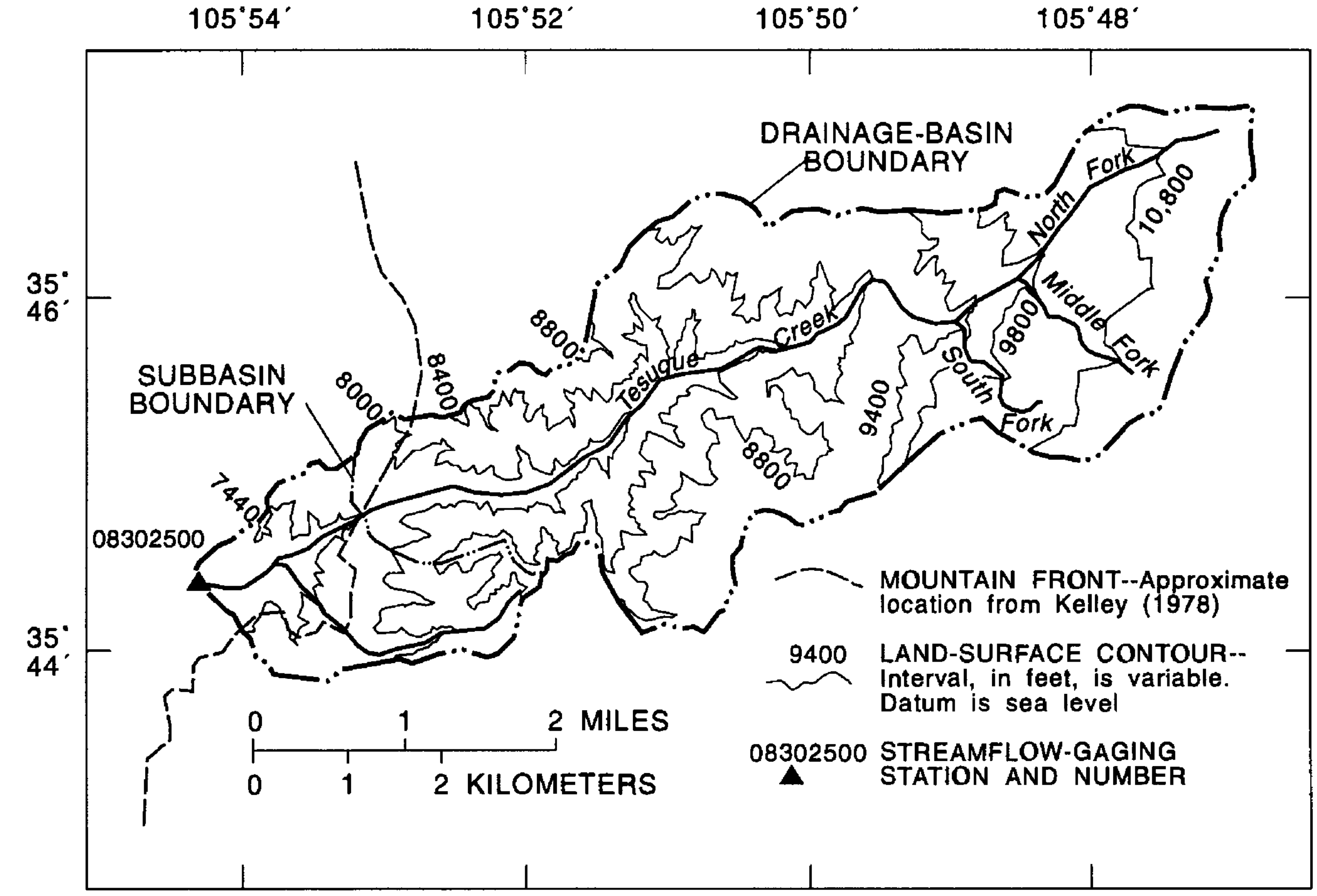
By using the calculated values for precipitation, evapotranspiration, and runoff, mountain-front recharge is estimated as follows:

24.06 inches - 16.56 inches - 3.77 inches = 3.73 inches

The estimated amount of water that could recharge the Española Basin at the mountain front was calculated to be 3.73 inches per year over the Rio en Medio drainage basin (table 11). About 1,710 acre-feet per year or 2.36 cubic feet per second may be available to enter the basin as subsurface inflow at the mountain front (table 24). Because the length of mountain front receiving recharge from the Rio en Medio drainage basin is about 1.5 miles, recharge would enter the basin at a rate of about 1.6 cubic feet per second per mile of mountain front.

Tesuque Creek Drainage Basin

The Tesuque Creek drainage basin (figs. 1 and 11) encompasses 11.22 square miles, as measured from the mountain-front contact between the Precambrian and Quaternary and Tertiary rocks at an altitude of 7,440 feet to the eastern limit of the basin at an altitude of 12,000 feet. No streamflow-gaging stations currently operate on Tesuque Creek. The record for station 08302500 is for the period from April 1936 to December 1952 (table 1). The altitude of the former gage was 7,100 feet above sea level, a mile downstream from the mountain front. A mean flow of about 2,290 acre-feet per year was measured at this location during the 16-year period of record (tables 2 and 3). The Tesuque Creek drainage basin encompasses an area of 11.67 square miles as measured between streamflow-gaging station 08302500 and the mountain crest. The additional area of the drainage basin between the gage and the boundary is 0.45 square mile. A west/southwest-trending drainage, the Tesuque Creek drainage basin is about 6.5 miles from west to east and 1.7 miles from north to south. The upper watershed area is fairly broad: 26 percent of the drainage area is higher than 9,800 feet (table 12). About 1 mile north of Bishops Lodge, Tesuque Creek joins with Little Tesuque Creek, which drains the area just to the south, to form the Rio Tesuque (fig. 1).



Base compiled from the following sources: hydrography from U.S. Geological Survey digital data, 1:100,000, 1983; topographic contours and drainage basin and subbasin boundaries digitized from U.S. Geological Survey, 1:24,000, 1953, 1977. Universal Transverse Mercator projection, zone 13

Figure 11.--Tesuque Creek drainage basin, New Mexico.

Precipitation

Calculated seasonal and annual precipitation for the Tesuque Creek surface-water drainage basin is presented in tables 12-15. A total of 24.18 inches of effective precipitation per year will be produced in the drainage basin when the effect of snow evaporation during the winter is included. The upper watershed includes 0.46 square mile of tundra and unforested areas that retain large expanses of snow that are subjected to sublimation during winter months. Of total precipitation, 7.70 inches is estimated to fall during the winter, 8.40 inches during the spring, and 8.08 inches during the summer/fall.

Evapotranspiration

Tables 12-14 present the calculation of evapotranspiration over the Tesuque Creek surface-water drainage basin, which is based on techniques outlined in Troendle and Leaf (1980). All of the Tesuque drainage basin above the altitude of 9,400 feet has a low-energy/north aspect. The percentages of the Tesuque Creek drainage basin that have an intermediate-energy/east-west aspect (as applied to figs. 6-8) are as follows:

Range in altitude (feet)	Percentage
8,800-9,400	35
8,400-8,800	40
8,000-8,400	33
7,440-8,000	24

From these figures, an estimated 1.50 inches of precipitation is evapotranspired during the winter, 5.85 inches during the spring, and 9.34 inches during the summer/fall. A total of 16.69 inches of water, or 69 percent of the estimated annual precipitation, was calculated to be lost by this method to evapotranspiration (table 15).

Runoff

Tesuque Creek consists of three forks that drain the high, wide upper watershed of this drainage basin between the altitudes of 9,200 and 11,600 feet. The "North," "Middle," and "South" Forks join together 9,200 feet above sea level to form Tesuque Creek (fig. 11). The stream flows west-southwest another 3 miles to the mountain front and an additional mile beyond to the site of former streamflow-gaging station 08302500.

Because so few long-term streamflow data were available for Tesuque Creek, Reiland and Koopman (1975) used linear-regression analyses of the 16 years of monthly data available for the Tesuque Creek streamflow-gaging station 08302500 versus the corresponding combined flow during the period of concurrent record for streamflow-gaging stations 08292500 (Rio Nambe near Nambe) and 08292450 (Nambe Canal near Nambe) to extend the record to 1972. Reiland

and Koopman (1975) obtained seasonally variable relations that were used to calculate monthly streamflow for Tesuque Creek at the location of streamflow-gaging station 08302500. A total of 2,042 acre-feet per year was calculated to be discharged by Tesuque Creek at that location (Reiland and Koopman, 1975, p. 18). The Rio Nambe records used in those calculations had been extended through linear-regression techniques: Reiland and Koopman had used linear-regression analyses of monthly flow at streamflow-gaging station 08294300 (Rio Nambe at Nambe Falls near Nambe) for corresponding flow at station 08291000 (Rio Santa Cruz at Cundiyo) to estimate flows for the former station. Reiland and Koopman (1975) then created the missing months of flow measurements for the lower stations by assuming that the total flow at stations 08292500 and 08292450 would be equal to 101.2 percent of the flow at station 08294300.

Mean monthly flows of Tesuque Creek measured at streamflow-gaging station 08302500 are listed in table 2. An annual yield of about 2,290 acre-feet or 3.83 inches of runoff was calculated to leave the Tesuque Creek drainage basin at this point. However, as was previously mentioned, station 08302500 is located a mile into the Española Basin beyond the contact of the Precambrian rocks and the basin sediments. It is likely that by the time the flow of Tesuque Creek was measured at the streamflow-gaging station, the stream had lost a significant quantity of water to the permeable sediments of the underlying Tesuque Formation. On the basis of observations and calculations made by Barrows and Spiegel (Spiegel and Baldwin, 1963, p. 196-198), Tesuque Creek was assumed to lose water to the underlying strata at a rate of 1.0 cubic foot per second per mile (1.21 inches over the drainage area). An adjusted annual yield of 5.04 inches of runoff (1.21 inches + 3.83 inches) therefore was calculated for the entire Tesuque Creek drainage basin at the mountain front (table 15). Seasonal yields for the complete basin area (table 15) were estimated by assuming that the relative proportions of measured seasonal flows (table 3) apply to the entire basin.

