PLAN OF STUDY TO DEFINE HYDROGEOLOGIC CHARACTERISTICS OF THE MADERA LIMESTONE IN THE EAST MOUNTAIN AREA OF CENTRAL NEW MEXICO

By Dale R. Rankin

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CONVERSION FACTORS AND VERTICAL DATUM

Multiply	By	To obtain
Length		
inch	25.4	millimeter
foot	0.3048	meter
mile	1.609	kilometer
Area		
square mile	2.590	square kilometer
Volume		
gallon	3.785	liter
acre-foot	1,233	cubic meter
Flow rate		
gallon per minute	0.06309	liter per second
Transmissivity		
foot squared per day	0.09290	meter squared per day

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

$$°F = (1.8 \times °C) + 32$$

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

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EXECUTIVE SUMMARY

The east mountain area, located along the eastern slopes of the northern Manzano and Sandia Mountains, is a forested, rural, and scenic region that covers approximately 320 square miles, and includes parts of Bernalillo, Sandoval, Santa Fe, and Torrance Counties. The east mountain area has experienced dramatic growth in population and development over the past 20 years, and this trend is continuing. Limited ground-water supplies are the sole source of water for domestic, municipal, industrial, and agricultural uses throughout the area. Because the east mountain area is geologically complex and hydrologically variable, water quality and water quantity can differ markedly from one location to the next. Thin soils and unconsolidated alluvial deposits overlie fractured bedrock throughout the area. The fracturing in the bedrock strongly affects the hydrologic characteristics of the region and is the most significant and problematic aspect in characterizing ground-water flow.

County officials, residents, and others are concerned about the regional water supply because of an increasing population, variable and limited ground-water supplies, and the complicated geologic terrain that controls the hydrologic characteristics of the region. County officials recognize their role in regional water-resource planning and management. To fulfill this role, a variety of essential hydrologic data-collection activities and interpretive studies are needed to better define ground-water flow and hydraulic properties of the Madera Limestone, the principal aquifer in the east mountain area.

Most previous studies have been short-term, site-specific investigations of the hydrology, geology, and water quality in the area. Coordinated, comprehensive planning for regional water-resource management of the east mountain area requires technical data from long-term, regional hydrologic studies.

Bernalillo County has contributed substantially in developing the current base of geohydrologic information about water resources in the east mountain area. Much of this information has been gained through cooperative investigations with the U.S. Geological Survey (USGS). In March 1997, the USGS proposed development of a plan to guide long-term hydrologic studies in the east mountain area to the Bernalillo County Environmental Gross Receipts Tax Advisory Board. In accordance with the proposal, a meeting was held in December 1997 to discuss problems related to the region's water resources. The meeting consisted of representatives from the Bernalillo County Environmental Health Department, the New Mexico Office of the State Engineer, the New Mexico Bureau of Mines and Mineral Resources, the University of New Mexico Department of Earth and Planetary Sciences and the Department of Civil Engineering, the Waste-Management Education and Research Consortium, private consultants, and the USGS. The participants (see the "Acknowledgments" section of this report for the names of individuals) represented a variety of disciplines, and provided the needed expertise to effectively discuss data-collection activities and studies to improve understanding of ground-water flow and hydraulic properties of the Madera Limestone. This report is the result of that meeting.

The hydrogeologic characteristics of the Madera Limestone are divided into two parts in the report. The section titled "Geologic framework of the Madera Group" describes nomenclature and stratigraphy, areal extent and thickness, and depositional history, lithology, and structure. The section titled "Hydrologic framework of the Madera Limestone" describes the aquifer type, hydraulic heads, hydraulic properties, and water quality. This section also provides an overview of ground-water flow and discusses ground-water flow direction, ground-water withdrawal and depletion, streamflow and springs, recharge, septic-field effluent, and imported water.

This report presents a prioritized, comprehensive plan of study to define hydrogeologic characteristics of the Madera Limestone in the east mountain area. To prioritize the study elements outlined in the "Plan of study" section, data-collection activities and studies are categorized as "essential" or "useful." Information that is necessary to improve the understanding of or quantifies an element is prioritized as essential. Information that could add additional understanding, but is not necessary to quantify a study element, is prioritized as useful.

Essential Information and Activities

- Consolidate and evaluate existing information
- Expand the well network
- Quantify recharge to the Madera Limestone
- Quantify discharge from the Madera Limestone
- Define hydraulic properties of the Madera Limestone
- Characterize ground-water flow in the Madera Limestone

Useful Information and Activities

- Conduct remote sensing
- Develop a water budget by aquifer
- Consolidate geographical information system data
- Improve drilling records
- Use USGS data bases for storage and retrieval of information
- Update "Ground water in the Sandia and northern Manzano Mountains, New Mexico" (Titus, 1980)
- Involve neighborhood associations and residents with data collection

Abstract

The east mountain area of central New Mexico includes the eastern one-third of Bernalillo County and portions of Sandoval, Santa Fe, and Torrance Counties. The area covers about 320 square miles.

The Madera Limestone, the principal aquifer in the east mountain area, is the sole source of water for domestic, municipal, industrial, and agricultural uses for many residents. Some water is imported from wells near Edgewood by the Entranosa Water Cooperative, which serves a population of approximately 3,300. The remaining population is served by small water systems that derive supplies locally or by individually owned domestic wells.

The population of the east mountain area has increased dramatically over the past 20 years. In 1970, the population of the east mountain area was about 4,000. Demographic projections suggest that approximately 1,000 people per year are moving into the area, and with a growth rate of 3.0 percent the population will be 16,700 in 2000. Consequently, ground-water withdrawals have increased substantially over the past 20 years, and will continue to increase.

Little is known about the flow characteristics and hydrogeologic properties of the Madera Limestone. This report describes existing information about the geologic and hydrologic framework and flow characteristics of the Madera Limestone, and presents a plan of study for data-collection activities and interpretive studies that could be conducted to better define the hydrogeologic characteristics of the Madera Limestone.

Data-collection activities and interpretive studies related to the hydrogeologic components of the Madera Limestone are prioritized. Activities that are necessary to improve the quantification of a component are prioritized as essential. Activities that could add additional understanding of a component, but would not be necessary to improve the quantification of a component, are prioritized as useful.

INTRODUCTION

The east mountain area includes the eastern one-third of Bernalillo County and portions of Sandoval, Santa Fe, and Torrance Counties. The area covers about 320 square miles and is defined by the crest line of the Sandia and Manzano Mountains to the west, the termination of the Sandia Mountains to the north, the community of Edgewood to the east, and the Bernalillo/Torrance County line to the south (fig. 1).

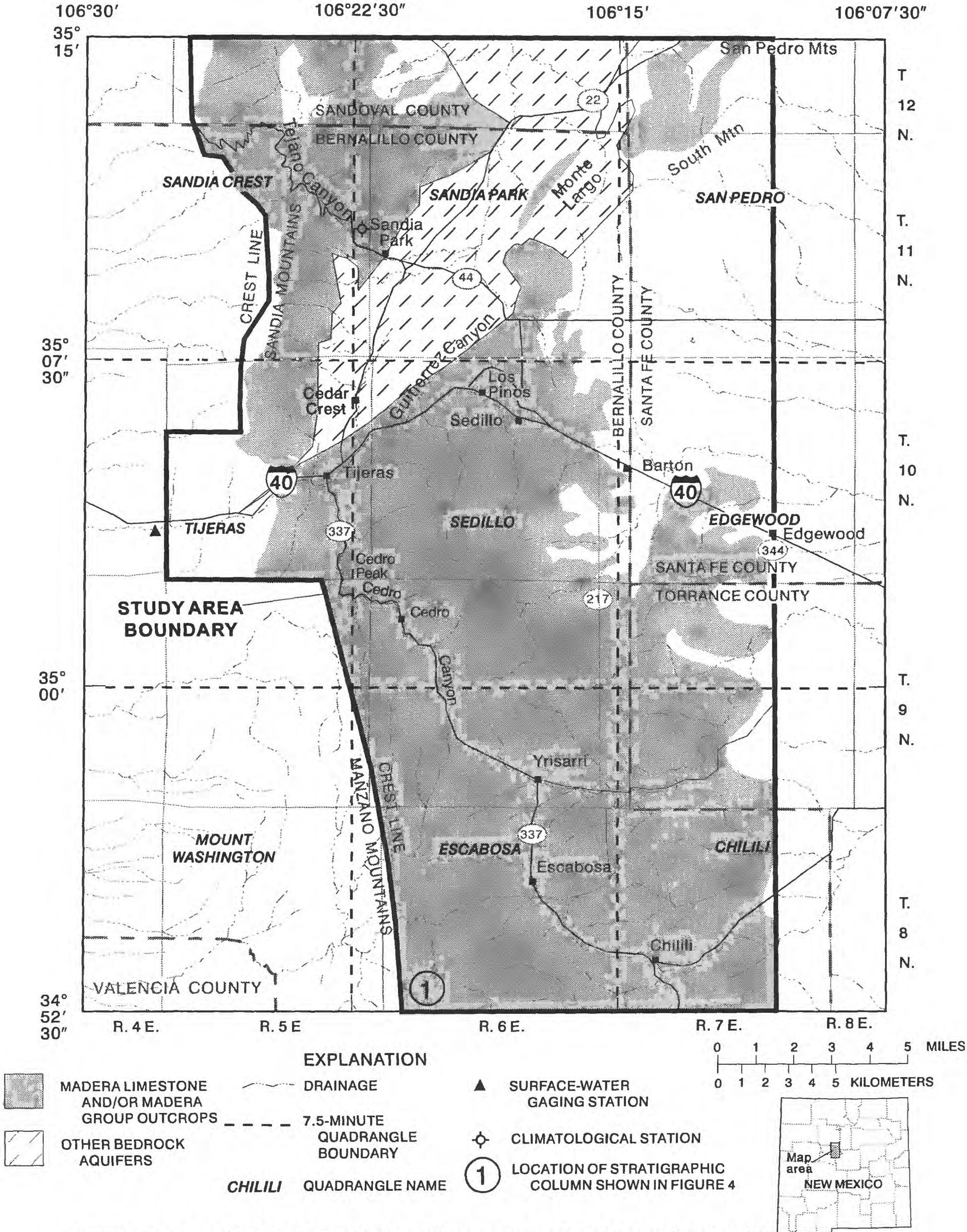


Figure 1.--Areal extent of the Madera Limestone and/or Madera Group within the study area, and location of other bedrock aquifers.

The population of the east mountain area has increased dramatically over the past 20 years. In eastern Bernalillo County alone, the population increased from approximately 4,000 to more than 12,000 from 1970 to 1990 (Summers, 1991, p. 59). Demographic projections provided by the East Mountain Area Plan (City of Albuquerque, 1992) suggest that approximately 1,000 people per year are moving into the area, and with a growth rate of 3.0 percent the population will be 16,700 in 2000. Situated along the eastern slopes of the Manzano and Sandia Mountains, the area offers a rural and forested setting enjoyed by a diverse population located in old, established communities and new developments. Most development consists of single-family dwellings with individual wells and septic systems.

Ground water is the sole source of water for domestic, municipal, industrial, and agricultural uses throughout the east mountain area. Most ground-water supplies come from aquifers within the east mountain area, but some water is imported from wells near Edgewood by the Entranosa Water Cooperative, which serves a population of approximately 3,300 (Wilson and Lucero, 1997). The remaining population is served by small water systems that derive supplies locally or by individually owned domestic wells.

The Madera Limestone is the principal aquifer in the east mountains, subcropping or cropping out over 200 square miles, or about two-thirds of the area (fig. 1). Water is obtained from a variety of other bedrock aquifers in a hydrogeologically complex area north of Interstate 40 (fig. 1). Water supplies in the east mountain area are limited and variable. Titus (1980) concluded that approximately 20 percent of wells drilled in the Madera Limestone are dry holes or wells with limited yields. Discussing limestone units in the east mountain area, Kues (1990, p. 1) stated "Ground-water availability depends on the lithology of the water-yielding unit and proximity to faults."

Purpose and Scope

This report presents a prioritized, comprehensive plan of study to define hydrogeologic characteristics of the Madera Limestone in the east mountain area in central New Mexico. The Madera Limestone is the focus of this report because it is the most areally extensive aquifer in the study area, and, as such, is regarded as the principal aquifer in the study area (Titus, 1980). The Madera Limestone also represents a relatively straightforward geologic and hydrologic environment for implementation of the data-collection activities and studies described in this report. The appropriate location for the data-collection activities and interpretive studies is where the Madera Limestone crops out at land surface or where water supplies are accessible.

The anthropogenic, climatologic, geologic, and hydrologic factors that influence the hydrogeologic characteristics of the Madera Limestone are considered within the scope of this report. No study can be proposed that would result in a complete understanding of the area's water supply. The geologic and hydrologic complexity and variability of the area, coupled with limited financial resources at the local, State, and Federal levels, preclude the possibility of evaluating site-specific determinations of ground-water availability. The study elements proposed in this report, however, are realistic objectives that would provide a better understanding of the hydrogeologic characteristics of the Madera Limestone.

County officials are aware that management decisions related to growth and development in the east mountain area must be based on reliable, timely, and impartial information. The interpretive studies and data-collection activities described in this report will provide hydrologic information that would help planners and managers make informed decisions regarding future growth and development in the east mountain area. This report was prepared in cooperation with the Bernalillo County Environmental Health Department (BCEHD).

Previous Investigations

Limited geologic and hydrologic investigations have been conducted in the east mountain area. Smith (1957) studied the geology and water resources of Torrance County. Kelley (1963) produced a geologic map of the Sandia Mountains and vicinity, and Myers mapped the Tajique (1966) and Escabosa (1969) quadrangles. Myers and McKay mapped the Mount Washington (1970) and Bosque Peak (1971) quadrangles. Kelley and Northrop (1975) discussed the geology of the Sandia Mountains and vicinity, and Hudson (1978, 1980) monitored ground-water levels, spring discharge, and surface-water discharge in parts of Tijeras Canyon.

Titus (1980) described ground-water conditions in the Sandia and northern Manzano Mountains, and

Kues (1990) reported ground-water availability and quality in eastern Bernalillo County and vicinity. Turner (1992a, b) studied the geology and hydrology of eastern Bernalillo and southern Santa Fe Counties and reported on the geophysical and ground-water hydrodynamic, hydrogeothermal, and hydrogeochemical analysis of eastern Bernalillo, southern Santa Fe, and northern Torrance Counties. White (1994) studied the hydrology of the Estancia Basin. Kues and Garcia (1995) summarized ground-water-quality and ground-water-level data in Bernalillo County, and Rankin (1996) tabulated water-quality and ground-water-level data in Bernalillo County. Blanchard and Kues (in press) investigated the effects of domestic wastewater in eastern Bernalillo County. Geologists at the New Mexico Bureau of Mines and Mineral Resources (NMBMMR), under the STATEMAP program, are currently (1999) producing 7.5-minute geologic quadrangles for portions of the study area as part of the Middle Rio Grande Basin Study (fig. 2) (Bauer, 1998).

In addition to conducting local investigations, the U.S. Geological Survey (USGS) has studied the hydrology of fractured systems in locations across the country and been involved with development of studies similar to the plan presented in this report. Driscoll (1992) authored a plan of study to assess the quantity, quality, and distribution of surface and ground water in the Black Hills area of South Dakota. Greene (1993) conducted a study of the hydraulic properties of the Madison aquifer system in the Rapid City, South Dakota, area. Kyllonen and Peter (1987) investigated the geohydrology and water quality of the northern Black Hills, South Dakota, and the Bear Lodge Mountains of Wyoming. In 1990, the USGS began investigating the bedrock in the Mirror Lake watershed, New Hampshire, to develop and evaluate field techniques and interpretive methods to characterize ground-water flow and chemical transport in fractured rock terrain (A.M. Shapiro, U.S. Geological Survey, written commun., 1998), and Paillet and Kapucu (1989) characterized fractures and fracture permeability in the Mirror Lake watershed. Heisig (1999) studied fractured bedrock in the Windham area, Greene County, New York.