Estimated Subsurface Recharge

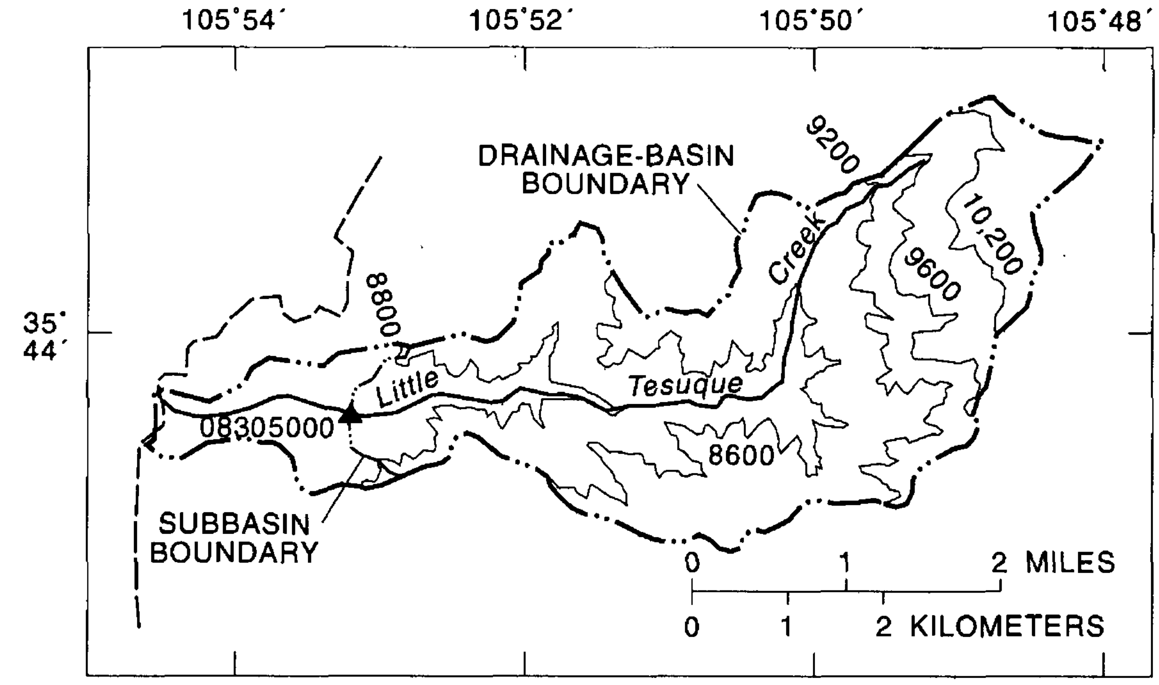
By using the calculated values for precipitation, evapotranspiration, and runoff, mountain-front recharge is estimated as follows:

$$24.18 \text{ inches} - 16.69 \text{ inches} - 5.04 \text{ inches} = 2.45 \text{ inches}$$

The estimated amount of water that could recharge the Española Basin at the mountain front was calculated to be 2.45 inches. About 1,530 acre-feet per year or 2.11 cubic feet per second may be available to enter the Española Basin as subsurface inflow from the mountain block (table 24). Because the length of mountain front receiving recharge from the Tesuque Creek drainage basin is about 2.5 miles, recharge would enter the basin at a rate of about 0.8 cubic foot per second per mile of mountain front.

Little Tesuque Creek Drainage Basin

The Little Tesuque Creek drainage basin (figs. 1 and 12) is the smallest in area and lowest in altitude of the five basins studied. Located just west of the Santa Fe River drainage basin and south of the Tesuque Creek drainage basin, the Little Tesuque Creek drainage basin encompasses 7.06 square miles, as measured from streamflow-gaging station 08305000 in the west at an altitude of about 7,500 feet, to the upper end of the watershed in the east at an altitude of more than 11,000 feet. However, measured from the contact of the Precambrian and Pennsylvanian rocks of the mountain block and the Tertiary sediments of the Española Basin, the drainage basin encompasses 7.66 square miles. Streamflow-gaging station 08305000 is located about 1 mile east of the mountain-front boundary. The intervening area between about 7,200 and 7,500 feet above sea level totals 0.6 square mile. Approximately 5.5 miles from west to east and 1.25 miles from north to south, the Little Tesuque Creek drainage trends basically east-west, draining the western slopes of the Sangre de Cristo Mountains.



Base compiled from the following sources: hydrography from U.S. Geological Survey digital data, 1:100,000, 1983; topographic contours and drainage basin and subbasin boundaries digitized from U.S. Geological Survey, 1:24,000, 1953, 1977. Universal Transverse Mercator projection, zone 13

EXPLANATION

MOUNTAIN FRONT--Approximate location from Kelley (1978)

9600 LAND-SURFACE CONTOUR--Interval, in feet, is variable. Datum is sea level

08305000 ▲ STREAMFLOW-GAGING STATION AND NUMBER

Figure 12.--Little Tesuque Creek drainage basin, New Mexico.

Only 17 percent of the basin area exceeds an altitude greater than 9,600 feet, and less than 8 percent of the basin area is greater than 10,200 feet (table 16). The upper watershed is completely covered with trees and lacks the open country of the alpine tundra zone. Most of the drainage basin developed on the metamorphic and igneous rocks that form the core of the Sangre de Cristo Mountains. However, about 2 miles upstream from the mountain front, limestone of the Magdalena Group crops out in the streambed of the creek. The low altitude of the upper watershed and the presence of the permeable limestone combine to limit the perennial flow of the Little Tesuque Creek to a 2-mile reach in the middle of its drainage basin.

Precipitation

Calculated seasonal and annual precipitation for the Little Tesuque Creek surface-water drainage basin is presented in tables 16-19. A total of 22.96 inches of effective precipitation per year will be produced in the 7.66-square-mile basin. About 7.28 inches of this total is estimated to fall during the winter, 7.84 inches during the spring, and 7.84 inches during the summer/fall.

Evapotranspiration

Values for seasonal and annual evapotranspiration, which were calculated using techniques outlined in Troendle and Leaf (1980), are presented in tables 16-19. Above 9,200 feet the Little Tesuque Creek drainage basin has a low-energy/north aspect. The percentages of the Little Tesuque Creek drainage basin that have an intermediate-energy/east-west aspect (as applied to figs. 6-8) are as follows:

Range in altitude (feet)	Percentage
8,600-9,200	25
8,000-8,600	45
7,520-8,000	50
7,160-7,520	25

From these figures, an estimated 1.47 inches of precipitation is evapotranspired during the winter, 5.74 inches during the spring, and 9.23 inches during the summer/fall. A total of 16.44 inches of water, or 72 percent of the estimated annual precipitation, was calculated to be lost by this method to evapotranspiration (table 19).

Runoff

Approximately 5 years of streamflow data are available for the Little Tesuque Creek at streamflow-gaging station 08305000 (table 1), located about 1 mile east of the mountain front at 7,520 feet above sea level (figs. 1 and 12). Streamflow measurements are available for this station from April 1936 to September 1941. Mean monthly and total annual mean streamflow is presented in table 2. A total basin yield of 862 acre-feet per year was calculated to leave the Little Tesuque Creek watershed as streamflow (table 3). An annual volume of 862 acre-feet per year is equivalent to an annual watershed yield of 2.11 inches of water. This figure was not adjusted for any additional volume of runoff that might occur over the additional 0.6 square mile of drainage area that lies between the streamflow-gaging station and the mountain front. The low rate of precipitation and high rate of evapotranspiration over this area, in addition to the limestone members of the Magdalena Group that crop out in the streambed, would effectively prevent significant amounts of water from contributing to streamflow in this area.