Masters theses and Doctoral dissertations deal with geology and hydrology of the east mountain area. For example, Caprio (1960) authored a thesis that discussed water resources of the Sandia Mountains.

Consultants, including Clay Kilmer and Associates, Ltd., have conducted hydrologic studies in the east mountain area. These data could be consolidated with other information and used to evaluate hydrogeologic characteristics.

Acknowledgments

The author acknowledges the contribution by Bernalillo County in developing much of the current base of hydrogeologic information for the east mountain area.

As a result of a proposal by the USGS to the Bernalillo County Environmental Gross Receipts Tax Advisory Board (BCEGRTAB), a meeting was held in Albuquerque, New Mexico, during December 2-3, 1997 (see "Supplemental Information" section of this report). The purpose of this meeting was to identify data-collection activities and interpretive studies that could be conducted to learn more about ground-water flow and hydraulic properties of the Madera Limestone. Many of the information needs, data-collection activities, and interpretive studies described in this report are a result of suggestions and ideas presented at this meeting. The author thanks the meeting participants and gratefully acknowledges their participation in the study plan development. Those individuals are: Jeffrey Peterson, environmental health scientist and geohydrologist, BCEHD; Frank Titus, ground-water scientist and special scientific advisor to the New Mexico Office of the State Engineer (NMOSE); Paul Bauer, senior field geologist and STATEMAP manager, NMBMMR; Andy Core, water resources engineering specialist, NMOSE; Glen Hammock, consulting hydrologist; Gwinn Hall, graduate student, Department of Civil Engineering, and Mike Campana, professor of hydrology, Department of Earth and Planetary Sciences, University of New Mexico; and Allen Shapiro, Dave Wilkins, and Dennis Woodward, USGS hydrologists.

HYDROGEOLOGIC CHARACTERISTICS OF THE MADERA LIMESTONE

The hydrogeologic characteristics of the Madera Limestone are divided into two broad topics: (1) the geologic framework of the Madera Group, which includes nomenclature and stratigraphy, areal extent

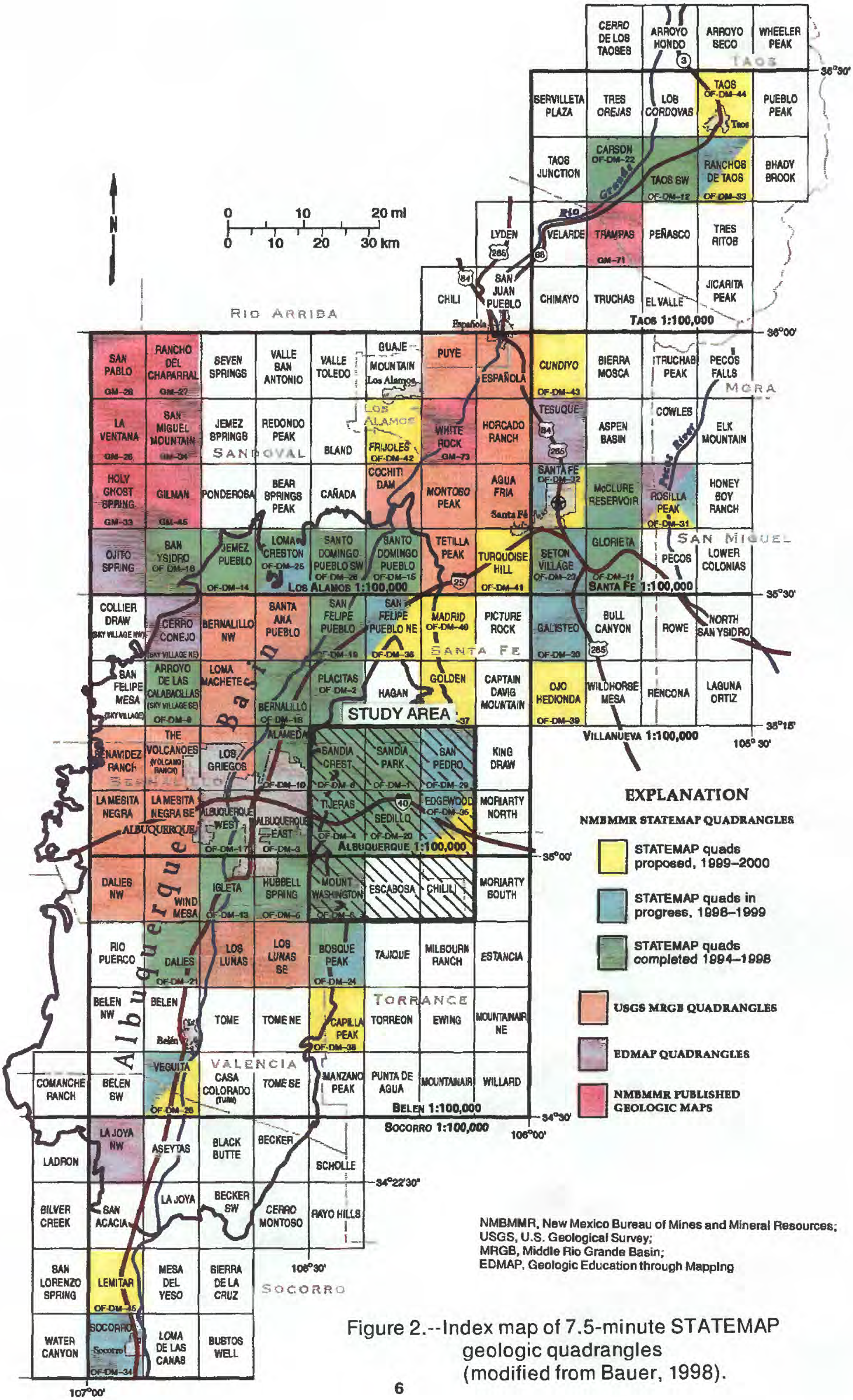


Figure 2.--Index map of 7.5-minute STATEMAP geologic quadrangles (modified from Bauer, 1998).

and thickness, and depositional history, lithology, and structure; and (2) the hydrologic framework of the Madera Limestone, which includes aquifer type, hydraulic heads, hydraulic properties, water quality, an overview of fracture flow, ground-water flow direction, ground-water withdrawal and depletion, streamflow and springs, recharge, septic-field effluent, and imported water.

Geologic Framework of the Madera Group

The understanding of the geology in the east mountains has improved substantially since W.G. Tight sketched his map in 1907 (fig. 3) (Kelley and Northrop, 1975). NMBMMR is now in the fifth year of a program, New Mexico STATEMAP, designed to produce and distribute state-of-the-art, detailed, digital geologic quadrangle maps of population centers along the Rio Grande watershed. Part of the National Cooperative Geologic Mapping Program, these multipurpose maps "help identify ground-water aquifers, aid in locating water-supply wells, and assist in locating potential polluting operations, such as landfills, safely away from the aquifer" (Bauer, 1998, p. 1). Relevant east mountain geologic quadrangles include Sandia Crest, Sandia Park, San Pedro, Tijeras, Sedillo, Edgewood, Escabosa, and Chilili (fig. 1).

Nomenclature and Stratigraphy

Previous investigators have referred to the Middle and Late Pennsylvanian and Early Permian Madera unit as the Madera Group (Myers, 1973, 1982), the Madera Formation (Kelley and Northrop, 1975), and the Madera Limestone (Titus, 1980). In conformance with Myers (1982) and White (1994), "Madera Group" refers to the rock unit, and, in conformance with local usage, "Madera Limestone" refers to the aquifer discussed in this report.

In the study area, the Madera Group consists of two formations: the Los Moyos Limestone and the Wild Cow Formation, which is composed of three members (Myers, 1982; fig. 4). Outside the study area in the southern Manzanos, the overlying Bursum Formation, where present, is included as part of the Madera Group. The Los Moyos Limestone is composed of cliff-forming layers of gray limestone, dark shales, and minor amounts of siltstone, sandstone, and conglomerate. The overlying Wild Cow Formation is a sequence of alternating layers of sandstone, conglomerate, siltstone, shale, and thin- to thick-bedded gray limestone. Where present, the Bursum Formation is a sequence of red sandstone, red and green shale and siltstone, and gray limestone (Myers, 1973, 1982).

Areal Extent and Thickness

The Madera Group crops out over all the east slope of the Manzano Mountains and more than half the east slope of the Sandia Mountains. Approximately two-thirds of the east mountain area, or about 200 square miles, is overlain by the Madera Group. The thickness of the Madera Group generally ranges from about 1,300 to 1,400 feet (Titus, 1980). Read and others (1944) described two complete sections of the Madera Group, one near Monte Largo and another in the Tejano Canyon area (fig. 1), of 1,275 and 1,305 feet in thickness, respectively. In the Cedro Peak area, Brown (1962) pieced together a measured section 1,375 feet in thickness. Titus (1980) stated that measurements inferred from drilling records indicate an eastward thickening of the Madera Group to approximately 2,000 feet. In addition, the thickness of the Madera Group has been estimated from stratigraphic sections presented in geologic quadrangle maps by Myers (1966, 1969) and Myers and McKay (1970, 1971); from structural sections by Kelley (Kelley and Northrop, 1975); and from geologic sections provided by Titus (1980).

Depositional History, Lithology, and Structure

The Paleozoic Era began approximately 570 million years ago with regional downwarping of flat, nearly featureless Precambrian strata. This subsidence allowed shallow seas to spread across much of New Mexico. For about 240 million years, carbonate mud and sand were deposited, except in central New Mexico; the absence of these deposits in central New Mexico suggests that the Sandia area was topographically above the seas and undergoing erosion.

With the beginning of Pennsylvanian time, approximately 330 million years ago, the entire area subsided, allowing the seas to spread across central New Mexico. For the next 40 million years, subsidence continued, allowing the ancient seas to remain and deposit lime mud, sand, and argillaceous mud; the Madera Group was deposited during this time (Kelley and Northrop, 1975).

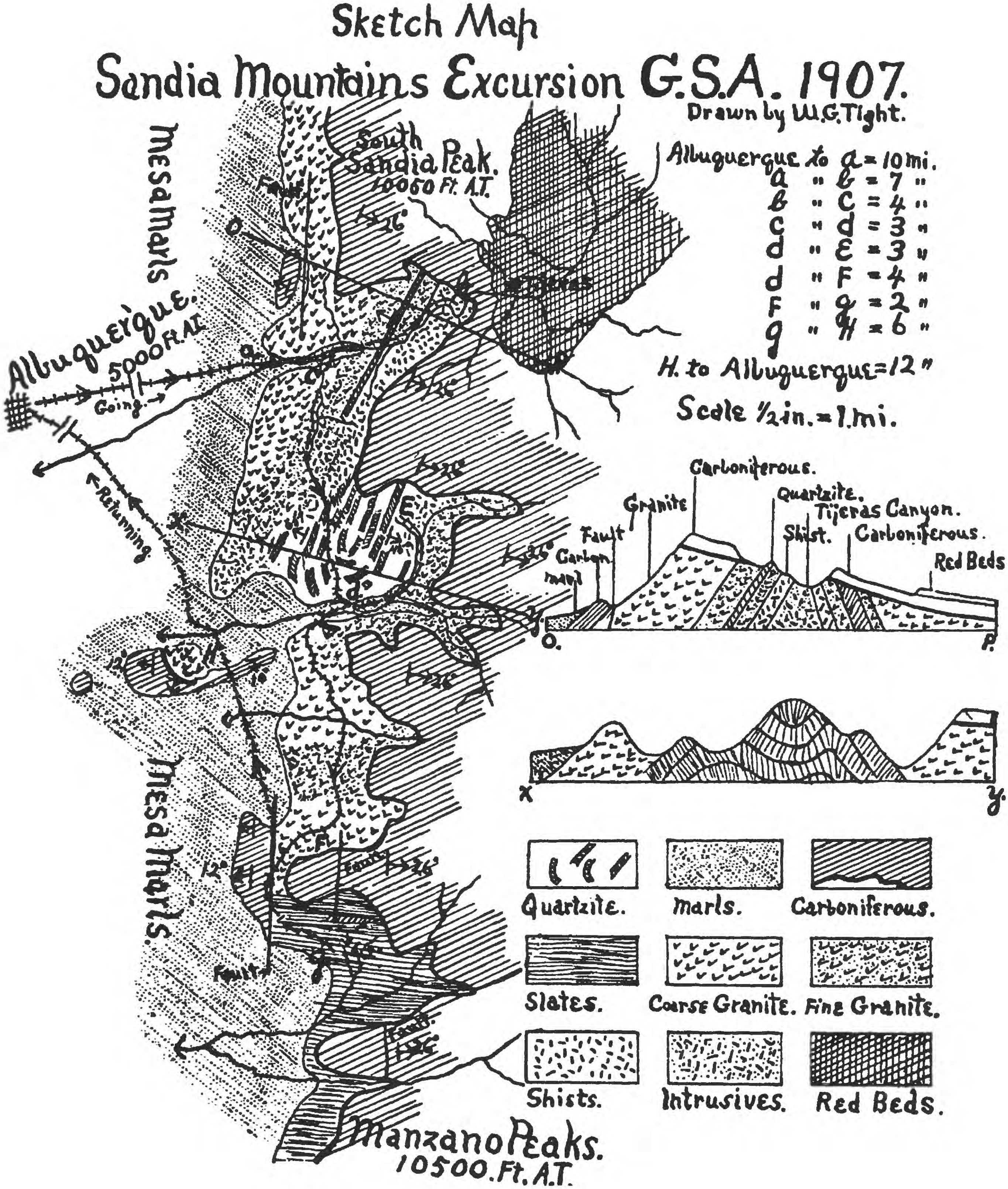


Figure 3.--Geologic sketch map of the Manzano-Sandia Mountains, 1907 (from Kelley and Northrop, 1975).

Lithologically, the Madera Group is a mixed sequence of medium- to thick-bedded, light-gray limestone and greenish to tan and rarely reddish arkose and feldspathic siltstones. Dark mudstone intervals with variable amounts of thin-bedded black micrites are also present. Limestones, which vary in thickness from 0.7 to 65 feet, dominate the formation. The arkosic sandstones are typically coarse to medium grained. Fossils include crinoid stems, brachiopods, corals, and bryozoans (Ferguson and others, 1996).

Structurally, the Madera Group was deposited as horizontal, laminar beds. The Precambrian surface on which the underlying Sandia Formation (fig. 4) was deposited was a peneplain (a low, featureless, gently undulating surface of considerable area). Until 60-70 million years ago, the only structure in the Sandia area had been produced in the Precambrian basement orogenies; the Sandia area was a low plain, underlain by flat-lying Paleozoic/Mesozoic strata, with some slight deformation as a result of subsidence-related tilting (Kelley and Northrop, 1975). The major deformations in the Madera Group in the east mountain area are primarily the result of crustal extension and the Sandia-Manzano Uplifts over the past 60 million years. Although the Sandia and Manzano Mountains are separate physiographic entities, they are both formed by a major east-tilted fault block. Topographically, the Sandia and Manzano Mountains are separated by Tijeras Canyon; structurally, they are separated by a major fault system formed by the Tijeras and Gutierrez Faults (fig. 5). The junction of these faults is located near the village of Tijeras. Trending northeast from their junction, the faults are roughly parallel and bound a 1.5- to 2.5-mile slice that is downdropped at the southwest end and uplifted on the northeast (Titus, 1980). The east slope of the Sandias has relatively steeply dipping Pennsylvanian strata at angles averaging 15-20 degrees (Kelley and Northrop, 1975); the east slope of the Manzanos, in contrast, dips 3-4 degrees (Titus, 1980).