Estimated Subsurface Recharge

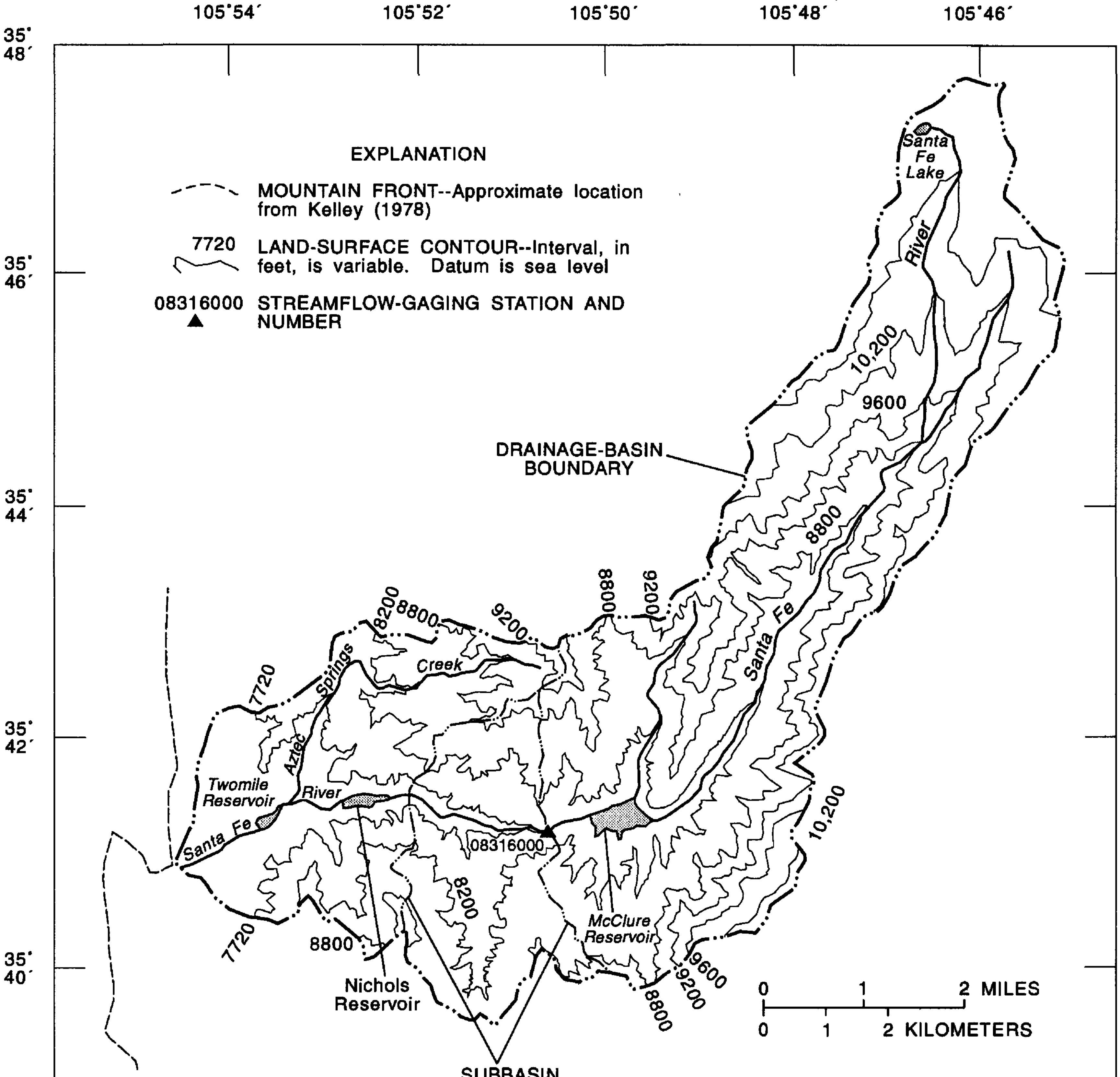
By using the calculated values for precipitation, evapotranspiration, and runoff, mountain-front recharge is estimated as follows:

22.96 inches - 16.44 inches - 2.11 inches = 4.41 inches

The amount of water that could recharge the Española Basin at the mountain front was calculated to be 4.41 inches per year over the Little Tesuque drainage basin. About 1,790 acre-feet per year or 2.47 cubic feet per second may be available to enter the basin as subsurface inflow from the mountain block (table 24). Because the length of mountain front receiving recharge from the Little Tesuque Creek drainage basin is about 2 miles, recharge would enter the basin at a rate of about 1.2 cubic feet per second per mile of mountain front.

Santa Fe River Drainage Basin

The Santa Fe River drainage basin (figs. 1 and 13) is the southernmost of the drainage basins in the study area, and is the only one that trends basically north-south rather than east-west. Its headwaters are in the glacial valleys below Lake Peak and Penitente Peak (fig. 1) at 12,409 and 12,249 feet above sea level. The Santa Fe River flows south from Santa Fe Lake at an altitude of 11,500 feet for about 8 miles through high country before turning west. After flowing westward for another 3.5 miles, the river reaches the mountain front at an altitude almost 1 mile below that of its headwaters. The crest of the southern Sangre de Cristo Mountains defines the eastern rim of the southward-trending upper watershed. From the upper watershed to streamflow-gaging station 08316000, located 0.4 mile downstream from McClure Reservoir at 7,788 feet above sea level, the drainage basin encompasses 18.24 square miles. About 39 percent of this part of the drainage basin is more than 9,600 feet above sea level. The length of this part of the drainage basin is 9.5 miles, and the average width is 2.2 miles. The average slope of the streambed is 8 percent; about 80 percent of the drainage area slopes between 31 and 64 percent (Hardaway and Thompson, 1962). Between station 08316000 and the mountain front, which is 400 feet lower, the Santa Fe River drains an additional 10.46 square miles, for a total drainage area east of the mountain front of 28.70 square miles.



Base compiled from the following sources: hydrography from U.S. Geological Survey digital data, 1:100,000, 1983; topographic contours and drainage basin and subbasin boundaries digitized from U.S. Geological Survey, 1:24,000, 1953, 1977. Universal Transverse Mercator projection, zone 13

Figure 13.--Santa Fe River drainage basin, New Mexico.

Three reservoirs in the lower canyon of the Santa Fe River upstream from the mountain front currently (1988) operate to impound water for municipal use by the city of Santa Fe (fig. 1). Nichols Reservoir, completed in March 1943, is several miles upstream from the mountain front at an altitude of 7,500 feet. It currently has a capacity of 685 acre-feet. McClure Reservoir, completed in 1935, is 2.1 miles upstream from Nichols Reservoir at an altitude of about 7,900 feet. It has been modified several times and currently (1988) has a capacity of 2,615 acre-feet. A smaller reservoir, Twomile Reservoir, is about 0.5 mile east of the mountain front, 2 miles east of the center of Santa Fe. The canyon of the Santa Fe River has been closed to the public upstream from Twomile Reservoir since 1926. In the time since that closure the U.S. Forest Service has documented a substantial increase in vegetation along the valley floor and in marsh and meadow areas, and a minor increase in forest undergrowth (Spiegel and Baldwin, 1963, p. 162-163). The revegetation of the canyon may be affecting the surface-water yield of the drainage basin.

Precipitation

Calculated seasonal and annual precipitation averaged for the Santa Fe River surface-water drainage basin is presented in tables 20-23. An average of 23.62 inches of effective precipitation per year will be produced in the basin when the effects of snow evaporation are considered. The upper watershed includes 2.03 square miles of tundra and unforested areas that retain large expanses of snow. Of total precipitation 7.59 inches is estimated to fall during the winter, 8.14 inches during the spring, and 7.89 inches during the summer/fall.

Evapotranspiration

Tables 20-22 present the calculation of evapotranspiration over the Santa Fe River drainage basin, which is based on techniques outlined in Troendle and Leaf (1980). The percentages of the Santa Fe River watershed that have an intermediate-energy/east-west aspect (as applied to figs. 6-8) are as follows:

Range in altitude (feet)	Percentage
11,100-12,000	45
10,200-11,100	39
8,800-9,000	13
8,200-8,800	16
7,720-8,200	10
7,200-7,720	31

The rest of the area has a low-energy/north aspect. From the graphs, an estimated 1.47 inches of precipitation is evapotranspired during the winter, 5.77 inches during the spring, and 9.20 inches during the summer/fall. A total of 16.44 inches of water, or 70 percent of the annual estimated precipitation, was calculated by this method to be lost to evapotranspiration (table 23).

Runoff

The streamflow of the Santa Fe River has been measured continuously since January 1913 (table 1). At the present time (1988) streamflow-gaging station 08316000 is located 0.4 mile downstream from McClure Reservoir and 5.3 miles east of the city of Santa Fe (figs. 1 and 13). The datum of the gage is 7,718 feet above sea level. Prior to April 24, 1913, the streamflow-gaging station was a staff gage 2 miles downstream from the present site and at a different datum. From April 24, 1913, to November 4, 1930, the station was at a site 1.5 miles downstream from the present site, and from April 11, 1931, to September 30, 1942, it was at a location 0.3 mile upstream from the present site, each at a different datum. At the end of water year 1986, the maximum discharge for the period of record was 1,500 cubic feet per second on April 14, 1921, and the minimum discharge was 0.05 cubic foot per second on April 7 and 8, 1981. The average discharge for the 73-year period of record through water year 1986 was 8.07 cubic feet per second or 5,850 acre-feet per year (U.S. Geological Survey, 1987).

Since 1926 McClure Reservoir has affected the flow of the Santa Fe River at the streamflow-gaging station. Prior to 1947, the reservoir was fairly small with a capacity of only 650 acre-feet, but in 1947, the dam was raised 36.5 feet and the capacity of the reservoir greatly increased. Currently (1988) the reservoir can hold 2,615 acre-feet of water and has a surface area of approximately 90 acres. The monthly and yearly flows presented in tables 2 and 3 are computed natural flows for the river, calculated by adjusting the recorded flow of the Santa Fe River for change in storage in the reservoir and evaporation from the free-water surface. The computed natural flows for 1914 to 1951 were obtained from Spiegel and Baldwin (1963, p. 250, table 21). Values for water years 1952 to 1986 were calculated by using month-end change in storage records (U.S. Geological Survey, 1952-87) and an estimated surface area of the reservoir. An average annual streamflow of 6,170 acre-feet was calculated for the 18.28-square-mile watershed area upstream from the gage. Spiegel and Baldwin (1963, p. 155-156) estimated that 680 acre-feet of runoff contributed to the flow of the river between that gage and Twomile Reservoir. A total of 6,850 acre-feet per year or 4.47 inches of water is therefore estimated to be the streamflow yield from the Santa Fe River watershed at the mountain front (table 23). Streamflow was adjusted seasonally by assuming that the additional estimated flow was seasonally distributed as the measured streamflow in table 3. The total adjusted streamflow is 19 percent of annual precipitation (table 23).