A geologic map of the Sandia Mountains (Kelley and Northrop, 1975) shows high-angle faults trending west, northwest, north, and northeast, with numerous subparallel and transverse faults forming a "complicated and varied pattern." Woodward (1982) suggested that high-angle reverse faulting in the southeastern part of the Sandias formed in response to a local compressional stress field in the hinge of the eastward-tilted Sandia fault block in the late Cenozoic. Titus (1980) concurred with Kelly and Northrop's description, stating that the east side of the Sandias has been "intensely faulted." Charles Ferguson, research associate with NMBMMR and chief mapper of the Sandia Park quadrangle (fig. 1), reports that the Madera Group is "more folded than faulted" with a high degree of fracturing associated with the folding (written commun., 1998). In Ferguson's opinion, there are significantly fewer faults within the Madera Group along the dip slope of the Sandias than depicted by Kelley and Northrop (1975). The faults that Kelley and Northrop mapped are, to a large degree, based on aerial photograph interpretation.

Geologic maps of the Manzano Mountains by Myers (1966, 1969) and Myers and McKay (1970, 1971) show numerous north- and northeast-trending, high-angle faults along the crest line and dip slope. Titus (1980) described faulting in the Madera Group on the eastern slope of the Manzano Mountains as aligned in a northeast to southwest pattern. Faults mapped by Adam Read (NMBMMR), chief mapper of the Tijeras and Sedillo quadrangles (fig. 1), are often quite different from those mapped by Myers and McKay, and Read's fault density is equal to or somewhat less than that depicted by those authors. Difficulties in recognition, vegetation cover, and burial suggest many as yet undiscovered faults. Read stated that "there are likely many unmapped (and unrecognizable) fracture zones within the Madera that could be very important from a hydrological standpoint" (written commun., 1998).

Hydrologic Framework of the Madera Limestone

The understanding of the hydrology in the east mountain area has not increased substantially since the NMBMMR published "Ground water in the Sandia and northern Manzano Mountains, New Mexico" (Titus, 1980). Many of the results published in that report were interpreted from data collected in the early 1960's: the water-table or potentiometric-surface map (Titus, 1980, fig. 4), for example, was constructed using data collected in 1962-63. The increase in population over the last 40 years has undoubtedly changed the water-supply potential of the Madera Limestone.

The following sections discuss aquifer type, hydraulic heads, and hydraulic properties, including storage coefficient, permeability, hydraulic conductivity, and transmissivity. These properties help

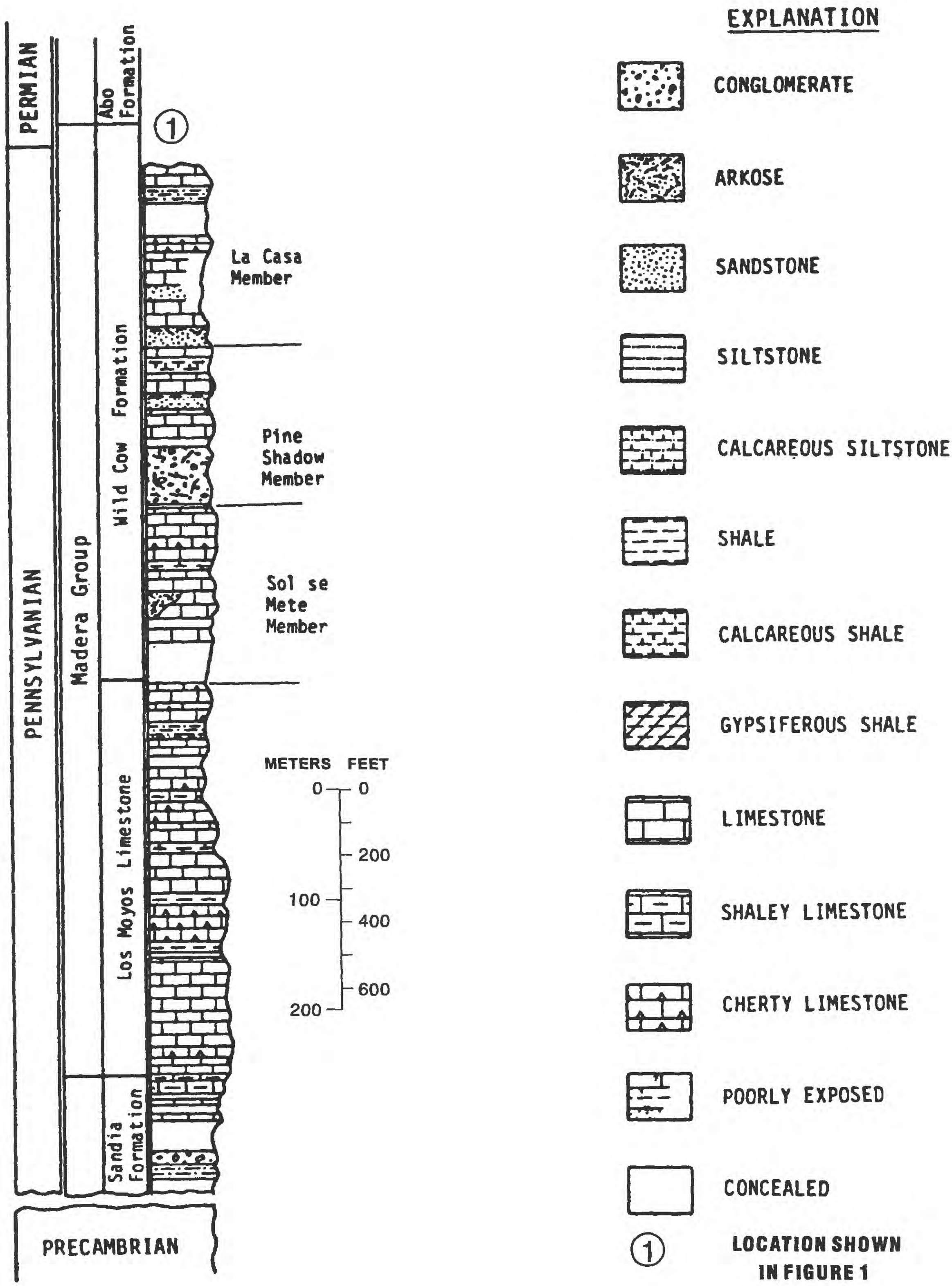


Figure 4.--Stratigraphy of the Madera Group (modified from Myers, 1982, p. 235).

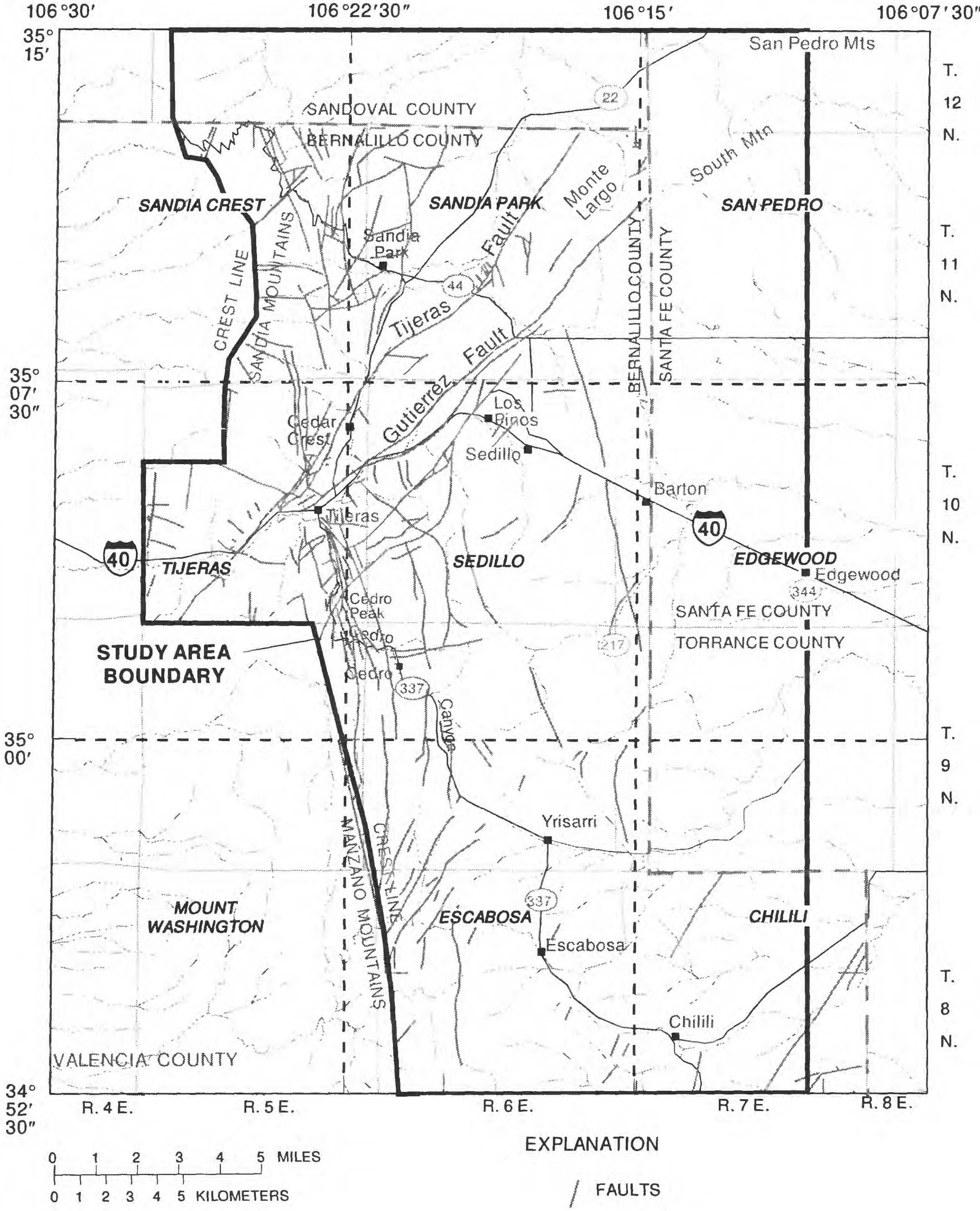


Figure 5.--Faults in and near the study area (modified from Kelley and Northrop, 1975, map 3).

predict long-term availability of ground-water supplies and effects from development. Also included within the hydrologic framework of the Madera Limestone are sections about fracture flow, ground-water flow direction, withdrawal and depletion, streamflow and springs, recharge, septic-field effluent, and imported water.

Aquifer Type

Aquifers are often defined in terms of existing under either confined or unconfined conditions. A confined aquifer, also called an artesian aquifer, is overlain by an impermeable, confining layer. An unconfined aquifer has no confining beds between the zone of saturation and the land surface. Large fluctuations in water levels in wells caused by barometric-pressure changes, which are normally seen under confined conditions, are commonly observed in the Madera Limestone (Clay Kilmer, Clay Kilmer and Associates, Ltd., oral commun., 1998).

Hydraulic Heads

The distribution of hydraulic head in an aquifer system represents the flow conditions and effects of stresses imposed on the aquifer. Although some aquifer characteristics can only be inferred by analyzing changes in hydraulic head, hydraulic head can be measured directly. Vertical and horizontal components of the hydraulic-head gradient can change throughout an aquifer system, especially in areas of recharge and discharge. In areas of ground-water flow dominated by fractures, hydraulic head can vary a great deal over small distances.

Hydraulic-head data, or water-level data, are used to develop potentiometric-surface maps that indicate the altitude of a ground-water surface. The potentiometric-surface map of the east mountain area by Titus (1980) represents conditions in the early 1960's, and the water-level contours in the Madera Limestone were constructed based on few data.

The USGS, in cooperation with BCEHD, has established a network of 75 privately owned, domestic wells (fig. 6) used for water-quality and water-level data collection. Since 1995, water-quality samples have been collected at least once from each well. Forty-eight of these 75 wells have water-level data collected at the time of sample collection. Twenty-seven of these 75 wells are known to be completed in the Madera Limestone. These data are not sufficient to define the potentiometric surface; additional water-level data are needed for wells completed in the Madera Limestone.

Hydraulic Properties

The storage coefficient is the volume of water that an aquifer takes into or releases from storage per unit surface area of aquifer per unit change in hydraulic head. The coefficient is a dimensionless quantity; in most confined aquifers, storage coefficient typically ranges from 10^{-5} to 10^{-3} (Freeze and Cherry, 1979). Kilmer (1998) conducted an aquifer test in the Madera Limestone near the Cedro Peak area (fig. 1); his analysis of test data shows storage coefficients ranging from 10^{-4} to 10^{-2}.

Permeability is a characteristic of the rock and is essentially a description of the interconnectedness of openings in the rock. Permeability in the Madera Limestone is expected to be highly variable. Values of permeability in a karst limestone (Freeze and Cherry, 1979) are expected to range from 0.000108 to 1.08 feet squared, or about four orders of magnitude. Fractures and fracture zones within the Madera Limestone are highly permeable and account for permeability in the aquifer. According to Shapiro and others (1995), fractures are the principal conduits for water movement in limestones. Titus (1980) recognized that fracturing and dissolution in the Madera Limestone had created permeable zones through which water can move. During their investigation of permeability in fractured bedrock in the Mirror Lake watershed, New Hampshire, Paillet and Kapucu (1989) estimated the vertical and horizontal distribution of fracture permeability using geophysical logging methods. They concluded that permeability in rock containing multiple intersecting fractures is dependent on the aperture, orientation, and interconnection of fractures. A primary structural feature that also must be considered in characterizing permeability is bedding. Bedding originates during the formation of rocks through depositional processes, and bedding planes often represent pathways for ground-water flow. In the Madera Limestone, for example, bedding plane separations in shales provide additional permeability (Titus, 1980).

Hydraulic conductivity is the rate at which water moves through a permeable rock and is characteristic of the fluid and the rock. Typical values of hydraulic conductivity in a limestone are extremely variable, ranging from less than 1 to more than 3,000 feet/day

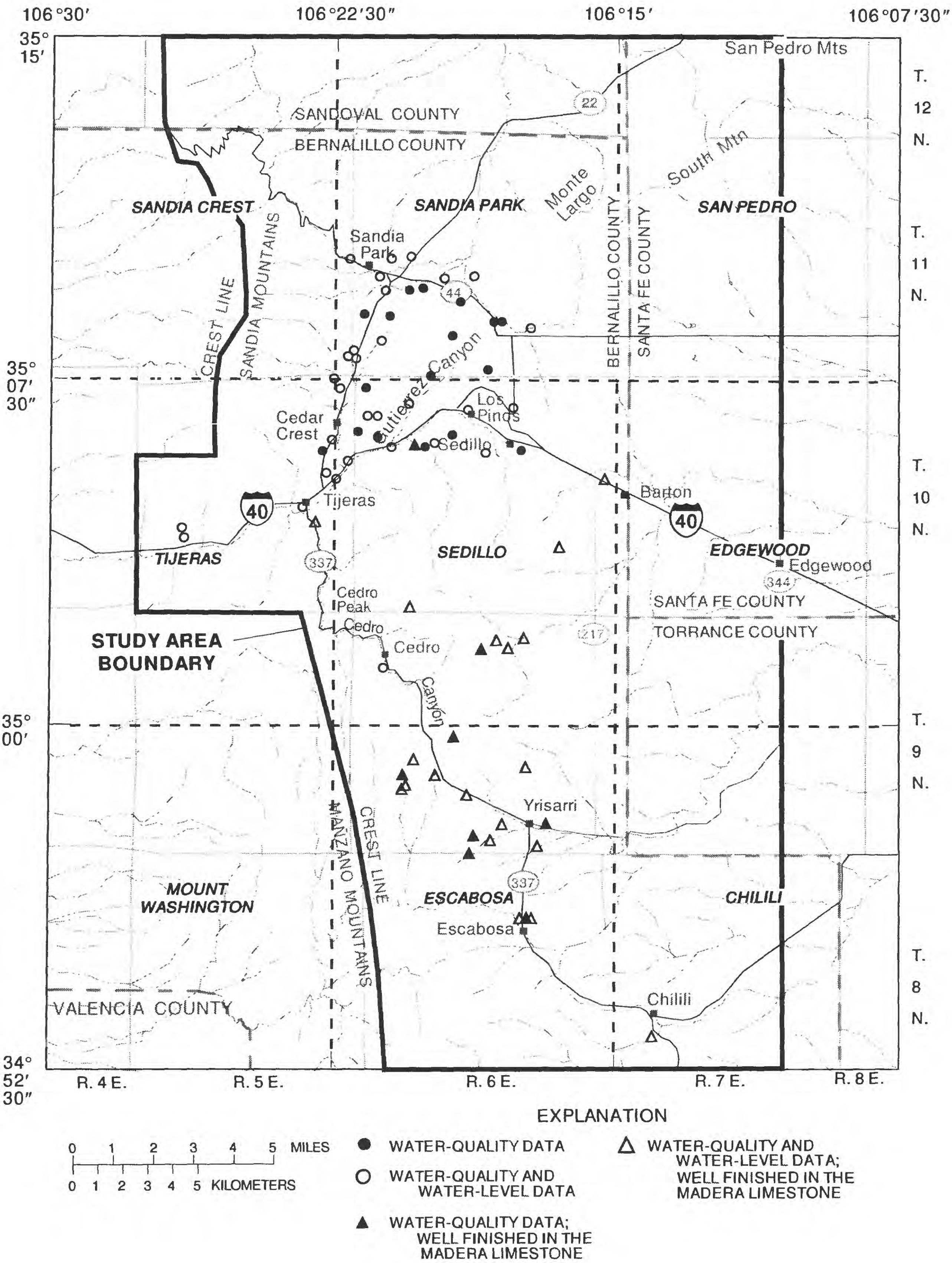


Figure 6.--Well network in the study area.