Estimated Subsurface Recharge

By using the calculated values for precipitation, evapotranspiration, and runoff, mountain-front recharge is estimated as follows:

23.62 inches - 16.44 inches - 4.47 inches = 2.71 inches

The estimated amount of water that could recharge the Española Basin at the mountain front was calculated to be 2.71 inches over the Santa Fe River drainage basin. About 4,170 acre-feet of water per year or 5.75 cubic feet per second (table 24) may be available to enter the Española Basin as subsurface inflow from the mountain block. Because the length of mountain front receiving recharge from the Santa Fe River drainage basin is about 3.5 miles, recharge would enter the basin at a rate of about 1.6 cubic feet per second per mile of mountain front.

DISCUSSION OF RESULTS

The seasonal and annual water budgets for the drainage basins are presented in tables 7, 11, 15, 19, and 23. From these tables, it is evident that on an average annual basis, most precipitation that eventually becomes mountain-front recharge falls during the winter months. During the spring little or no new precipitation is available for recharge, but melting snow from winter storms probably enters the ground-water system of the mountains. Recharge deficits during the summer/fall season indicate a lack of recharge to the mountain block and a significant quantity of soil-moisture depletion. This seasonal distribution of recharge is consistent with the observations of other investigators discussed previously. Because the volume of soil moisture depleted during the summer months needs to be replaced before recharge to the mountain block can occur, average annual calculations probably give representative estimates of recharge in the study area.

The annual potential subsurface inflow from the Rio Nambe drainage basin was calculated to be 5,520 acre-feet or about 12 percent of annual precipitation; from the Rio en Medio drainage basin, 1,710 acre-feet or about 15 percent of annual precipitation; from the Tesuque Creek drainage basin, 1,530 acre-feet or about 11 percent of annual precipitation; from the Little Tesuque Creek drainage basin, 1,790 acre-feet or about 19 percent of annual precipitation; and from the Santa Fe River drainage basin, 4,170 acre-feet or about 12 percent of annual precipitation (table 24). A total volume of about 14,700 acre-feet of water or 12.7 percent of average annual precipitation over the drainage basins was calculated to contribute to subsurface inflow to the Tesuque aquifer system from the Sangre de Cristo Mountains by these five drainage basins (table 24).

The values calculated using the water-budget method were used to estimate the quantity of subsurface inflow to enter along the Sangre de Cristo Mountains in the model of the Tesuque aquifer system (McAda and Wasiolek, 1988). Values calculated in this report and values simulated by the model are shown in table 24. The final calibrated model calculated that along that length of the mountain front corresponding to the Rio Nambe drainage basin, 2,210 acre-feet of water per year, or 4.9 percent of annual precipitation, enters the aquifer system; along that length of the mountain front corresponding to the Rio en Medio drainage basin, 760 acre-feet of water per year, or 6.8 percent of annual precipitation, enters the aquifer system; along that length of the mountain front corresponding to the Tesuque Creek drainage basin, 760 acre-feet of water per year, or 5.2 percent of annual precipitation, enters the aquifer system; along that length of the mountain front corresponding to the Little Tesuque Creek drainage basin, 870 acre-feet of water per year, or 9.3 percent of annual precipitation, enters the aquifer system; and along that length of the mountain front corresponding to the Santa Fe River drainage basin, 3,330 acre-feet of water per year, or 9.2 percent of annual precipitation, enters the aquifer system. A total of 7,930 acre-feet of water per year was simulated to enter the Tesuque aquifer system as subsurface inflow along the western front of the Sangre de Cristo Mountains from the five drainage basins (table 24). The model simulated an additional 2.35 cubic feet per second, or 1,700 acre-feet per year, that enters the aquifer along the 3.5-mile length of the mountain front between the Tesuque Creek and Rio en Medio drainages. This area corresponds to the Rio Chupadero watershed (fig. 1), for which a water budget was not determined. A total volume of about 9,600 acre-feet per year, or about 8 percent of average annual precipitation, was simulated to enter the Tesuque aquifer system as subsurface inflow along the entire mountain front between and including the Rio Nambe and Santa Fe River drainage basins.

SUMMARY

Subsurface recharge is considered to be that component of mountain-front recharge that enters an adjacent basin-aquifer system in the subsurface, directly from the mountain block. Water enters the Tesuque aquifer system of the Española Basin in north-central New Mexico as subsurface recharge from the Sangre de Cristo Mountains. Within the study area, subsurface recharge was estimated by developing water budgets for basins of five streams that drain the western side of the Sangre de Cristo Mountains north of the city of Santa Fe: the Rio Nambe, Rio en Medio, Tesuque Creek, Little Tesuque Creek, and Santa Fe River.

To calculate subsurface recharge, the steady-state water budget was assumed to encompass the time period of a year, and the volume of water entering the Tesuque aquifer system during that year was assumed to be balanced by an equal volume that leaves the system in that same year, with no change in aquifer storage. Also assumed was that the volume of average annual precipitation that is not evapotranspired or discharged to streams within a year potentially is available to percolate down through the overburden and fractured rock of the mountain block and eventually recharge the Tesuque aquifer system at the mountain front.

Water budgets developed for the basins of five streams draining the western side of the Sangre de Cristo Mountains of northern New Mexico indicate that subsurface inflow along the mountain front is recharging the Tesuque aquifer system of the Española Basin. Approximately 14,700 acre-feet of water per year, or about 13 percent of the average annual precipitation over the mountains, is calculated to leave the mountain block and enter the basin as subsurface recharge from the drainage basins of the Rio Nambe, Rio en Medio, Tesuque Creek, Little Tesuque Creek, and Santa Fe River. About 5,520 acre-feet per year, or about 12 percent of average annual precipitation, is calculated to enter from the Rio Nambe drainage basin; about 1,710 acre-feet per year, or about 15 percent of average annual precipitation, is calculated to enter from the Rio en Medio drainage basin; about 1,530 acre-feet, or about 11 percent of average annual precipitation, is calculated to enter from the Tesuque Creek drainage basin; about 1,790 acre-feet, or about 19 percent of average annual precipitation, is calculated to enter from the Little Tesuque Creek drainage basin; and about 4,170 acre-feet per year, or about 12 percent of average annual precipitation, is calculated to enter from the Santa Fe River drainage basin. Seasonal water budgets indicate that most of the subsurface recharge enters the overburden and fractured rock of the mountain block during the winter and spring.

These calculated subsurface recharge values were used to estimate the fluxes permitted to occur from constant-head cells along a constant-head boundary defining the mountain front of the Sangre de Cristo Mountains in a numerical computer model of the Tesuque aquifer system near Santa Fe, New Mexico. The fluxes were output from the steady-state model. They were adjusted by modifying model input such as aquifer properties, discharge to the Rio Grande, and recharge from streams over reasonable ranges. For transient model simulations, the constant-head boundary was converted to a specific-flux boundary, and the fluxes simulated during steady state were used as input to the model. Simulated subsurface recharge totaled about 9,600 acre-feet per year, or about 8 percent of average annual precipitation, over the length of the boundary between and including the Rio Nambe and Santa Fe River drainage basins and also including the Rio Chupadero drainage basin, for which no water budget was determined.

SELECTED REFERENCES

Anderholm, S.K., 1994, Ground-water recharge near Santa Fe, north-central New Mexico: U.S. Geological Survey Water-Resources Investigations Report 94-4078, 68 p., 2 pls.

Anderson, T.W., 1972, Electric-analog analysis of the hydrologic system, Tucson Basin, southeastern Arizona: U.S. Geological Survey Water-Supply Paper 1939-C, 34 p.

Belan, R.A., 1972, Hydrology of a portion of the Santa Catalina Mountains: Tucson, University of Arizona, unpublished M.S. thesis, 68 p.

Belan, R.A., and Matlock, W.G., 1973, Groundwater recharge from a portion of the Santa Catalina Mountains, *in* Hydrology and water resources in Arizona and the Southwest: Meetings of Arizona Section, American Water Resources Association, and Hydrology Section, Arizona Academy of Science, Tucson, Ariz., 1973, Proceedings, American Water Resources Association, v. 3, p. 33-40.

Ben-Asher, J., 1978, Evaluation of evapotranspiration from climatological data and its relation to a basin water balance, *in* Israel Meteorological Research Papers, Meteorology of semi-arid zones: Joint Conference, American Meterological Society--Israel Meteorological Society, Bet Dagag, 1978, v. 2, p. 297-314.

Besbes, M., Delhomme, J.P., and DeMarsily, G., 1978, Estimating recharge from ephemeral streams in arid regions--A case study at Kairouan, Tunisia: Water Resources Research, v. 14, no. 2, p. 281-290.

Bredehoeft, J.D., Papadopulos, S.S., and Cooper, H.H., Jr., 1982, Groundwater--The water-budget myth, *in* Studies in geophysics--Scientific basis of water-resource management: Washington, D.C., National Academy Press, p. 51-57.

Bureau of Reclamation, 1976, Nambe Falls Reservoir area and capacity tables: U.S. Department of the Interior, 11 p.

Cordova, R.M., Sandberg, G.W., and McConkie, W., 1972, Ground-water conditions in the central Virgin River basin, Utah: State of Utah Department of Natural Resources Technical Publication 40, 64 p.

Eakin, T.E., 1966, A regional interbasin groundwater system in the White River area, southeastern Nevada: Water Resources Research, v. 2, p. 251-272.

Feth, J.H., 1964, Hidden recharge: Groundwater, v. 2, no. 4, p. 14-17.

Feth, J.H., Barker, D.A., Moore, L.G., Brown, R.J., and Veirs, C.E., 1966, Lake Bonneville--Geology and hydrology of the Weber Delta district, including Ogden, Utah: U.S. Geological Survey Professional Paper 518, 76 p., 11 pls.

Gabin, V.L., and Lesperance, L.E., 1977, New Mexico climatological data: W.K. Summers and Associates, 436 p.

SELECTED REFERENCES--Continued

Gallaher, B.M., 1979, Recharge properties of the Tucson Basin aquifer as reflected by the distribution of a stable isotope: Tucson, University of Arizona, unpublished M.S. thesis, 92 p.

Garstka, W.U., 1964, Snow and snow survey, *in* Handbook of Applied Hydrology, V.T. Chow, ed.: p. 10-1 to 10-57.

Gates, J.S., 1963, Hydrogeology of Middle Canyon, Oquirrh Mountains, Tooele Valley, Utah: U.S. Geological Survey Water-Supply Paper 1619-K, 40 p.

_____1965, Reevaluation of the ground-water resources of Tooele Valley, Utah: Utah State Engineer Technical Publication 12, 68 p.

Gosz, J.R., 1975, Stream chemistry as a tool in evaluating ski area development: Symposium on Man, Leisure and Wildlands--A Complex Interaction, Vail, Colo., 12 p.

Graustein, W.C., 1981, The effects of forest vegetation on solute acquisition and chemical weathering--A study of the Tesuque watersheds near Santa Fe, New Mexico: New Haven, Conn., Yale University, unpublished Ph.D dissertation, 645 p.

Gross, G.W., Hoy, R.N., and Duffy, C.J., 1976, Application of environmental tritium in the measurement of recharge and aquifer parameters in a semi-arid limestone terrain: Las Cruces, New Mexico State University, Water Resources Research Institute, OWRR Project B-041-NMEX, 212 p.

Hardaway, G.D., and Thompson, J.R., 1962, A study of water yield from the Santa Fe River watershed: Rocky Mountain Forest and Range Experiment Station Paper 70, 18 p.

Hart, D.L., 1989, Test wells SF-1A, 1B, 1C, and SF-2A, 2B, and 2C, Santa Fe County, New Mexico: U.S. Geological Survey Open-File Report 89-37, 24 p.

Hawley, J.W., 1978, Correlation Chart 2--Middle to upper Cenozoic stratigraphic units in selected areas of the Rio Grande rift in New Mexico, *in* Guidebook to Rio Grande rift in New Mexico and Colorado: Socorro, New Mexico Bureau of Mines and Mineral Resources Circular 163, p. 239-241.

Hearne, G.A., 1985, Mathematical model of the Tesuque aquifer system near Pojoaque, New Mexico: U.S. Geological Survey Water-Supply Paper 2205, 75 p.

Hearne, G.A., and Dewey, J.D., 1988, Hydrologic analysis of the Rio Grande basin north of Embudo, New Mexico, Colorado and New Mexico: U.S. Geological Survey Water-Resources Investigations Report 86-4113, 244 p.

Huntley, David, 1979, Ground-water recharge to the aquifers of northern San Luis Valley, Colorado: Geological Society of America Bulletin, v. 90, pt. II, p. 1196-1281.

Kafri, U., and Ben-Asher, J., 1976, Evaluation of recharge through soils in a mountain region--A case study on the Empire and Jonito Basins, *in* Hydrology and water resources in Arizona and the Southwest: Meetings of the Arizona Section, American Water Resources Association, and Hydrology Section, Arizona Academy of Science, Tucson, Ariz., 1976, Proceedings, v. 6, p. 203-213.

_____1978, Computer estimates of natural recharge through soils in southern Arizona, U.S.A.: Journal of Hydrology, v. 38, no. 1/2, p. 125-138.

Keith, S.J., 1980, Seasonal and spatial trends of ephemeral flow in the Tucson Basin--Implications for ground water recharge, *in* Hydrology and water resources in Arizona and the Southwest: Meetings of the Arizona Section, American Water Resources Association, and Hydrology Section, Arizona-Nevada Academy of Science, Las Vegas, Nev., Tucson, Ariz., 1980.

Kelley, V.C., 1978, Geology of the Española Basin, New Mexico: Socorro, New Mexico Bureau of Mines and Mineral Resources Geologic Map 48, scale 1:125,000.

Kunkel, K.E., 1984, Temperature and precipitation summaries for selected New Mexico locations: New Mexico Department of Agriculture, 190 p.

Lee Wilson and Associates, 1978, Santa Fe County water plan: Consultant report, variously paged.

Maxey, G.B., 1968, Hydrogeology of desert basins: Groundwater, v. 6, no. 5, p. 10-22.

Maxey, G.B., and Eakin, T.E., 1949, Ground water in White River valley, White Pine, Nye, and Lincoln Counties, Nevada: State of Nevada, Office of the State Engineer Water Resources Bulletin 8, 59 p.

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

Mifflin, M.D., 1968, Delineation of ground-water flow systems in Nevada: Reno, University of Nevada Desert Research Institute, Technical Report Series H-W, Hydrology and Water Resources Publication 4, 109 p.

Rantz, S.E., and Eakin, T.E., 1971, A summary of methods for the collection and analysis of basic hydrologic data for arid regions: U.S. Geological Survey Open-File Report, 125 p.

Rao, B.K., 1986, Ground-water resources in the Carrizozo area, New Mexico: New Mexico Geological Society Guidebook, 37th Field Conference, Truth or Consequences, 1986.

Reiland, L.J., 1975, Estimated mean monthly and annual runoff at selected sites in the Pojoaque River drainage basin, Santa Fe County, New Mexico: U.S. Geological Survey Open-File Report 74-150, 21 p.

SELECTED REFERENCES--Continued

Reiland, L.J., and Koopman, F.C., 1975, Estimated availability of surface and ground water in the Pojoaque River drainage basin, Santa Fe County, New Mexico: U.S. Geological Survey Open-File Report 74-151, 35 p.

Rio Grande Compact Commission, 1976-87, Report of the Rio Grande Compact Commission: Albuquerque, N. Mex. (published annually).

Rogers, A.S., 1958, Physical behavior and geologic control of radon in mountain streams: U.S. Geological Survey Bulletin 1052-E, p. 187-211.

Simpson, E.S., Thorud, D.B., and Freedman, I., 1970, Distinguishing seasonal recharge to groundwater by deuterium analysis in southern Arizona, *in* World Water Balance, Reading: International Association of Scientific Hydrology, 1970, Proceedings, p. 112-121.

Soil Conservation Service, 1972a, Gross annual lake evaporation, New Mexico: U.S. Department of Agriculture Map 4-R-33582.

_____1972b, Normal annual precipitation, New Mexico: U.S. Department of Agriculture Map 4-R-33714.

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

Theis, C.V., 1940, The source of water derived from wells: Civil Engineering, v. 10, no. 5, p. 277-280.

Troendle, C.A., and Leaf, C.F., 1980, Hydrology, *in* An approach to water resources evaluation of non-point silvicultural sources: U.S. Environmental Protection Agency Report EPA-600/8-80-012, chap. 3.

U.S. Geological Survey, 1950, Compilation of records of surface waters of the United States through September 1950, Part 8, Western Gulf of Mexico Basins: U.S. Geological Survey Water-Supply Paper 1312, 633 p.

_____1950-60, Records of surface waters for the United States from October 1950 to September 1960, Part 8, Western Gulf of Mexico Basins: U.S. Geological Survey Water-Supply Paper 1732. Annual reports as follows: 1954, Water-Supply Paper 1342; 1955, Water-Supply Paper 1392; 1956, Water-Supply Paper 1442; 1957, Water-Supply Paper 1512; 1958, Water-Supply Paper 1573; 1959, Water-Supply Paper 1632.

_____1962-65, Surface water records of New Mexico, water years 1961-64 (published annually).

_____1966-75, Water resources data for New Mexico, water years 1965-74--Part 1. Surface water records: U.S. Geological Survey Water-Data Reports NM-65-1 to NM-74-1 (published annually).

SELECTED REFERENCES--Concluded

U.S. Geological Survey, 1976-88, Water resources data for New Mexico, water years 1975-87: U.S. Geological Survey Water-Data Reports NM-75-1 to NM-87-1 (published annually).

Water Resources Research Center, 1980, Final report--Regional recharge research for southwest alluvial basins: Department of Hydrology and Water Resources of the College of Earth Sciences of the University of Tucson for the U.S. Geological Survey, 275 p., 4 appendices.

Table 1.--Streamflow-gaging stations and major reservoirs on the streams in the study area

U.S. Geological Survey station number	Station name	Drainage area (square miles)	Period of record (month/year)
08294200	Nambe Falls Reservoir near Nambe	34.1	02/1976-present[1]
08294210	Rio Nambe below Nambe Falls Dam near Nambe	34.1	01/1979-present[1]
08294300	Rio Nambe at Nambe Falls near Nambe	34.2	03/1963-12/1978
08302500	Tesuque Creek above diversions near Santa Fe	11.6	04/1936-12/1952
08305000	Little Tesuque Creek near Santa Fe	7.06	04/1936-09/1941
08315500	McClure Reservoir near Santa Fe	17.4	09/1929
			07/1930-10/1930
			04/1931-06/1946
			09/1947-present[1]
08316000	Santa Fe River near Santa Fe	18.2	01/1913-present[1]

[1]As of 1988.