(Spitz and Moreno, 1996); Shapiro and others (1995) noted that hydraulic conductivity in a fractured medium can have a range of more than 10 orders of magnitude and that aquifers with larger values are able to transmit more water.

Transmissivity is the rate at which water is transmitted through a unit width of an aquifer under a unit hydraulic gradient, or the hydraulic conductivity multiplied by the saturated thickness. Transmissivity varies significantly in a fractured limestone aquifer; if a saturated aquifer thickness of 200 feet is assumed, typical values of transmissivity range from about 8,000 to about 270,000 feet squared per day (Spitz and Moreno, 1996). Results from the aquifer test conducted by Kilmer (1998) demonstrate this variability. Analysis of test data shows transmissivities ranging from about 20 to about 2,000 feet squared per day. Kilmer concluded that "the Madera aquifer is highly variable," and suggested that the larger value of transmissivity is a result of preferential flow along fractures (Kilmer, 1998, p. 8).

Data about storage coefficient, specific yield, permeability, hydraulic conductivity, and transmissivity are used in conjunction with other data to predict long-term availability of ground-water supplies and effects from development. These terms can be related to one another; for example, transmissivity is a two-dimensional concept--the hydraulic conductivity multiplied by the aquifer thickness; permeability can be related to hydraulic conductivity by incorporating fluid properties (A.M. Shapiro, written commun., 1998).

Water Quality

The quality of water depends on a variety of factors, including climate, geologic effects, composition of atmospheric precipitation, and the effect of development. To be considered potable, water must be free from disease-causing organisms and minerals, organic substances, and chemicals that could produce adverse physiological effects. Additionally, drinking water should be aesthetically pleasing, free from turbidity, odor, color, or objectionable taste, and have a reasonable temperature (Cotruvo and Vogt, 1990).

Previous investigations by Titus (1980), Kues (1990), Kues and Garcia (1995), and Rankin (1996) indicate that ground-water supplies in the Madera Limestone are generally potable, with some notable exceptions. Titus (1980) found fluoride concentrations exceeding the U.S. Environmental Protection Agency (USEPA) maximum contaminant level (MCL) of 4.0 milligrams per liter (mg/L) in two water samples from the Madera Limestone. An MCL is an enforceable standard related to health risks (Cotruvo and Vogt, 1990). Excessive fluoride in drinking water can result in dental fluorosis, a staining or pitting of permanent teeth (U.S. Environmental Protection Agency, 1986). Kues and Garcia (1995) found nitrate concentrations exceeding the USEPA MCL of 10.0 mg/L in one water sample from the Madera Limestone; excessive nitrate in drinking water is potentially more serious, causing blue-baby syndrome, or methemoglobinemia, and can be fatal (Health and Environment Digest, 1991). Kues and Garcia (1995) and Rankin (1996) found concentrations exceeding the USEPA secondary maximum contaminant level (SMCL) for chloride (250 mg/L), iron (0.3 mg/L), sulfate (250 mg/L), or dissolved solids (500 mg/L) in some of the water samples from the Madera Limestone. An SMCL is a non-enforceable standard related to the aesthetic quality of water (Cotruvo and Vogt, 1990). Excessive concentrations of these constituents can affect the odor, color, and taste of drinking water. USEPA regulations concerning MCL's and SMCL's apply to public water systems, not individual domestic wells.

The hardness of water, defined as the ability of water to precipitate soap (Tate and Arnold, 1990), is another measure of the aesthetic quality of water. Because hardness is not attributed to a single constituent, it is often expressed in terms of an equivalent amount of calcium carbonate ($CaCO_3$). Durfor and Becker (1964) established a method of classifying hardness: water with concentrations greater than 180 mg/L as $CaCO_3$ is considered to be very hard. In 1995 and 1997, the author collected water samples from 27 wells completed in the Madera Limestone (fig. 6). In these samples hardness values ($CaCO_3$) ranged from 52 to 820 mg/L; the average value was 410 mg/L, and 23 of the 27 samples exceeded 180 mg/L. Although USEPA MCL's do not specify values for hardness, the World Health Organization has suggested an upper limit of 500 mg/L as $CaCO_3$ (Hem, 1985).

Specific conductance, the ability of water to conduct an electrical charge, has a direct relation to the concentration of dissolved solids in the water (Hem, 1985, p. 67); a specific conductance of 800 microsiemens per centimeter (µS/cm) at 25 degrees Celsius is equivalent to a dissolved-solids concentration of about 520 mg/L. In samples the author collected in 1995 (Rankin, 1996) and 1997 (unpublished data), specific conductance ranged from 630 to 2,090 μS/cm; the average value was 1,100 μS/cm, and 18 of the 25 samples exceeded 800 μS/cm.

Overview of Fracture Flow

Secondary structural features such as fractures can control the movement of ground water. Fracture is a general term for any break in a rock, whether or not it causes displacement, due to mechanical failure by stress. Fractures include faults, joints, cracks, and fissures (Bates and Jackson, 1980, p. 244). Fractures exist in many geologic formations and are evident in exposures of the Madera Group (fig. 7). Although fractures are produced naturally under a variety of geologic processes, they primarily are a result of the deformation of rocks and soil. Once a fracture is formed, permeability can be enhanced by continued deformation or by solution channeling (Doe, 1997), a process whereby channels are formed by the solution of carbonate rock (Bates and Jackson, 1980, p. 595). Conversely, permeability may decrease because of mechanical closure, chemical precipitation, or fracture-wall alteration (Doe, 1997).

Fractures in bedrock aquifers are the principal conduits for ground-water flow (Shapiro and others, 1995). The term "fracture flow" as used in this report refers to ground-water flow dominated by faults, joints, cracks, and fissures, collectively known as fractures. Fracture flow is different from flow in a porous medium such as sand or gravel; the most important distinction is that in a porous medium, all points are connected by straight-line paths; in a fractured medium, flow follows distinct, discrete pathways (Doe, 1997). In general, the manner in which ground water flows to a pumped well in a porous medium can be quite different from that in a fractured medium. Radial-flow conditions in a porous medium consist of a discharging well that causes a cone of depression in the surrounding aquifer and drawdown that decreases with distance away from the well. Flow lines from all directions converge at the well, and equipotential lines are concentric around the well (fig. 8). In a porous medium, however, radial flow does not always occur; in many instances, there is nonradial flow in the vicinity of the pumped well. Linear-flow conditions in a fractured medium consist of a discharging well that causes flow into the fracture from the aquifer; the open fracture is a planar surface that forms an extended well (fig. 9). In a fractured medium, drawdown is a function of the perpendicular distance away from the extended well (Jenkins and Prentice, 1982). Flow in a fractured rock does not have to be linear; however, linear-flow regimes are not the only type of hydraulic conditions encountered during aquifer tests in fractured rock (A.M. Shapiro, written commun., 1998).

In fractured formations such as the Madera Group, hydraulic properties can vary considerably, depending on the degree of fracture connection and related characteristics of the fractures, such as aperture, density, frequency, spacing, length, orientation, wall roughness, and the presence of filling material within the fracture. Over the past 20 years, new and improved techniques and tools have been developed to help define the characteristics of fracture flow. Surface geophysics offers a variety of methods used in ground-water investigations including electrical, electromagnetic, seismic, gravimetric, and magnetic surveys (Zohdy and others, 1974), and radar technology is being developed that will help define fracturing (A.M. Shapiro, written commun., 1998). Advances in geophysical imaging techniques include borehole television, the borehole formation microscanner (FMS), and the borehole acoustic televiewer (ATV). Borehole television can provide an undistorted, color image of an entire borehole wall; fracture information is then analyzed from the image. The FMS measures the resistivity of rock material and has proven effective in detecting fractures (Doe, 1997). Paillet and Kapucu (1989) have used borehole geophysical methods to estimate the distribution of fracture permeability in bedrock in the Mirror Lake watershed, New Hampshire, and they were able to determine fracture orientation in a series of boreholes using ATV technology (fig. 10).

New technologies for determining the hydraulic characteristics of fractures include the borehole heat-pulse flowmeter (HPFM) and the electromagnetic flowmeter (EMFM). By using data derived from these methods, the vertical components and directions of hydraulic-head gradients can be determined (Doe, 1997). Water-yielding fractures can be defined using more conventional geophysical logging methods as well. Heisig (1999) was able to identify fractures in the Batavia Kill Valley, New York, using gamma, fluid-conductance, temperature, and caliper logs. New methods that use transient water-level data have been developed to estimate the actual direction of ground-water flow in fractured bedrock. Rophe and others (1992) analyzed subsurface flow and formation anisotropy, calculated from equipotential surfaces.

Figure 7.--Fractured Madera Group in a road cut in Cedro Canyon.

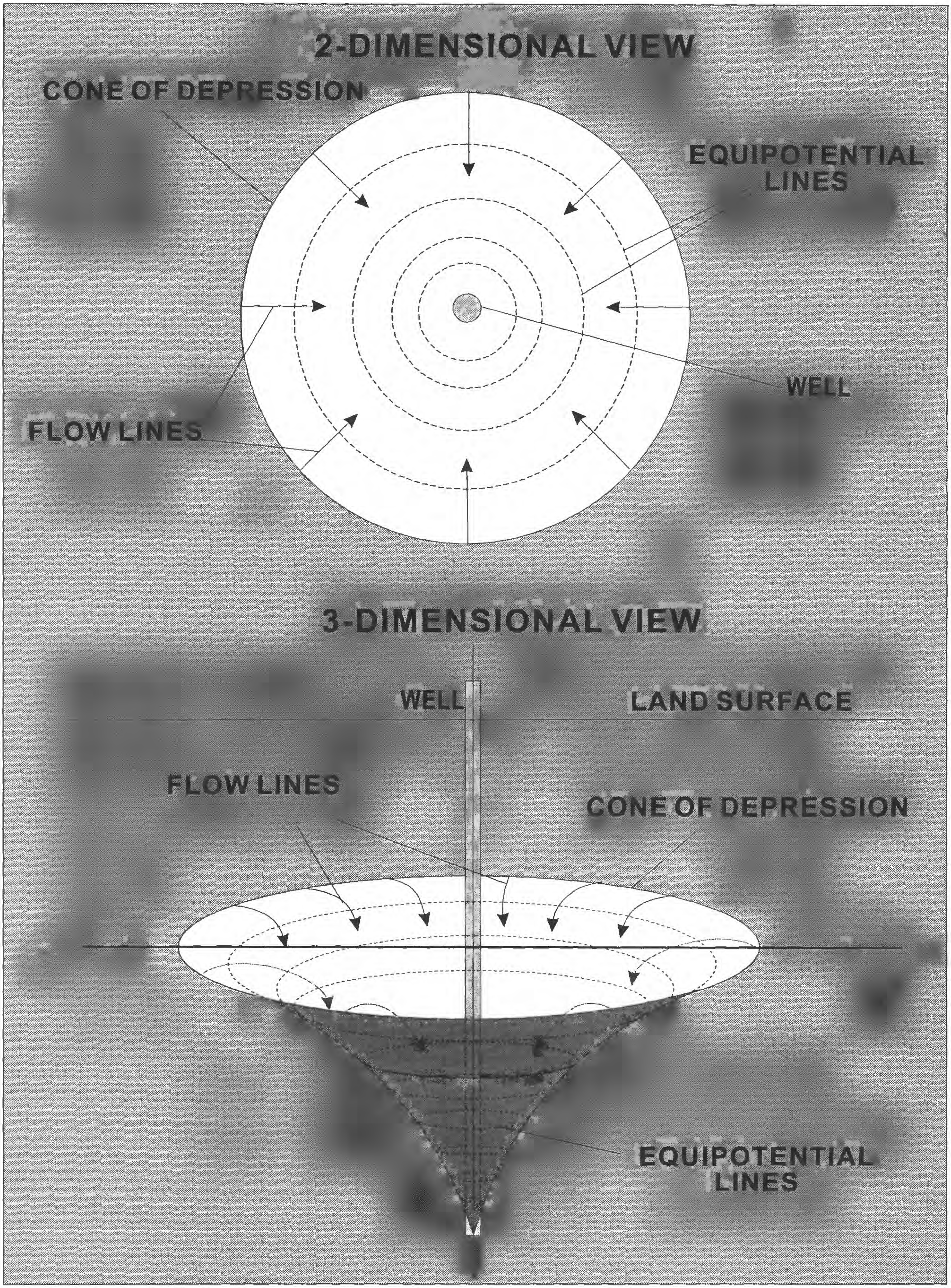
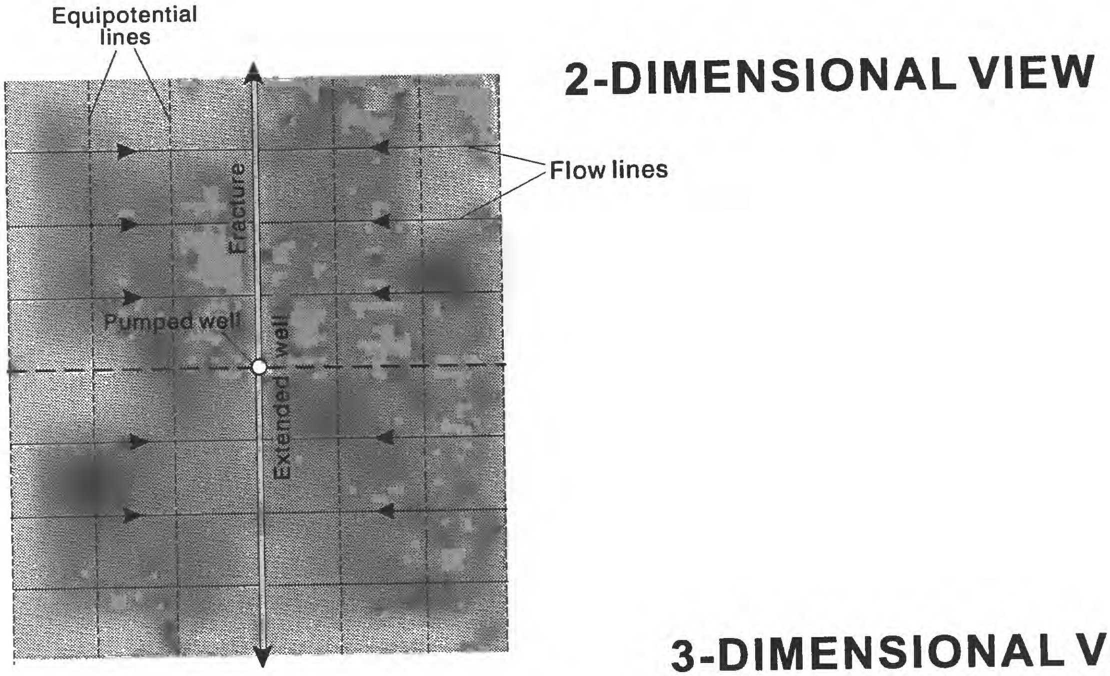


Figure 8.--Conceptual model of radial flow in a porous medium.