Table 2.--Mean monthly streamflow from the drainage basins in the study area, in acre-feet

Month	Stream and U.S. Geological Survey station number						
	Rio Nambe 08294300	Rio Nambe 08294210	Rio Nambe[1] 08294210	Rio en Medio[2]	Tesuque Creek 08302500	Little Tesuque Creek 08305000	Santa Fe River[3] 08316000
October	422	363	420	98	120	28	250
November	323	238	310	74	86	14	170
December	260	150	260	60	64	12	120
January	220	106	210	54	60	14	120
February	202	131	190	49	58	22	150
March	304	268	310	77	129	130	370
April	685	1,010	870	197	369	220	1,010
May	1,412	2,816	1,950	396	652	273	1,680
June	1,415	3,587	2,230	310	402	90	1,010
July	758	1,780	1,100	154	148	17	430
August	666	1,146	840	153	110	14	510
September	545	646	590	118	91	28	350
Mean annual	7,212	12,241	9,280	1,740	2,289	862	6,170

[1]Mean monthly streamflows at station 08294210 were adjusted on a monthly basis for calendar years 1979-86 for changes in the volume of water in storage in Nambe Falls Reservoir and for evaporation from the surface of that reservoir. The resulting monthly streamflows were then averaged on a prorated basis with the monthly streamflows for calendar years 1963-78 measured at station 08294300.

[2]Mean monthly streamflows are estimated values from Reiland and Koopman (1975, table 3).

[3]Mean monthly streamflows at station 08316000 for water years 1952-86 were adjusted on a monthly basis for changes in the volume of water in storage in McClure Reservoir and for evaporation from the surface of that reservoir. The resulting monthly streamflows were averaged on a prorated basis with the adjusted monthly streamflows reported by Spiegel and Baldwin (1963, table 21) for water years 1914-51.

Table 3.--Seasonal and annual streamflow from the drainage basins in the study area, in acre-feet

Season[1]	Rio Nambe 08294300	Rio Nambe 08294210	Rio Nambe[2] 08294210	Rio en Medio[3]	Tesuque Creek 08302500	Little Tesuque Creek 08305000	Santa Fe River[4] 08316000
	Stream and U.S. Geological Survey station number						
Winter	1,427	988	1,390	335	388	90	810
Spring	3,816	7,681	5,360	980	1,552	713	4,070
Summer/fall	1,969	3,572	2,530	425	349	59	1,290
Annual	7,212	12,241	9,280	1,740	2,289	862	6,170

[1]Winter extends from October through February, spring from March through June, and summer/fall from July through September.

[2]Mean monthly streamflows at station 08294210 were adjusted on a monthly basis for calendar years 1979-86 for changes in the volume of water in storage in Nambe Falls Reservoir and for evaporation from the surface of that reservoir. The resulting monthly streamflows were averaged on a prorated basis with the monthly streamflows for calendar years 1963-78 measured at station 08294300.

[3]Mean monthly streamflows are estimated values from Reiland and Koopman (1975, table 3).

[4]Mean monthly streamflows at station 08316000 for water years 1952-86 were adjusted on a monthly basis for changes in the volume of water in storage in McClure Reservoir and for evaporation from the surface of that reservoir. The resulting monthly streamflows were averaged on a prorated basis with the adjusted monthly streamflows reported in Spiegel and Baldwin (1963, table 21) for water years 1914-51.

Table 4.--Winter season precipitation and evapotranspiration calculated for the Rio Nambe drainage basin

Range in altitude (feet)	Area (square miles)	Proportion of total area	Precipitation: Annual (inches)	Precipitation: Percentage of total occurring in winter	Precipitation: Winter rate (inches)	Precipitation: Winter amount[1] (inches)	Evapotranspiration: Winter rate[2] (inches)	Evapotranspiration: Winter amount (inches)
6,500-7,000	0.77	0.02	13.24	25.00	3.31	0.07	1.40	0.03
7,000-7,600	2.33	0.07	15.88	27.00	4.29	0.30	1.42	0.10
7,600-8,200	4.66	0.14	18.76	29.00	5.44	0.74	1.49	0.21
8,200-8,800	5.78	0.17	21.64	30.00	[3]6.33	1.08	1.54	0.26
8,800-9,400	5.69	0.17	24.52	32.00	7.85	1.30	1.56	0.27
9,400-10,000	4.32	0.13	26.92	33.50	9.02	1.17	1.47	0.19
10,000-10,600	4.15	0.12	29.80	34.50	[3]10.02	1.20	1.46	0.18
10,600-11,200	3.13	0.09	32.68	36.00	[3]10.47	0.94	1.40	0.13
11,200-12,600	3.41	0.10	36.84	39.00	[3]12.00	1.20	1.40	0.14
Total	34.24	1.01				8.00		1.51

[1]"Amount" is defined as the rate of precipitation multiplied by the proportion of total basin area within each altitude range.
[2]Figure 6 provides winter evapotranspiration rates.
[3]Adjusted for sublimation.

Table 5.--Spring season precipitation and evapotranspiration calculated for the Rio Nambe drainage basin

Range in altitude (feet)	Area (square miles)	Proportion of total area	Precipitation: Annual (inches)	Precipitation: Percentage of total occurring in spring	Precipitation: Spring rate (inches)	Precipitation: Spring amount[1] (inches)	Evapotranspiration: Spring rate[2] (inches)	Evapotranspiration: Spring amount (inches)
6,500-7,000	0.77	0.02	13.24	29.50	3.91	0.08	3.80	0.08
7,000-7,600	2.33	0.07	15.88	30.50	4.84	0.34	4.40	0.31
7,600-8,200	4.66	0.14	18.76	32.00	6.00	0.84	5.10	0.71
8,200-8,800	5.78	0.17	21.64	33.00	7.14	1.21	5.70	0.97
8,800-9,400	5.69	0.17	24.52	34.00	8.34	1.42	6.00	1.02
9,400-10,000	4.32	0.13	26.92	36.00	9.69	1.26	6.10	0.79
10,000-10,600	4.15	0.12	29.80	37.50	11.17	1.34	6.30	0.76
10,600-11,200	3.13	0.09	32.68	38.00	[3]11.73	1.06	6.20	0.56
11,200-12,600	3.41	0.10	36.84	39.00	[3]12.00	1.20	6.20	0.62
Total	34.24	1.01				8.75		5.82

[1]"Amount" is defined as the rate of precipitation multiplied by the proportion of total basin area within each altitude range.
[2]Figure 7 provides spring evapotranspiration rates.
[3]Adjusted for sublimation.

Table 6.--Summer/fall season precipitation and evapotranspiration calculated for the Rio Nambe drainage basin

Range in altitude (feet)	Area (square miles)	Propor- tion of total area	Precipitation: Annual (inches)	Precipitation: Percent- age of total occur- ring in summer/ fall	Precipitation: Summer/ fall rate (inches)	Precipitation: Summer/ fall amount[1] (inches)	Evapotranspiration: Summer/ fall rate[2] (inches)	Evapotranspiration: Summer/ fall amount (inches)
6,500-7,000	0.77	0.02	13.24	45.50	6.02	0.12	8.90	0.18
7,000-7,600	2.33	0.07	15.88	42.50	6.75	0.47	9.00	0.63
7,600-8,200	4.66	0.14	18.76	39.00	7.32	1.02	9.10	1.27
8,200-8,800	5.78	0.17	21.64	37.00	8.01	1.36	9.25	1.57
8,800-9,400	5.69	0.17	24.52	34.00	8.34	1.42	9.30	1.58
9,400-10,000	4.32	0.13	26.92	30.50	8.21	1.07	9.30	1.21
10,000-10,600	4.15	0.12	29.80	28.00	8.34	1.00	9.30	1.12
10,600-11,200	3.13	0.09	32.68	26.00	8.50	0.76	9.30	0.84
11,200-12,600	3.41	0.10	36.84	22.00	8.10	0.81	9.30	0.93
Total	34.24	1.01				8.03		9.33

[1]"Amount" is defined as the rate of precipitation multiplied by the proportion of total basin area within each altitude range.
[2]Figure 8 provides summer/fall evapotranspiration rates.

Table 7.--Seasonal and annual water budgets for the Rio Nambe drainage basin

Season	Precipitation (inches)	Precipitation (acre-feet)	Evapotranspiration (inches)	Evapotranspiration (acre-feet)	Runoff (inches)	Runoff (acre-feet)	Recharge (inches)	Recharge (acre-feet)
Winter	8.00	14,590	1.51	2,760	0.76	1,390	5.73	10,440
Spring	8.75	15,950	5.82	10,610	2.94	5,360	-0.01	-20
Summer/ fall	8.03	14,640	9.33	17,010	1.39	2,530	-2.69	-4,900
Annual	24.78	45,180	16.66	30,380	5.09	9,280	3.03	5,520

Table 8.--Winter season precipitation and evapotranspiration calculated for the Rio en Medio drainage basin

Range in altitude (feet)	Area (square miles)	Proportion of total area	Precipitation: Annual (inches)	Percentage of total occurring in winter	Winter rate (inches)	Winter amount[1] (inches)	Evapotranspiration: Winter rate[2] (inches)	Winter amount (inches)
7,000-7,600	0.85	0.10	15.88	27.00	4.29	0.43	1.44	0.14
7,600-8,200	1.40	0.16	18.76	28.50	5.35	0.86	1.49	0.24
8,200-9,000	1.42	0.16	22.12	31.00	6.86	1.10	1.50	0.24
9,000-9,600	1.99	0.23	25.48	32.50	8.28	1.90	1.53	0.35
9,600-10,200	0.92	0.11	28.84	34.00	9.81	1.08	1.46	0.16
10,200-11,000	1.22	0.14	31.08	35.50	[3]8.27	1.16	1.60	0.22
11,000-12,280	0.86	0.10	35.69	38.00	[3]11.39	1.14	1.53	0.15
Total	8.66	1.00				7.67		1.50

[1]"Amount" is defined as the rate of precipitation multiplied by the proportion of total basin area within each altitude range.
[2]Figure 6 provides winter evapotranspiration rates.
[3]Adjusted for sublimation.

Table 9.--Spring season precipitation and evapotranspiration calculated for the Rio en Medio drainage basin

Range in altitude (feet)	Area (square miles)	Proportion of total area	Precipitation: Annual (inches)	Percentage of total occurring in spring	Spring rate (inches)	Spring amount[1] (inches)	Evapotranspiration: Spring rate[2] (inches)	Spring amount (inches)
7,000-7,600	0.85	0.10	15.88	30.50	4.84	0.48	4.43	0.44
7,600-8,200	1.40	0.16	18.76	32.00	6.00	0.96	5.09	0.81
8,200-9,000	1.42	0.16	22.12	33.00	7.30	1.17	5.58	0.89
9,000-9,600	1.99	0.23	25.48	35.00	8.92	2.05	6.10	1.40
9,600-10,200	0.92	0.11	28.84	36.50	10.53	1.16	6.33	0.70
10,200-11,000	1.22	0.14	31.08	37.50	[3]10.19	1.43	6.70	0.94
11,000-12,280	0.86	0.10	35.69	38.50	[3]11.54	1.15	6.52	0.65
Total	8.66	1.00				8.40		5.83

[1]"Amount" is defined as the rate of precipitation multiplied by the proportion of total basin area within each altitude range.
[2]Figure 7 provides winter evapotranspiration rates.
[3]Adjusted for sublimation.

Table 10.--Summer/fall season precipitation and evapotranspiration calculated for the Rio en Medio drainage basin

Range in altitude (feet)	Area (square miles)	Proportion of total area	Precipitation: Annual (inches)	Precipitation: Percentage of total occurring in summer/fall	Precipitation: Summer/fall rate (inches)	Precipitation: Summer/fall amount[1] (inches)	Evapotranspiration: Summer/fall rate[2] (inches)	Evapotranspiration: Summer/fall amount (inches)
7,000-7,600	0.85	0.10	15.88	42.50	6.75	0.68	9.00	0.90
7,600-8,200	1.40	0.16	18.76	39.50	7.41	1.19	9.10	1.46
8,200-9,000	1.42	0.16	22.12	36.00	7.96	1.27	9.25	1.48
9,000-9,600	1.99	0.23	25.48	32.50	8.28	1.90	9.30	2.14
9,600-10,200	0.92	0.11	28.84	29.50	8.51	0.94	9.30	1.02
10,200-11,000	1.22	0.14	31.08	27.00	8.39	1.17	9.30	1.30
11,000-12,280	0.86	0.10	35.69	23.50	8.39	0.84	9.30	0.93
Total	8.66	1.00				7.99		9.23

[1]"Amount" is defined as the rate of precipitation multiplied by the proportion of total basin area within each altitude range.
[2]Figure 8 provides summer/fall evapotranspiration rates.

Table 11.--Seasonal and annual water budgets for the Rio en Medio drainage basin

Season	Precipitation (inches)	Precipitation (acre-feet)	Evapotranspiration (inches)	Evapotranspiration (acre-feet)	Runoff (inches)	Runoff (acre-feet)	Recharge (inches)	Recharge (acre-feet)
Winter	7.67	3,540	1.50	690	0.73	340	5.44	2,510
Spring	8.40	3,880	5.83	2,710	2.12	980	0.45	190
Summer/fall	7.99	3,690	9.23	4,260	0.92	420	-2.16	-990
Annual	24.06	11,110	16.56	7,660	3.77	1,740	3.73	1,710

Table 12.--Winter season precipitation and evapotranspiration calculated for the Tesuque Creek drainage basin

			Precipitation				Evapotranspiration	
Range in altitude (feet)	Area (square miles)	Proportion of total area	Annual (inches)	Percentage of total occurring in winter	Winter rate (inches)	Winter amount[1] (inches)	Winter rate[2] (inches)	Winter amount (inches)
7,440-8,000	1.42	0.13	17.90	28.00	5.01	0.65	1.50	0.19
8,000-8,400	1.80	0.16	20.20	29.50	5.96	0.95	1.53	0.24
8,400-8,800	2.03	0.18	22.12	31.00	6.86	1.23	1.56	0.28
8,800-9,400	2.49	0.22	24.52	32.00	7.85	1.73	1.54	0.34
9,400-9,800	0.63	0.06	26.92	33.00	8.88	0.53	1.40	0.08
9,800-10,800	1.55	0.14	29.48	34.50	10.17	1.42	1.40	0.20
10,800-12,000	1.30	0.12	34.60	37.00	[3]9.95	1.19	1.45	0.17
Total	11.22	1.01				7.70		1.50

[1]"Amount" is defined as the rate of precipitation multiplied by the proportion of total basin area within each altitude range.
[2]Figure 6 provides winter evapotranspiration rates.
[3]Adjusted for sublimation.

Table 13.--Spring season precipitation and evapotranspiration calculated for the Tesuque Creek drainage basin

			Precipitation				Evapotranspiration	
Range in altitude (feet)	Area (square miles)	Proportion of total area	Annual (inches)	Percentage of total occurring in spring	Spring rate (inches)	Spring amount[1] (inches)	Spring rate[2] (inches)	Spring amount (inches)
7,440-8,000	1.42	0.13	17.90	31.50	5.64	0.73	4.86	0.63
8,000-8,400	1.80	0.16	20.20	32.50	6.56	1.05	5.32	0.85
8,400-8,800	2.03	0.18	22.12	33.00	7.30	1.31	5.72	1.03
8,800-9,400	2.49	0.22	24.52	34.50	8.46	1.86	6.07	1.34
9,400-9,800	0.63	0.06	26.92	36.00	9.69	0.58	6.10	0.37
9,800-10,800	1.55	0.14	29.48	37.50	11.05	1.55	6.20	0.87
10,800-12,800	1.30	0.12	34.60	38.50	[3]10.96	1.32	6.30	0.76
Total	11.22	1.01				8.40		5.85

[1]"Amount" is defined as the rate of precipitation multiplied by the proportion of total basin area within each altitude range.
[2]Figure 7 provides spring evapotranspiration rates.
[3]Adjusted for sublimation.

Table 14.--Summer/fall season precipitation and evapotranspiration calculated for the Tesuque Creek drainage basin

Range in altitude (feet)	Area (square miles)	Proportion of total area	Precipitation: Annual (inches)	Precipitation: Percentage of total occurring in summer/fall	Precipitation: Summer/fall rate (inches)	Precipitation: Summer/fall amount[1] (inches)	Evapotranspiration: Summer/fall rate[2] (inches)	Evapotranspiration: Summer/fall amount (inches)
7,440-8,000	1.42	0.13	17.90	40.50	7.25	0.94	9.10	1.18
8,000-8,400	1.80	0.16	20.20	38.00	7.68	1.23	9.20	1.47
8,400-8,800	2.03	0.18	22.12	36.00	7.96	1.43	9.25	1.66
8,800-9,400	2.49	0.22	24.52	33.50	8.21	1.81	9.30	2.05
9,400-9,800	0.63	0.06	26.92	31.00	8.35	0.50	9.30	0.56
9,800-10,800	1.55	0.14	29.48	28.00	8.25	1.15	9.30	1.30
10,800-12,000	1.30	0.12	34.60	24.50	8.48	1.02	9.30	1.12
Total	11.22	1.01				8.08		9.34

[1]"Amount" is defined as the rate of precipitation multiplied by the proportion of total basin area within each altitude range.
[2]Figure 8 provides summer/fall evapotranspiration rates.

Table 15.--Seasonal and annual water budgets for the Tesuque Creek drainage basin

[Runoff adjusted for additional basin area to mountain front]

Season	Precipitation (inches)	Precipitation (acre-feet)	Evapotranspiration (inches)	Evapotranspiration (acre-feet)	Runoff (inches)	Runoff (acre-feet)	Recharge (inches)	Recharge (acre-feet)
Winter	7.70	14,620	1.50	900	0.84	500	5.36	3,220
Spring	8.40	5,020	5.85	3,500	3.43	2,050	-0.88	-530
Summer/fall	8.08	4,840	9.34	5,540	0.77	460	-2.03	-1,160
Annual	24.18	14,480	16.69	9,940	5.04	3,010	2.45	1,530

Table 16.--Winter season precipitation and evapotranspiration calculated for the Little Tesuque Creek drainage basin

Range in altitude (feet)	Area (square miles)	Proportion of total area	Precipitation: Annual (inches)	Precipitation: Percentage of total occurring in winter	Precipitation: Winter rate (inches)	Precipitation: Winter amount[1] (inches)	Evapotranspiration: Winter rate[2] (inches)	Evapotranspiration: Winter amount (inches)
7,160-7,520	0.78	0.10	16.07	27.00	4.34	0.43	1.52	0.15
7,520-8,000	0.56	0.07	18.09	28.00	5.07	0.35	1.62	0.11
8,000-8,600	1.94	0.25	20.68	30.00	6.20	1.55	1.60	0.40
8,600-9,200	2.42	0.32	23.56	32.00	7.54	2.41	1.52	0.49
9,200-9,600	0.62	0.08	25.96	33.00	8.57	0.69	1.40	0.11
9,600-10,200	0.73	0.10	27.88	34.00	9.48	0.95	1.40	0.14
10,200-11,300	0.61	0.08	31.56	35.50	11.20	0.90	1.40	0.11
Total	7.66	1.00				7.28		1.47

[1]"Amount" is defined as the rate of precipitation multiplied by the proportion of total basin area within each altitude range.
[2]Figure 6 provides winter evapotranspiration rates.