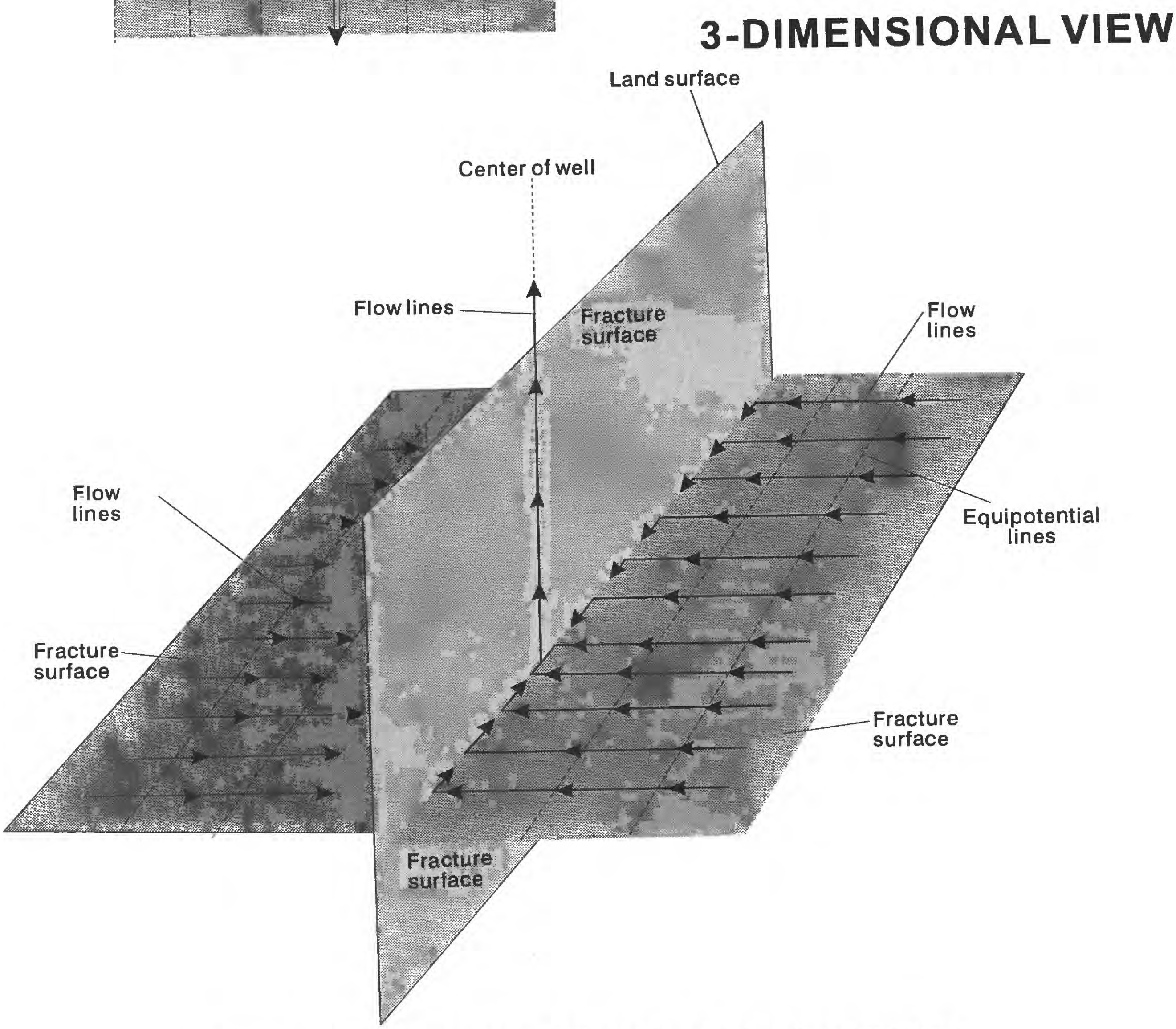


Figure 9.--Conceptual model of linear flow in a fractured medium (modified from Jenkins and Prentice, 1982, fig.1).

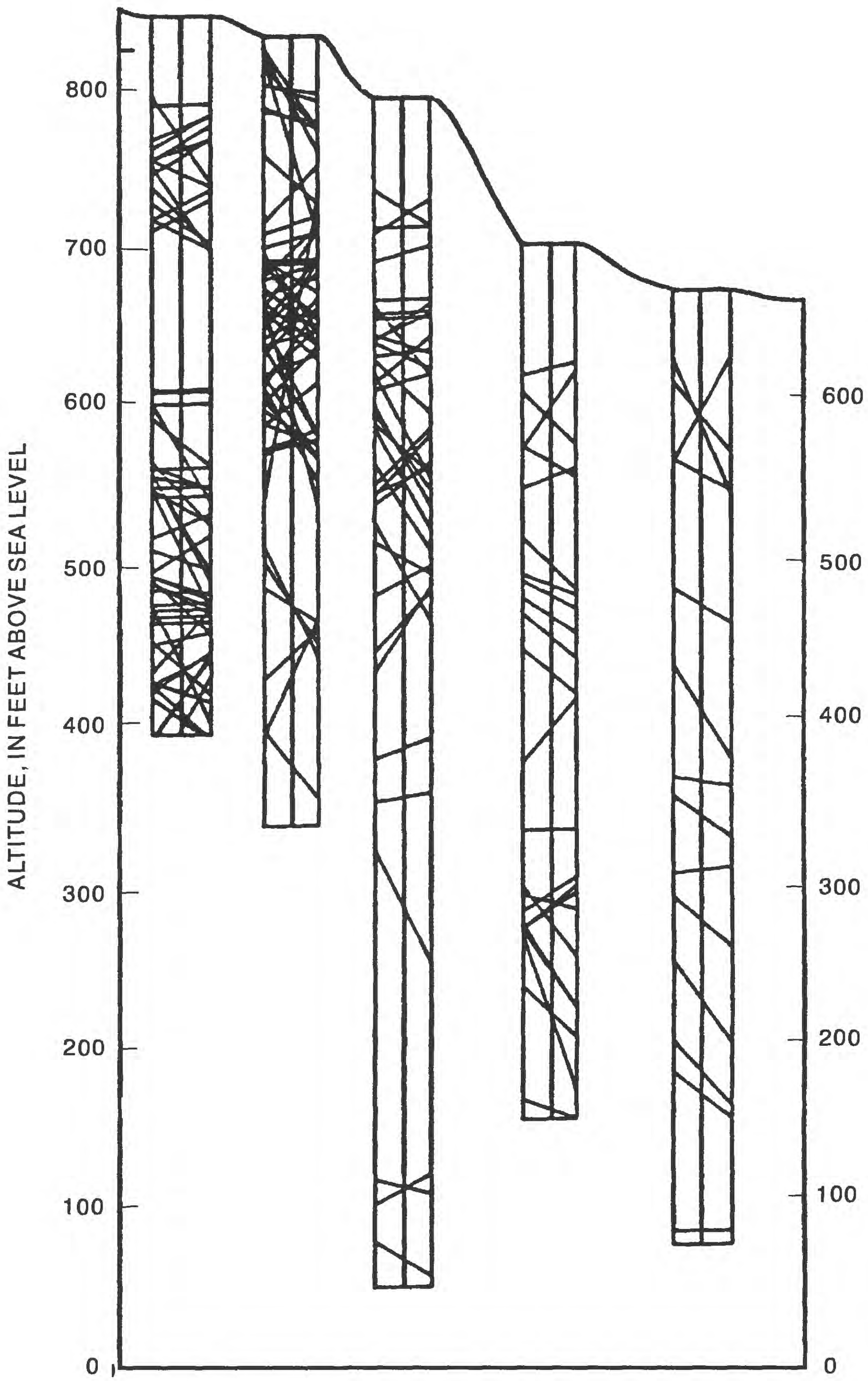


Figure 10.--Projection of fractures identified on acoustic-televiewer logs for a series of five boreholes (modified from Paillet and Kapucu, 1989).

The past 20 years of research have significantly advanced the conceptual understanding of fracture networks and provided practical tools for solving fracture-flow problems. Although assuming that the intricate geometry of a fracture network can be accurately determined is unrealistic, fracture information, complemented by direct measurements of hydraulic properties, can be used to effectively characterize fracture flow.

Ground-Water Flow Direction

Previous investigators (Titus, 1980; Kues, 1990) have presented maps of ground-water flow direction (figs. 11 and 12, respectively). These maps are based on hydraulic gradients indicated by water-level contours. Titus (1980) constructed his flow directions using hydraulic-head data collected in the early 1960's. Kues (1990) constructed flow directions using hydraulic-head data collected in 1984-85. The ground-water flow lines on both maps are generally in agreement with each other. However, more water-level data are needed to better establish the direction of ground-water flow. Confirming the flow direction of ground water in the east mountain area and throughout the Madera Limestone with greater control is essential.

Ground-Water Withdrawal and Depletion

The NMOSE defines withdrawal as "the quantity of water taken from a ground- or surface-water source;" depletion is defined as "that part of withdrawal that has been evaporated, transpired, incorporated into crops or products, consumed by man or livestock, or otherwise removed from the water environment" (Wilson and Lucero, 1997). To estimate withdrawals for the self-supplied domestic population (single or multifamily dwellings with wells permitted by the NMOSE), Wilson and Lucero (1997) used an areawide average of 80 gallons per capita per day. If the current (1999) self-supplied population of the east mountain area is conservatively estimated at 20,000 people, ground-water withdrawal is approximately 584 million gallons, or about 1,800 acre-feet, per year. A number of water systems (table 1) provide an additional 475 million gallons, or about 1,500 acre-feet, per year from aquifers in the east mountain area. Wilson and Lucero (1997) estimated depletion by multiplying withdrawal by a depletion factor that ranges from 0.45 to 0.50; if the total withdrawal of ground water from aquifers in the east mountain area is approximately 1 billion gallons, or 3,300 acre-feet, per year, depletion is approximately 500 million gallons, or about 1,650 acre-feet.

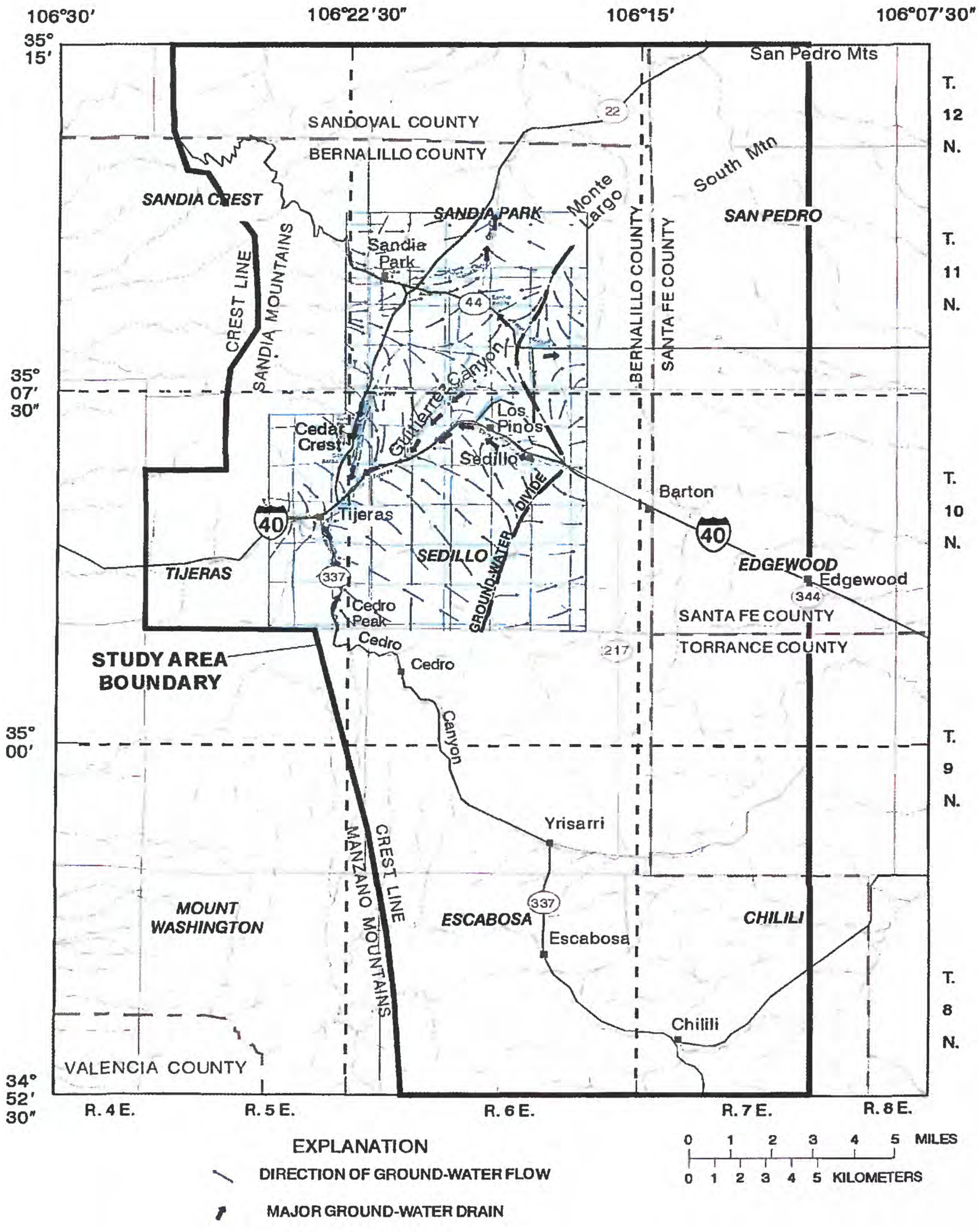
Although these estimates provide some idea of water use, Brian Wilson (New Mexico Office of the State Engineer, oral commun., 1998) acknowledges that data provided to the NMOSE are not always complete or accurate. Furthermore, many smaller community water systems fail to report water use. The majority of water users in the east mountain area are classified in the self-supplied domestic population and are not required to provide water-use information to the NMOSE. No information is available regarding depletion of ground water from a specific aquifer in the east mountain area (Andy Core, New Mexico Office of the State Engineer, oral commun., 1998).

Streamflow and Springs

With few exceptions, the east mountain area has no perennial streamflow. Perennial discharge from two springs flows into the Acequia Madre de San Antonio (fig. 13) and is used by residents of San Antonio (Gary Hefkin, Acequia Madre de San Antonio Community Ditch Association, oral commun., 1998). From samples collected in 1997, water-quality data for both springs are available from the USGS (Rankin, 1996); White and Kues (1992, p. 23) reported yields of 50-75 and 3 gallons per minute (gal/min), respectively, from these springs.

Approximately 150 miles of stream channels cross the Madera Limestone in the study area (fig. 1); however, flow only occurs in response to snowmelt or precipitation. These drainages are ungaged. A USGS gaging station (fig. 1) at Tijeras Arroyo above the Four Hills Bridge was operated from 1989 to 1991 (Ortiz and Lange, 1996), but the temporary nature of the installation might preclude the usefulness of streamflow data collected at this site. A "rule of thumb" states that a gaging station must operate for at least 5 years for the data to be statistically valid.

White and Kues (1992) published an inventory of springs in New Mexico. The authors identified 11 springs in the study area whose source is the Madera Limestone. Information regarding the physical characteristics of these 11 springs include yield estimates for each based on observations made in the early 1960's. Kues and White (1992) indicated that water-quality data for three of the springs are available (fig. 13). Whether these springs are permanent or ephemeral is unknown. Presumably more than 11 springs issue from the Madera Limestone in the study area; Kilmer (1998) referred to two springs, not included in the 1992 inventory, in the Cedro Peak area (fig. 13) that were flowing in June 1998 and noted that these springs become dry during dry periods.



EXPLANATION

DIRECTION OF GROUND-WATER FLOW

MAJOR GROUND-WATER DRAIN

GROUND-WATER DIVIDE

Figure 11.--Direction of ground-water flow in the San Antonito and upper Tijeras Canyon area (from Titus, 1980).

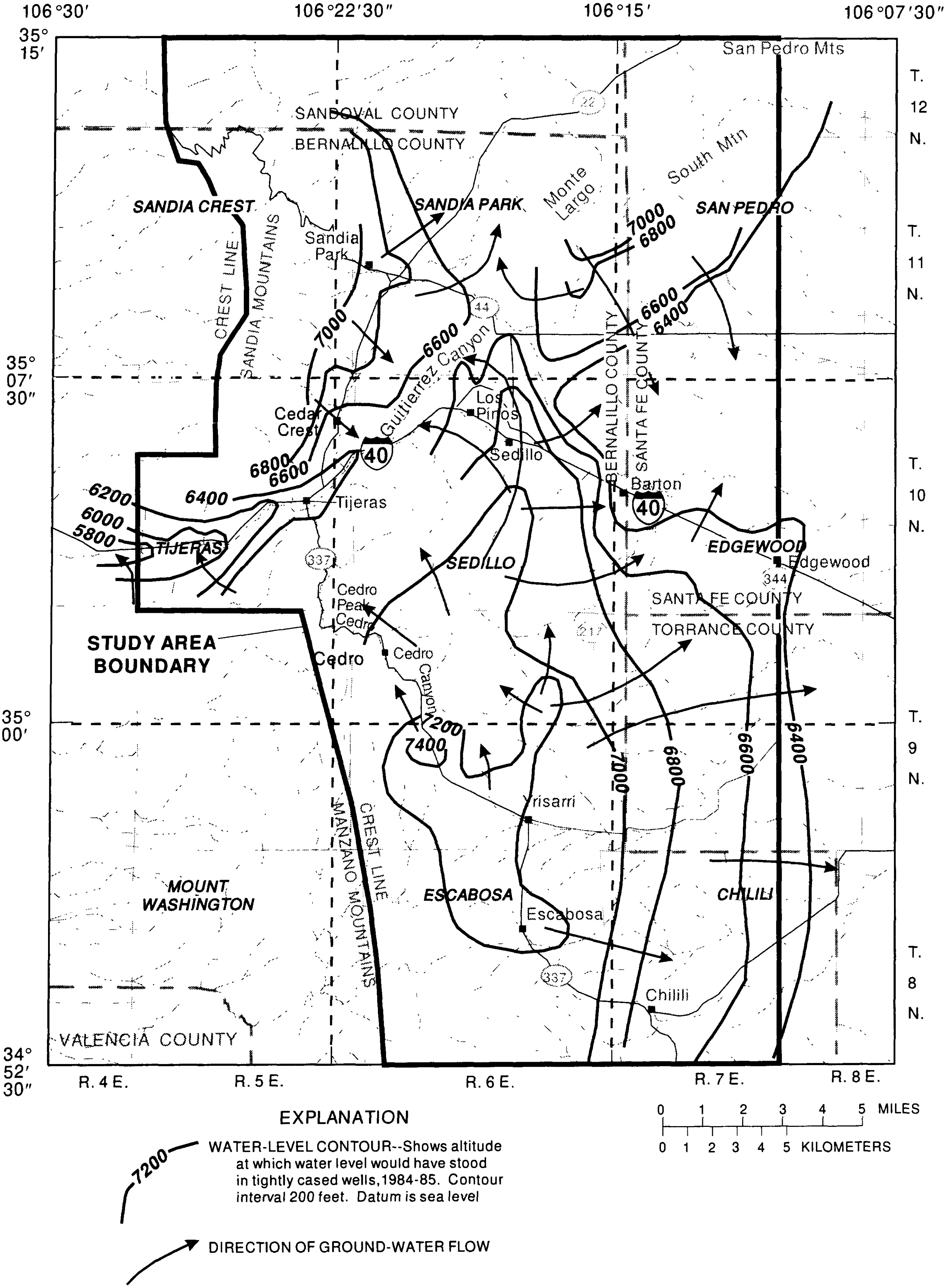


Figure 12.--Water-level contours and direction of ground-water flow in the study area, 1984-85 (modified from Kues, 1990, fig.6).

Table 1. --Summary of water consumption rates for Albuquerque and east mountain area water systems (modified from Kilmer, 1998)

[gpd, gallons per day; du, dwelling unit; cap, capita; --, no data. Water consumption rates presented in table 1 do not necessarily agree with those presented by Wilson and Lucero (1997) because of different reporting periods]

System name	Connections	Average total system use (gpd)	Average use (gpd/du)	Average use (gpd/ cap)	Persons per dwelling unit	Source of data
Albuquerque City Water System	--	--	--	150	--	1
Edgewood Water, Inc.	1,506	389,802	259	104	2.50	9
Entranosa Water Cooperative	561	152,000	271	126	2.15	1,2,4,5
Forest Park Property Owners Assoc.	64	10,000	156	65	2.40	1,2,4,5
Melody Ranch Water Company	76	14,060	185	75	2.50	8
Mountainview Tijeras MH Park	54	13,100	243	101	2.40	1,2,4,5
Quail Hollow Water Users Assoc.	11	2,700	245	100	2.45	1,2,4,5
Riviera de Sandia MH Park	117	18,000	154	70	2.20	1,2,4,5
Sandia Knolls Water Co.	335	70,000	209	93	2.25	1,2,4,5
Sandia Peak Utility	1,807	567,398	314	121	2.59	3
Sierra Vista Utilidades Cooperative	110	19,900	181	83	2.18	1,2,4,5
Tijeras Land Estates	14	4,300	307	128	2.40	1,2,4,5
Tranquillo Pines Water Users Coop.	240	41,400	173	72	2.40	1,2,4,5
Bernalillo County (population/housing)	--	--	--	--	2.59	6,7

Sources of data:

1. Molzen-Corbin & Associates, Inc., 1990, Bernalillo County east mountain area water system feasibility study draft final report: Consultant report to Bernalillo County.
2. Molzen-Corbin & Associates, Inc., 1991, Village of Tijeras water system master plan consultant report to the New Mexico Environment Department: Rural Infrastructure Special Appropriation Project No. 77-L(3)-GF.
3. Bill Baker, Superintendent, Sandia Peak Utilities, 1995 current numbers for Sandia Peak Water Utility, personal commun.
4. Bureau of Business and Economic Research, 1989, Socioeconomic projections for Albuquerque, 1980-2000: University of New Mexico.
5. Albuquerque/Bernalillo County Comprehensive Plan, 1988: Albuquerque/Bernalillo County Planning Division.
6. United States Bureau of the Census, 1980, Minor census divisions, Census of population: General population characteristics, Department of Commerce, Washington, D.C.
7. United States Bureau of the Census, 1980, Detailed housing characteristics: Summary Tape File 3, Department of Commerce, Washington, D.C.
8. Clay Kilmer & Associates, Ltd., 1996, Geohydrologic report for Blazing Saddle Ranch Subdivision, Torrance County, New Mexico: Consultant report to Associated Development, Inc., Moriarty, New Mexico.
9. Clay Kilmer & Associates, Ltd., 1996, Geohydrologic report for Prairie Hills Subdivision, Santa Fe County, New Mexico.

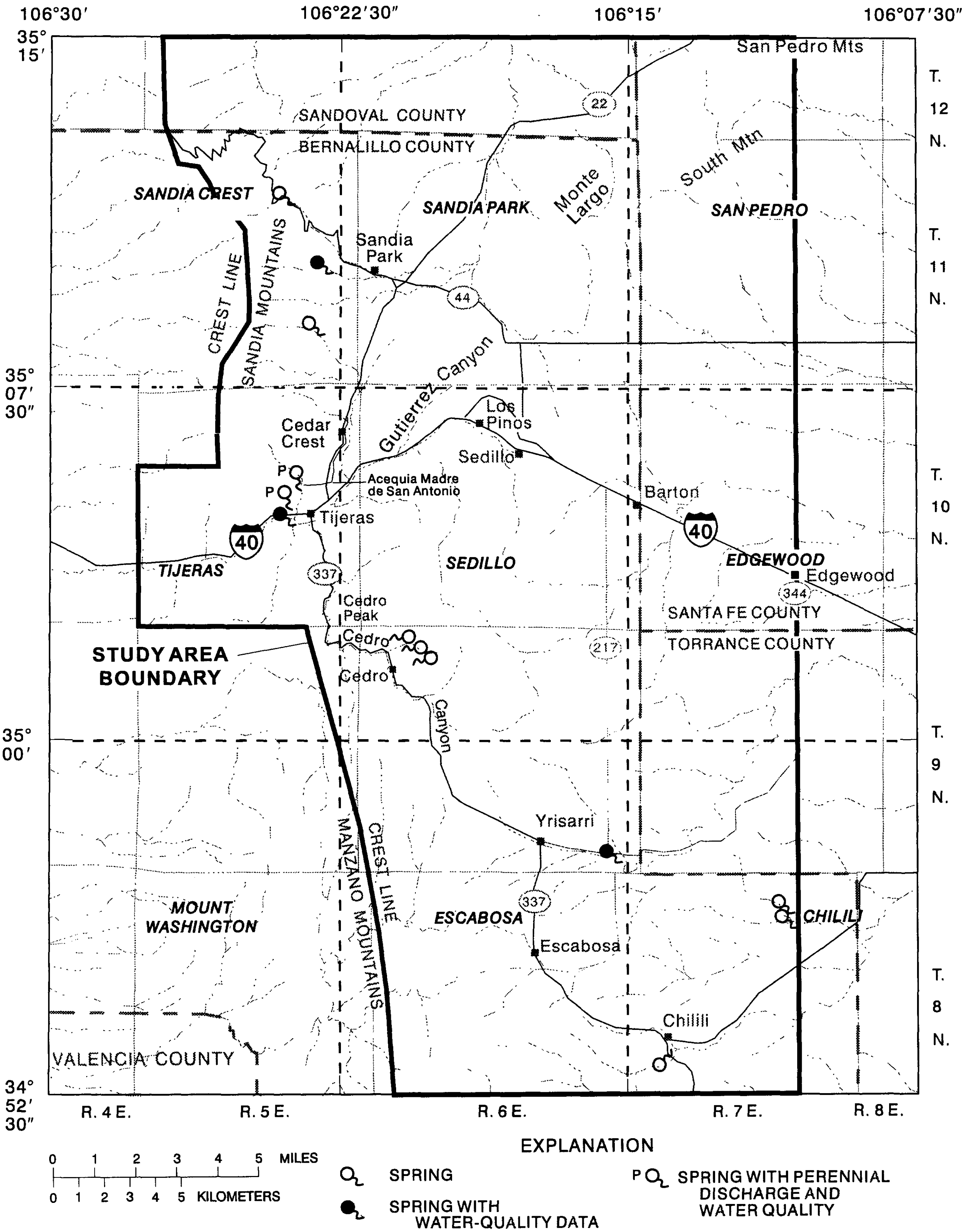


Figure 13.--Selected springs in the study area.

Recharge

The volume of water that recharges an aquifer is determined by three factors: (1) the volume of precipitation not lost by free-water evaporation, plant transpiration, soil-moisture evaporation, and runoff and therefore available for recharge; (2) the vertical hydraulic conductivity of surficial deposits and other strata in the recharge area of the aquifer; and (3) the transmissivity of the aquifer and potentiometric gradient, which determine how much water can move away from the recharge area (Fetter, 1988).

Presently (1998), the volume of water recharged to the Madera Limestone is unknown. Areas of recharge, spatial and temporal distribution of precipitation, evapotranspiration rates, potential recharge from precipitation, vertical hydraulic conductivity of surficial deposits, aquifer transmissivity, and potentiometric gradients are, to a lesser or greater extent, undetermined.

Septic-Field Effluent

Effluent from septic drain fields that reaches the water table is recharge to an aquifer (McAda, 1996). Septic-field effluent in the east mountain area was estimated by Summers (1991) to be about 65 acre-feet per year, or about 21 million gallons. Summers acknowledged that the volume of septic-tank effluent discharged is a crude estimate; his estimate assumes effluent discharge at the national average rate of 45 gallons per day per person.

Imported Water

The Entranosa Water Cooperative annually delivers an estimated 332 acre-feet of water to a population of about 3,262 to various locations in eastern Bernalillo County (Wilson and Lucero, 1997). Because this water crosses the Santa Fe/Bernalillo County line, the NMOSE considers the water to be imported. Although it does contribute to aquifer recharge, the ultimate fate of the water and the effect of its importation on the ground-water system in the east mountains are unknown. Titus (1980) stated that "If water were imported, distributed to customers, and then disposed of through the present individual septic tanks, the inevitable result would be a rise in the water levels in wells in the affected areas." Presently, no data are available to confirm Titus' statement.

PLAN OF STUDY

Essential Information and Activities

The information and activities considered to be essential to improve the understanding of fracture flow in the Madera Limestone and to help quantify aquifer characteristics of the Madera Limestone are (1) consolidate and evaluate existing information; (2) expand the observation-well network; (3) quantify recharge to the Madera Limestone; (4) quantify discharge from the Madera Limestone; (5) define hydraulic properties of the Madera Limestone; and (6) characterize ground-water flow in the Madera Limestone. This section expands on the information and activities, and table 2 summarizes the priority and estimated duration of essential and useful activities.

Consolidate and Evaluate Existing Information

Despite the absence of long-term, comprehensive studies of water resources within the study area, limited investigations of the hydrology and geology of the east mountain area have been done. The results of many of these investigations are widely distributed and recognized by the scientific community (see the "Previous investigations" section of this report); however, the results of all studies pertaining to the hydrology and geology of the east mountain area need to be consolidated and evaluated. These data could then be incorporated into ongoing studies.

Drilling and well records and well permit applications are on file at the NMOSE. These contain information regarding well location, yield, depth and completion data, lithologic descriptions, and other pertinent material that need to be consolidated and evaluated. Data also probably are available from site-specific studies, aquifer tests, and hydrologic investigations conducted for subdivision approval in the study area. Doctoral dissertations and Masters theses represent a potential source of information. In addition, the USGS and Bernalillo County maintain geographical information systems (GIS) coverages/ data sets for hydrologic and geologic information, land use, soil types and distribution, precipitation patterns, housing and population density, and a variety of other topics. Consolidating the information contained in these systems would be useful.