Table 17.--Spring season precipitation and evapotranspiration calculated for the Little Tesuque Creek drainage basin

Range in altitude (feet)	Area (square miles)	Proportion of total area	Precipitation: Annual (inches)	Precipitation: Percentage of total occurring in spring	Precipitation: Spring rate (inches)	Precipitation: Spring amount[1] (inches)	Evapotranspiration: Spring rate[2] (inches)	Evapotranspiration: Spring amount (inches)
7,160-7,520	0.78	0.10	16.07	30.50	4.90	0.49	4.50	0.45
7,520-8,000	1.56	0.07	18.09	31.50	5.70	0.40	5.10	0.36
8,000-8,600	1.94	0.25	20.68	32.50	6.72	1.68	5.63	1.41
8,600-9,200	2.42	0.32	23.56	34.00	8.01	2.56	5.98	1.91
9,200-9,600	0.62	0.08	25.96	35.00	9.09	0.73	6.00	0.48
9,600-10,200	0.73	0.10	27.88	36.50	10.18	1.02	6.20	0.62
10,200-11,300	0.61	0.08	31.56	38.00	11.99	0.96	6.40	0.51
Total	7.66	1.00				7.84		5.74

[1]"Amount" is defined as the rate of precipitation multiplied by the proportion of total basin area within each altitude range.
[2]Figure 7 provides spring evapotranspiration rates.

Table 18. --Summer/fall season precipitation and evapotranspiration calculated for the Little Tesuque Creek drainage basin

Range in altitude (feet)	Area (square miles)	Proportion of total area	Precipitation: Annual (inches)	Precipitation: Percentage of total occurring in summer/fall	Precipitation: Summer/fall rate (inches)	Precipitation: Summer/fall amount[1] (inches)	Evapotranspiration: Summer/fall rate[2] (inches)	Evapotranspiration: Summer/fall amount (inches)
7,160-7,520	0.78	0.10	16.07	42.50	6.83	0.68	9.00	0.90
7,520-8,000	0.56	0.07	18.09	40.50	7.33	0.51	9.10	0.64
8,000-8,600	1.94	0.25	20.68	37.50	7.76	1.94	9.20	2.30
8,600-9,200	2.42	0.32	23.56	34.00	8.01	2.56	9.30	2.98
9,200-9,600	0.62	0.08	25.96	32.00	8.31	0.66	9.30	0.74
9,600-10,200	0.73	0.10	27.88	29.50	8.22	0.82	9.30	0.93
10,200-11,300	0.61	0.08	31.56	26.50	8.36	0.67	9.30	0.74
Total	7.66	1.00				7.84		9.23

[1]"Amount" is defined as the rate of precipitation multiplied by the proportion of total basin area within each altitude range.
[2]Figure 8 provides summer/fall evapotranspiration rates.

Table 19.--Seasonal and annual water budgets for the Little Tesuque Creek drainage basin

Season	Precipitation (inches)	Precipitation (acre-feet)	Evapotranspiration (inches)	Evapotranspiration (acre-feet)	Runoff (inches)	Runoff (acre-feet)	Recharge (inches)	Recharge (acre-feet)
Winter	7.28	2,970	1.47	600	0.22	90	5.59	2,280
Spring	7.84	3,200	5.74	2,350	1.75	710	0.35	140
Summer/fall	7.84	3,200	9.23	3,770	0.14	60	-1.53	-630
Annual	22.96	9,370	16.44	6,720	2.11	2.11	4.41	1,790

Table 20.--Winter season precipitation and evapotranspiration calculated for the Santa Fe River drainage basin

Range in altitude (feet)	Area (square miles)	Proportion of total area	Precipitation				Evapotranspiration	
			Annual (inches)	Percentage of total occurring in winter	Winter rate (inches)	Winter amount[1] (inches)	Winter rate[2] (inches)	Winter amount (inches)
7,200-7,720	2.76	0.10	16.65	27.50	4.58	0.46	1.52	0.15
7,720-8,200	4.78	0.17	19.05	29.00	5.52	0.94	1.48	0.25
8,200-8,800	7.87	0.27	21.64	30.50	6.60	1.78	1.46	0.39
8,800-9,200	3.83	0.13	24.04	32.00	7.69	1.00	1.45	0.19
9,200-9,600	2.32	0.08	25.96	33.00	8.57	0.69	1.40	0.11
9,600-10,200	2.38	0.08	27.88	34.00	9.48	0.76	1.40	0.11
10,200-11,100	2.73	0.10	31.24	35.50	11.09	1.11	1.56	0.16
11,100-12,000	2.03	0.07	35.23	37.50	[3]12.19	0.85	1.58	0.11
Total	28.70	1.00				7.59		1.47

[1]"Amount" is defined as the rate of precipitation multiplied by the proportion of total basin area within each altitude range.
[2]Figure 6 provides winter evapotranspiration rates.
[3]Adjusted for sublimation.

Table 21.--Spring season precipitation and evapotranspiration calculated for the Santa Fe River drainage basin

Range in altitude (feet)	Area (square miles)	Proportion of total area	Precipitation				Evapotranspiration	
			Annual (inches)	Percentage of total occurring in spring	Spring rate (inches)	Spring amount[1] (inches)	Spring rate[2] (inches)	Spring amount (inches)
7,200-7,720	2.76	0.10	16.65	31.0	5.16	0.52	4.69	0.47
7,720-8,200	4.78	0.17	19.05	32.0	6.10	1.04	5.60	0.95
8,200-8,800	7.87	0.27	21.64	33.0	7.14	1.93	5.60	1.51
8,800-9,200	3.83	0.13	24.04	34.0	8.17	1.06	5.63	0.73
9,200-9,600	2.32	0.08	25.96	35.0	9.09	0.73	6.00	0.48
9,600-10,200	2.38	0.08	27.88	36.5	10.18	0.81	6.21	0.50
10,200-11,100	2.73	0.10	31.24	37.5	11.71	1.17	6.59	0.66
11,100-12,000	2.03	0.07	35.23	38.5	[3]12.51	0.88	6.65	0.47
Total	28.70	1.00				8.14		5.77

[1]"Amount" is defined as the rate of precipitation multiplied by the proportion of total basin area within each altitude range.
[2]Figure 7 provides spring evapotranspiration rates.
[3]Adjusted for sublimation.

Table 22.--Summer/fall season precipitation and evapotranspiration calculated for the Santa Fe River drainage basin

Range in altitude (feet)	Area (square miles)	Proportion of total area	Precipitation: Annual (inches)	Precipitation: Percentage of total occurring in summer/fall	Precipitation: Summer/fall rate (inches)	Precipitation: Summer/fall amount[1] (inches)	Evapotranspiration: Summer/fall rate[2] (inches)	Evapotranspiration: Summer/fall amount (inches)
7,200-7,720	2.76	0.10	16.65	41.50	6.91	0.69	9.00	0.90
7,720-8,200	4.78	0.17	19.05	39.00	7.43	1.26	9.10	1.55
8,200-8,800	7.87	0.27	21.64	36.50	7.90	2.13	9.20	2.48
8,800-9,200	3.83	0.13	24.04	34.00	8.17	1.06	9.30	1.21
9,200-9,600	2.32	0.08	25.96	32.00	8.31	0.66	9.30	0.74
9,600-10,200	2.38	0.08	27.88	29.50	8.22	0.66	9.30	0.74
10,200-11,100	2.73	0.10	31.24	27.00	8.43	0.84	9.30	0.93
11,100-12,000	2.03	0.07	35.23	24.00	8.46	0.59	9.30	0.65
Total	28.70	1.00				7.89		9.20

[1]"Amount" is defined as the rate of precipitation multiplied by the proportion of total basin area within each altitude range.

[2]Figure 8 provides summer/fall evapotranspiration rates.

Table 23.--Seasonal and annual water budgets for the Santa Fe River drainage basin

[Runoff adjusted for additional basin area to mountain front]

Season	Precipitation (inches)	Precipitation (acre-feet)	Evapotranspiration (inches)	Evapotranspiration (acre-feet)	Runoff (inches)	Runoff (acre-feet)	Recharge (inches)	Recharge (acre-feet)
Winter	7.59	11,620	1.47	2,250	0.59	900	5.53	8,470
Spring	8.14	12,480	5.77	8,830	2.95	4,520	-0.58	-870
Summer/fall	7.89	12,100	9.20	14,100	0.93	1,430	-2.24	-3,430
Annual	23.62	36,200	16.44	25,180	4.47	6,850	2.71	4,170

Table 24.--Comparison of calculated and numerically simulated values of subsurface mountain-front recharge for the drainage basins in the study area

Drainage basin	Length of mountain front (miles)	Calculated subsurface recharge (acre-feet per year)	Calculated subsurface recharge (cubic feet per second)	Calculated subsurface recharge (percentage of precipitation	Simulated subsurface recharge (acre-feet per year)	Simulated subsurface recharge (cubic feet per second)	Simulated subsurface recharge (percentage of precipitation)
Rio Nambe	3.5	5,520	7.62	12.2	2,210	3.05	4.9
Rio en Medio	1.5	1,710	2.36	15.4	760	1.05	6.8
Tesuque Creek	2.5	1,530	2.11	10.6	760	1.05	5.2
Little Tesuque Creek	2.0	1,790	2.47	19.1	870	1.20	9.3
Santa Fe River	3.5	4,170	5.75	11.5	3,330	4.60	9.2
Total		14,720			7,930		
Average				[1]12.7			

[1]Number calculated by dividing the volume of calculated recharge (14,720 acre-feet per year) by the total volume of precipitation (116,340 acre-feet per year).

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