Table 2.--Prioritized plan of study to define hydrogeologic characteristics of the Madera Limestone in the east mountain area

EXPLANATION

Component addressed: component for which information will be gained from the study element. FFS, fracture-flow system; AC, aquifer characteristics; HH, hydraulic heads; WQ, water quality; R, recharge; D, discharge

Priority: usefulness of the information obtained by the study. E, will yield essential information; U, will yield useful information

Estimated time: estimated range of time to complete the study element. Continuous indicates data should be collected on a continuing basis

GIS, geographical information systems; USGS, U.S. Geological Survey

Study element	Component addressed	Priority	Estimated time, in years
Consolidate and evaluate existing information	FFS,AC,HH,WQ,R,D	E	Continuous
Expand the well network	FFS,AC,HH,WQ	E	Continuous
Define areas that contribute recharge	R	E	2-3
Quantify recharge from surface water and precipitation	R	E	3-5
Quantify recharge from septic-field effluent and imported water	R	E	1-2
Quantify withdrawal from domestic wells and public-supply systems	D	E	1-2
Quantify evapotranspiration	D	E	3-5
Quantify and sample springflow	D,WQ	E	1-2
Establish hydrogeologic boundaries	AC	E	1-2
Determine thickness and depth to the base	AC	E	1-2
Conduct and analyze aquifer tests	AC,HH	E	3-5
Characterize the fracture system	FFS	E	3-5
Determine the direction of ground-water flow	FFS,AC	E	3-5
Conduct and analyze borehole and surface geophysics	FFS,AC	E	3-5
Conduct and analyze tracer tests	FFS,AC	E	3-5
Determine the age of ground water	FFS,R	E	3-5
Conduct isotope sampling for all components of the hydrologic cycle	FFS,R	E	3-5

Table 2.--Prioritized plan of study to define hydrogeologic characteristics of the Madera Limestone in the east mountain area--Concluded

Study element	Component addressed	Priority	Estimated time, in years
Develop a regional ground-water-flow model	FFS,AC,HH,WQ,R,D	E	3-5
Conduct remote sensing	FFS	U	1-2
Develop a water budget by aquifer	R,D	U	3-5
Consolidate GIS data	FFS,AC,HH,WQ,R,D	U	Continuous
Improve drilling records	FFS,AC,HH,WQ,R,D	U	Continuous
Use USGS data bases for storage and retrieval of information	FFS,AC,HH,WQ,R,D	U	Continuous
Update Titus (1980) report	FFS,AC,HH,WQ,R,D	U	3-5
Involve neighborhood associations and residents with data collection	HH,WQ	U	Continuous

It is evident that potentially useful information is available, though scattered. Therefore, consolidating and evaluating this information would be essential for several reasons: (1) to identify wells, piezometers, and boreholes that could be included in the expanded monitoring-well network and possibly used as dedicated sites for sampling, water-level data collection, aquifer testing, or geophysical logging; (2) to avoid duplication of effort; (3) to save time and reduce costs; and (4) to establish a starting point for needed activities.

Expand the Well Network

The USGS, in cooperation with the BCEHD, has established a network of privately owned, domestic wells (fig. 6) used for water-quality and water-level data collection. Twenty wells were sampled monthly from January 1990 through 1993 (Kues and Garcia, 1995). In 1995, the network was expanded; the original 20 wells were sampled once in the summer of 1995, and an additional 32 wells were added to the network and sampled once (Rankin 1996). In 1997, the network was again expanded; 7 of the original 20 wells were sampled once; 5 of the additional 32 wells sampled in 1995 were sampled again, and an additional 23 wells were added to the network and sampled once, bringing the total number of wells to 75 that have been sampled at least once since 1995. During the period of operation of the network, water-level measurements could not be made in all wells when samples were collected. Forty-eight of the wells that were sampled have associated water-level data.

In selected areas of the northern part of the Escabosa and Sedillo quadrangles and the southern part of the Sandia Park quadrangle (fig. 6), the density of these wells is about 1 per square mile. In some areas, the density is greater than 1 per square mile. The observation-well network needs to be expanded in some parts of the study area. A density of one well per 2 to 4 square miles would be adequate for characterizing regional flow in the Madera Limestone, but would not provide the detailed information needed to examine local characteristics about a given supply well or well field. Presently, the wells in the water-quality-sampling and water-level data-collection network are privately owned domestic wells because dedicated observation wells are currently unavailable. The proposed expansion would include the addition of domestic wells, unused wells, piezometers, and boreholes.

Expanding the monitoring-well network is essential to collect water-quality samples from wells completed in the Madera Limestone, identify areas of changes in ground-water quality, and discern possible trends in water quality. Because of their large values of hydraulic conductivity, fractured carbonate aquifers such as the Madera Limestone are particularly susceptible to contamination. This was noted by Kues (1990, p. 50) who, referring to the Madera Limestone, stated "contaminants mixed with ground water * * * will move into and through the system rapidly. Wells commonly are located on or near faults, especially in areas where carbonate rock crops out."

Domestic Wells

Domestic wells are privately owned, cased wells used for domestic supply. Using domestic wells for the collection of water-quality samples can be problematic: obtaining permission is required and is sometimes difficult; water conditioners are often installed in the homeowner's water system, and care must be taken to obtain a sample prior to treatment. Many residents are unwilling or unable to disconnect these conditioners. The chemistry of water that is "softened" or otherwise treated does not accurately reflect the chemistry of water residing in the aquifer.

Using domestic wells for the collection of water-level data also is difficult; the homeowner may have recently pumped the well, and the resulting water level may be significantly lower than a water level measured under static, or nonpumping, conditions. Furthermore, domestic wells are sometimes not accessible.

Despite the drawbacks, using domestic wells has some advantages: domestic wells are available, widely distributed, and have no fee associated with their use. Domestic wells would, therefore, be included in expansion of the observation-well network, if they meet specified criteria for inclusion: location, depth, permission, accessibility, and well construction.

Unused Wells

Unused wells are existing cased wells not presently used for water supply. These wells may be owned privately or by other entities such as the State Highway and Transportation Department. Ownership would need to be determined and the necessary permission obtained for their use.

Unused wells would be inventoried and added to the network if they are found to be suitable for (1) measuring hydraulic heads at specific depths;

(2) aquifer testing; or (3) sampling ground water at discrete intervals and if they meet the same criteria as domestic wells for inclusion in the network. Unused wells would be used as dedicated monitoring sites--that is, sites used exclusively for monitoring purposes. These would be equipped with transducers and recording devices that measure hydraulic head continuously. These wells would be more easily accessible than domestic supply wells for water-level data collection and other data-collection activities, including aquifer tests.

Piezometers

A piezometer is a nonpumping well, generally of small diameter, that is used to measure the altitude of the water table or potentiometric surface. A piezometer generally has a short well-screen interval through which water can enter (Fetter, 1988). Piezometers would be installed where measurements of hydraulic head at different depths in the aquifer are needed and suitable existing wells are not available. Where possible, these piezometers would also be used for water sample collection.

Boreholes

Boreholes, or uncased wells, are needed for geophysical logging activities. Existing boreholes would be inventoried and added to the network if they are found to be suitable for these activities. Dedicated boreholes, used exclusively for geophysical data collection, would be drilled in selected locations and configured for maximum usefulness. The boreholes would be logged prior to casing. Boreholes are essential not only for geophysical logging activities, but also for packer, aquifer, and tracer testing. The NMOSE makes provisions for permitting this type of monitoring well (Charles Wohlenberg, New Mexico Office of the State Engineer, oral commun., 1998).

Quantify Recharge to the Madera Limestone

The volume of water that recharges the Madera Limestone is unknown. Estimates of the availability and sustainability of ground-water supplies in the Madera Limestone are dependent on reliable estimates of recharge. A number of data-collection activities would be undertaken that would help quantify recharge to the Madera Limestone. These activities include defining areas that contribute to recharge, quantifying recharge from surface water and precipitation, and quantifying recharge from imported water and septic-field effluent; they are discussed in the following sections.

Define Areas that Contribute Recharge

Areas of potential recharge need to be defined. The uncertainty in defining recharge areas increases with the complexity of the ground-water system; complex geometry of hydrogeologic units, aquifers with well-developed solution channels and fracturing, and areal recharge that varies considerably in space are some of the factors that contribute to that complexity. The USGS plays an active role in studies involving the identification of areas that contribute recharge to wells and provides analytical tools for such studies (Franke and others, 1998).

Quantify Recharge from Surface Water and Precipitation

A reliable estimate of the quantity of streamflow available for potential recharge to aquifers is important in hydrologic studies (Waltemeyer, 1994). Streamflow can be monitored with gaging stations where hydrologic data are systematically collected. This method requires installation and periodic maintenance of gaging stations; the data collected at the gages are supplemented with instantaneous streamflow measurements.

Mean annual streamflow, or average streamflow, can be estimated using methods reported by Waltemeyer (1994). In one method, estimates of average streamflow are obtained using basin and climatic characteristics. In a second method, estimates of average streamflow are obtained using channel-geometry measurements.

White (1994) described gain-and-loss measurements made in Tajique and Torreon Arroyos in Torrance County, in 1985 and 1987, respectively, to determine changes in streamflow. The measurements were made by locating the beginning of flow in each stream and making periodic measurements downstream until flow ceased. White stated that although "some of the streamflow * * * is lost to evapotranspiration, most of it likely recharges the aquifer."

There are many small arroyos and creeks throughout the east mountain area (fig. 1). Major drainages flowing across the outcrop of the Madera Limestone would be selected and streamflow monitored in one of the manners described above, so that water-loss zones could be identified and recharge to the Madera Limestone from streamflow could be estimated.

Precipitation is the primary source of recharge to the aquifers in the east mountain area. The National Oceanic and Atmospheric Administration maintains a climatological station at Sandia Park (fig. 1) where precipitation is monitored (National Oceanic and Atmospheric Administration, 1997). Precipitation data are also collected by many residents throughout the east mountains.

Rain gages would be installed at selected locations throughout the area to monitor rainfall and provide a better understanding of the spatial distribution of rainfall patterns. The water equivalent of snowfall would be calculated from measurements of snowpack in the Sandia and Manzano Mountains.

Because quantification of ground-water recharge requires both streamflow and precipitation data, a network of snow and rain gages is essential for delineating precipitation patterns within the study area. The correlation between the drainage pattern and the fracture pattern in the study area must be established; in some parts of the study area, drainage patterns are consistent with fracture patterns, as the upper reach of Cedro Canyon (fig. 5) illustrates. This correlation is important because it implies that flow in the alluvial deposits of canyon floors overlies major faults or fault zones and is more readily available as recharge. A stream channel above the water table loses a portion of its flow by infiltration through the channel bed (Titus, 1980). The portion of runoff lost to infiltration is pulled downward by gravity and eventually recharges ground water.

Quantify Recharge from Septic-Field Effluent and Imported Water

Septic-field effluent and imported water were discussed previously in the section "Hydrologic framework of the Madera Limestone." Although the volume of water that recharges the Madera Limestone from these sources is presumably small compared with recharge from surface water and precipitation, estimating recharge contributed by these two factors must be considered in estimating total recharge.

Quantify Discharge from the Madera Limestone

The volume of water discharged from the Madera Limestone is unknown; quantifying this discharge is essential. Estimates of the availability and sustainability of ground-water supplies in the Madera Limestone are dependent on reliable estimates of discharge. Activities that would help quantify discharge include quantifying withdrawal from domestic wells and public-supply systems, quantifying evapotranspiration (ET), and quantifying and sampling springflow. These activities are discussed in the following sections.

Quantify Withdrawal from Domestic Wells and Public-Supply Systems

Estimates of withdrawal and subsequent depletion from domestic wells and public-supply systems were presented in the section "Ground-water withdrawal and depletion." The volume of withdrawals from these sources represents the largest portion of ground water discharged from the Madera Limestone. Estimates of withdrawal need to be refined.

Quantify Evapotranspiration

Evapotranspiration (ET) is the loss of ground water from a land area through evaporation from soils and surface-water bodies and transpiration of plants (Bates and Jackson, 1980, p. 215). ET always represents a source of ground-water discharge; the quantity of discharge depends primarily on the amount and type of vegetation, temperature, humidity, soil type and moisture, and the depth to ground water.

ET may account for a significant portion of ground-water discharge from the Madera Limestone. Rainfall and soil moisture evaporate; ground water is removed through the roots of trees that are sufficiently developed to reach the saturated portion of the aquifer and through the roots of shrubs and plants within the unsaturated zone.

The USGS has developed a method to measure actual ET through the use of a portable field chamber (Stannard, 1998); the chamber has been used in the Albuquerque area (Thomas, 1995). The Penman equation (Ayra, 1988, p. 192-194) has been used to obtain estimates of potential ET from trees and large shrubs and plants.

Because the amount of ground water removed through ET is potentially large, it must be quantified. Otherwise, estimations of available ground-water supplies will be too great.

Quantify and Sample Springflow

Because springs represent points of discharge from an aquifer, conducting a comprehensive inventory of springs in the study area and monitoring yields and water quality from these springs are essential. The inventory of New Mexico springs by White and Kues (1992) contains information about the physical characteristics of springs, including yield measurements and estimates. According to the authors a few of these springs have associated chemical-quality data, including analyses of major ions and trace elements; none of the springs were tested for bacterial contamination. Titus (1980) presented similar data for selected springs in the east mountain area. Selected springs would be monitored for discharge and sampled for total coliform bacteria, a group of bacteria that are used as indicators of possible sewage contamination (Ortiz and Lange, 1996).

Define Hydraulic Properties of the Madera Limestone

This section begins with a discussion concerning the hydrogeologic boundaries of the Madera Limestone. It goes on to describe the need for determining the thickness and depth to the base of the Madera Limestone and the importance of aquifer testing.

Establish Hydrogeologic Boundaries

A hydrogeologic boundary is based on the physical attributes of an aquifer; the boundary can be a region of recharge where the aquifer is replenished (a recharge boundary) or the edge of the aquifer, where it terminates by either thinning or erosion (a barrier boundary) (Fetter, 1988). Establishing hydrogeologic boundaries of the study area is essential to define the scope of subsequent activities suggested in this plan of study.

Determine Thickness and Depth to the Base

Knowing the thickness and depth to the base of the Madera Limestone is essential because (1) hydraulic-conductivity values, when derived from transmissivity values, are based on calculations that require thickness; (2) the information is needed for subsequent modeling efforts; and (3) the information is needed for GIS applications, such as developing three-dimensional perspectives of the aquifer.

Conduct and Analyze Aquifer Tests

An aquifer test is a controlled field experiment made to determine the hydraulic properties of water-yielding and associated rocks (Stallman, 1971). These properties include storage coefficient, hydraulic conductivity, and transmissivity. Two types of aquifer tests are pumping and slug tests. A pumping test is made by pumping a well for a period of time and observing the change in hydraulic head in the aquifer; a slug test is made by instantaneously inducing a change in water level in the well, then observing the time taken for the water to recover to its original level.

Because of the extreme variability of fractures and hydraulic properties within a fractured limestone, attempting to quantify the regional hydraulic properties of the Madera Limestone with a few large-scale aquifer tests will not provide an adequate characterization of the entire aquifer. Numerous, evenly distributed tests and integration of the resulting data will provide a more accurate characterization of the whole aquifer.

Characterize Ground-Water Flow in the Madera Limestone

This section describes the essential activities needed to characterize ground-water flow in the Madera Limestone. These activities include characterization of the fracture system and the direction of ground-water flow, borehole and surface geophysical and tracer test analysis, ground-water aging, isotope sampling, and modeling.

Characterize the Fracture System

To characterize the fracture system in the Madera Limestone, three attributes of the fracture system need to be defined. These are fracture density, fracture orientation, and fracture aperture (collectively known as fracture geometry).

Fracture density is an important physical characteristic of fracturing because closely spaced fractures in fault zones increase permeability (Davis, 1984). Ground-water flow across distances greater than a few meters usually involves multiple fractures or fracture networks (Doe, 1997). Fracture density presumably is greatest where fault networks are present. Geologists at the NMBMMR have identified major fault networks in the study area through their mapping efforts. For example, Adam Read (written commun., 1998) mapped a significant fault network in Otero Canyon near Cedro (fig. 5). Fracture zones and fault networks have important hydrologic implications; aquifer properties within these areas will be significantly different from areas within the same aquifer where fracture density is not as great. These high-density areas would be identified as having potentially high permeability. Geologic maps, used in association with geophysical methods described in a later section, would be used to identify and locate areas with potentially higher permeability.

Fracture orientation is another important physical characteristic of fracturing. Fractures often display preferred orientations that will significantly affect the direction of ground-water flow, imparting an overall anisotropy or enhanced direction of flow (Doe, 1997). Orientation would be defined by the geophysical methods described in the "Conduct and analyze borehole and surface geophysics" section of this report.

Fracture aperture, the third important property of a fracture, refers to the size of the opening of the fracture. The flow capacity of a fracture varies exponentially: a small difference in the opening between fractures can result in very large differences in flow capacity (Doe, 1997). Aperture would be defined by the geophysical methods described in the "Conduct and analyze borehole and surface geophysics" section.

Determine the Direction of Ground-Water Flow

The direction of ground-water flow in the Madera Limestone must be determined for several reasons. Chemical and contaminant transport are dependent on the direction of ground-water flow. Availability of ground-water supplies is, to a large degree, based on the movement of ground water.

To better determine the direction of ground-water flow, more data are needed so that ground-water-level contours can be constructed. The proposed expansion of the observation-well network would provide the needed data, and the proposed tracer studies would help to further define the direction of ground-water movement.

Conduct and Analyze Borehole and Surface Geophysics

Throughout the east mountain area, water is withdrawn from bedrock formations, including the Madera Limestone, where faults, cracks, fissures, and joints (collectively referred to as fractures) and solution channels are the principal conduits of ground-water flow. Fractures and solution channels cannot be observed directly except in boreholes. Adam Read (written commun., 1998) suspects the existence of many unrecognized, and therefore unmapped, fracture zones within the Madera Limestone that could be "very important from a hydrological standpoint." Fractures expressed surficially may not be representative of fractures underground; furthermore, fracture characteristics may differ due to changes in lithology. A significant portion of the Madera Limestone is composed of shale and arkose. Comparing the fracture characteristics of these rock types and determining whether fractures in a limestone layer continue through adjacent shale and arkose layers would be useful because of the effect on ground-water movement (Paul Bauer, written commun., 1998).

Geophysical borehole techniques currently available include portable, personal computer-based geophysical loggers specifically designed for ground-water applications; television cameras used to view fractures directly that allow interactive determination of fracture and bedding orientation; acoustic televiewers that provide a magnetically oriented, 360-degree, photographlike image of the acoustic reflectivity of the borehole wall that allows interactive determination of fracture and bedding orientation (Williams and Lane, 1998); and the colloidal borescope, which provides direct measurements of flow velocity and direction from wells completed in fractures (Jeffrey Peterson, Bernalillo County Environmental Health Department, written commun., 1998). Bedrock exposed on borehole walls, however, represents only a small portion of the total volume of fractured rock; thus, geophysical methods that image fractures away from boreholes are being developed and tested. One of these methods, known as tomography, or borehole radar, uses seismic or radar signals transmitted from one borehole and received and monitored in an adjacent borehole (Shapiro and others, 1995). These methods are useful for describing the physical attributes of fractures--density, orientation, and aperture. Hydraulic characteristics of fractures also can be tested using the heat pulse flowmeter and the electromagnetic flowmeter. By using data collected by these instruments, vertical components and directions of hydraulic-head gradient can be defined; under pumping conditions, the flowmeter measurements can locate specific conducting features and define their hydraulic properties (Doe, 1997). Standard borehole geophysics used to develop fracture and lithologic information include gamma, fluid-conductance, temperature, and caliper logs (A.M. Shapiro, written commun., 1998).

Borehole testing often involves the use of packers. A packer consists of an inflatable bladder that is deployed downhole and inflated to form a seal. A packer system enables the hydrologist to isolate a portion of the borehole or well for sampling, evaluate the effects of fractures, and test aquifer properties. Packer testing can be performed in boreholes or wells using a packer string, in a straddle configuration (fig. 14), or multiple strings (Patrick Mills and James Rauman, U.S. Geological Survey, and Douglas Yeskis, U.S. Environmental Protection Agency, written commun., 1998).

Surface geophysical methods that use radar, seismic, and electrical signals generated at land surface to identify major water-yielding features, such as fault zones that may extend over thousands of feet, are being developed and tested at the USGS Mirror Lake Fractured-Rock Research Site in New Hampshire. In addition, surface geophysical methods are being developed to identify the principal orientation of smaller, more numerous fractures (Shapiro and others, 1995).

Conduct and Analyze Tracer Tests

Tracer tests are used to determine a variety of hydrologic processes. For example, the most direct method for determining ground-water velocity consists of introducing a tracer at one point in the flow field and observing its arrival time at other points. A method for determining velocity at a single well is the borehole dilution test, conducted by placing a known initial concentration of a tracer in a borehole and monitoring that tracer's concentration over time. The change in the tracer concentration is then related to the velocity of the formation using a simple mixing model (Freeze and Cherry, 1979). In fractured rock aquifers, it is necessary to isolate a short section of the open borehole using packers (A.M. Shapiro, written commun., 1998). Different types of tracers have been used, including table salt and baker's yeast, and present a negligible health hazard (Davis and others, 1980). Fluorescent dyes, freon, chlorofluorocarbons (CFC's), and radioisotopes, such as tritium (^3H), have been used as well (Freeze and Cherry, 1979). A tracer test using ^3H was designed to provide information on the nature of flow through fractures in a known fracture zone at the Savannah River Plant in South Carolina (Webster and others, 1970). Tracer tests, conducted under controlled hydraulic conditions, would be performed in the study area to determine time of travel, dispersion effects, and ground-water flow direction.

Determine the Age of Ground Water

In studies of ground-water quality, it is of considerable value to supplement water-quality data with ground-water age dating, which is useful in defining direction and velocity of ground-water flow as well as defining areas of recharge and discharge. The age of the water refers to the time that has passed since the water recharged the aquifer. Water recharged within the last 50 years ("young" ground water) is dated using two classes of environmental tracers: (1) those that indicate a particular event, such as tritium, which was used to mark atmospheric nuclear testing in the 1950's and early 1960's and (2) those present globally as a result of continuous, known atmospheric inputs over a period of time, such as CFC's (Plummer and others, 1993).

Busenberg and Plummer (1992) described a new method developed for sampling ground waters for trace concentrations of CFC's that has been successfully used in the Albuquerque Basin. Advantages of this method include reduced costs for sample collection and analysis, elimination of transporting sensitive equipment into the field for on-site determinations, and the longevity of samples, which can be stored for many months. In addition to CFC sampling and analysis, other constituents were sampled and analyzed to age date waters older than 50 years; carbon-14 (^{14}C), for example, can be used to date water between 2,000 and 35,000 years old. However, ^{14}C can be used to age date water only if the major ions ^3H and carbon-13 (^{13}C) also are analyzed (Laura Bexfield, U.S. Geological Survey, oral commun., 1998).

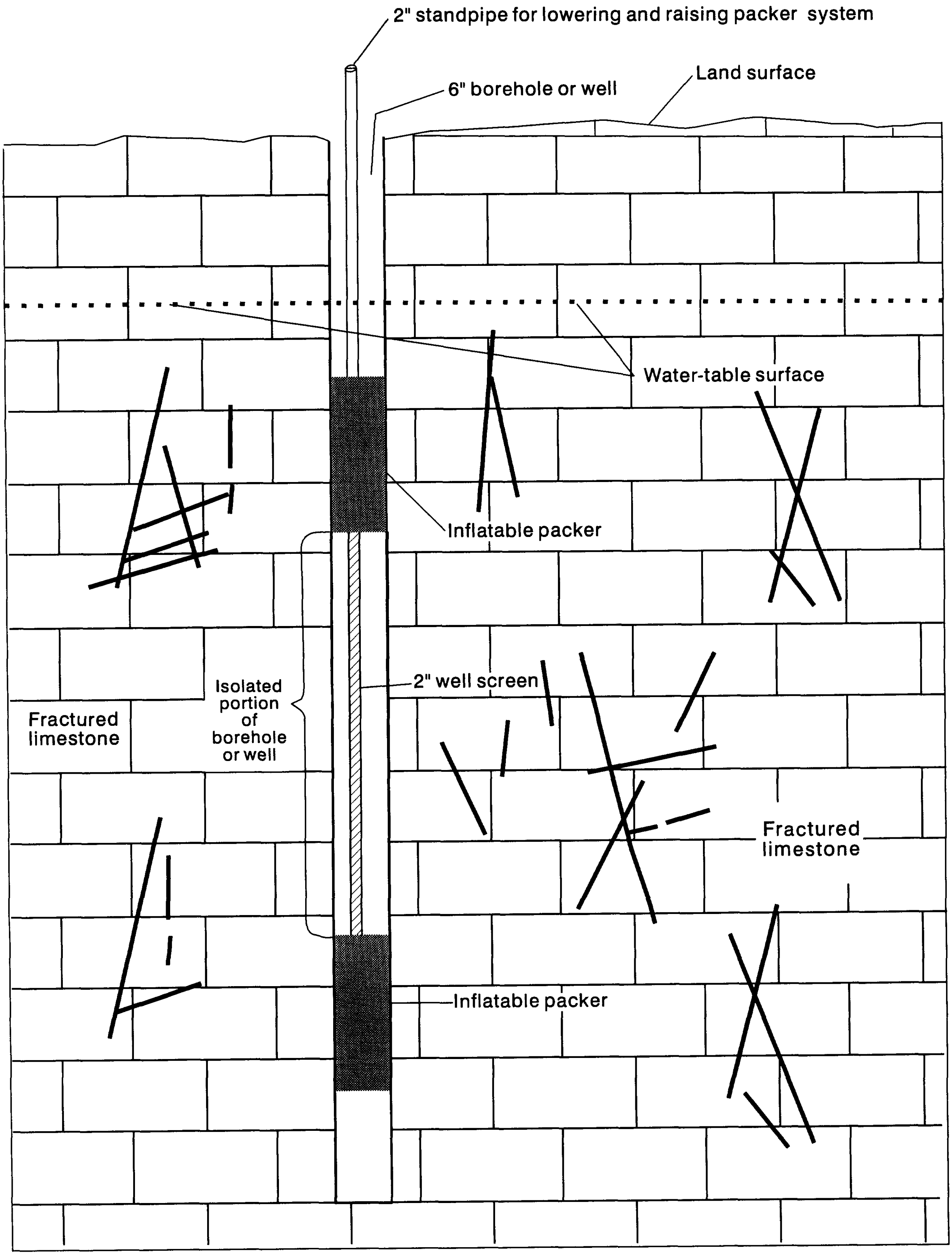


Figure 14.--Straddle packer configuration.

Conduct Isotope Sampling for All Components of the Hydrologic Cycle

In fractured systems, stable isotopes can be used to determine (1) the origin of the water by using the decrease in oxygen-18 (^{18}O) and deuterium (^{2}H) with increasing altitude; (2) the degree of mixing within a fractured system by looking at spatial and temporal variation in ^{2}H, ^{18}O, and ^{3}H; (3) the flow rate and residence time in small watersheds by using the seasonal variation in ^{18}O and ^{2}H content; and (4) the average age and type of flow using ^{3}H concentrations (Coplen, 1993). Stable isotope sampling in ground water, surface water, and precipitation would be an essential study element. Isotopic values of evaporated water, for example, can be used in recharge studies to discriminate between summer and winter precipitation (Coplen, 1993).

Develop a Regional Ground-Water-Flow Model

Ground-water-flow models are used to simulate a flow system. Past, present, or future conditions can be simulated. Physical and hydraulic parameters are used to first develop a conceptual model of the system; the conceptual model is then translated into a mathematical model. Regional-scale ground-water modeling will be needed at some point in the east mountain area to characterize regional-scale properties. The data-collection activities and studies described in this report would provide the information needed to develop a model of ground-water flow.

Useful Information and Activities

Information that could provide additional understanding of the hydrogeologic system in the east mountain area but would not be essential to improve the understanding of ground-water flow or hydraulic properties of the Madera Limestone is prioritized as useful. Useful information and activities include the following:

Conduct Remote Sensing

Because of the importance of faults in understanding ground-water flow and well yield, additional mapping may be necessary to characterize faults in the east mountain area. The mapping conducted by NMBMMR personnel may be sufficient; however, conducting and interpreting aerial photography and satellite imagery to fully characterize the fracture system would be useful.

Develop a Water Budget by Aquifer

A detailed hydrologic budget has not been published for aquifers in the east mountain area. A hydrologic budget, or water budget, represents an evaluation of all sources of supply to and corresponding discharges from an aquifer (Fetter, 1988). The basic principle of a water budget is that the difference between inflow and outflow is equal to the change in aquifer storage. A water budget would consider inflow (recharge) from ground water, surface water, precipitation, septic-field effluent and imported water, and outflow (discharge) from well withdrawals, evapotranspiration, ground water, springs, and surface water (fig. 15).

The quantities of inflow and outflow needed for a hydrologic budget for aquifers in the east mountain area are as yet undefined. Results from the studies and activities described in this report could be used to develop a budget for the Madera Limestone and other aquifers. Should an attempt be made to balance the additions to and depletions from the water supply of the area, however, the results would only be as accurate as the measurements or estimations of the inflows and outflows.

Consolidate Geographic Information System Data

A GIS is an organized collection of computer hardware, software, and geographic data designed to efficiently store, update, manipulate, analyze, and display all forms of geographically referenced information. A GIS is used to link spatial data with geographic information concerning a particular feature on a map (Environmental Systems Research Institute, Inc., 1992).

The USGS has data that are used to describe various geographic, hydrologic, geologic, biologic, and demographic features within the study area (J.M. Kernodle, U.S. Geological Survey, oral commun., 1998). Bernalillo County has collected similar information; consolidating the USGS GIS data with the Bernalillo County GIS data would be useful. The combination of the individual data sets would provide additional information than the individual data sets.

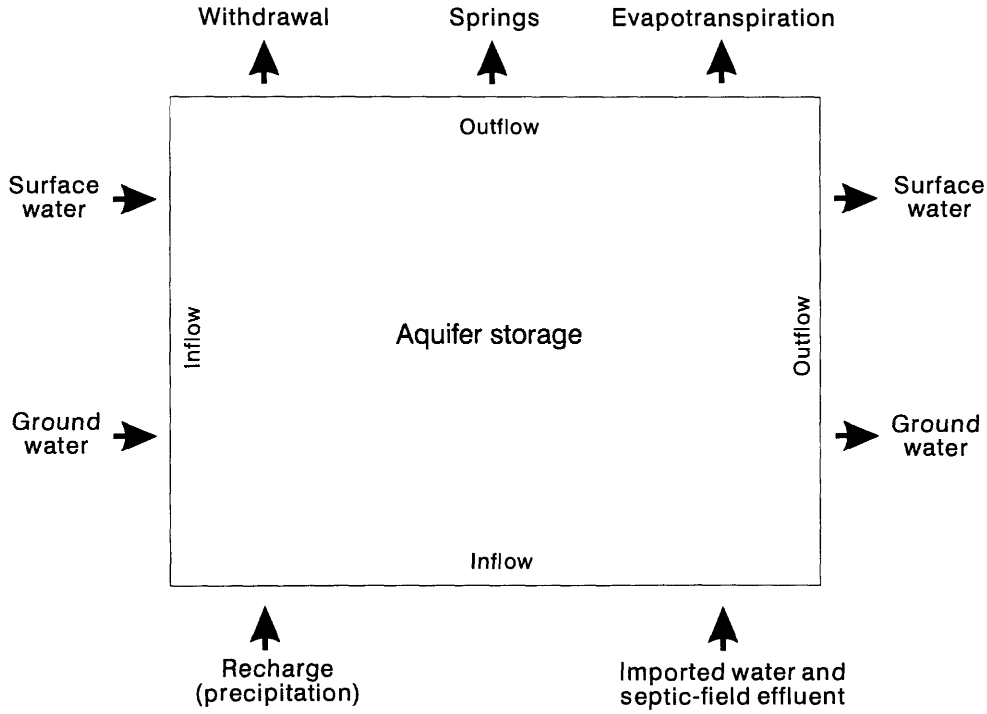


Figure 15.--Components of a water budget (modified from Thorn and others, 1993).

Improve Drilling Records

A drilling record or well record (fig. 16), completed by the driller, provides information concerning the location, construction, lithology, depth, and yield of a well. The record is then filed with the NMOSE.

The information contained in a drilling record can be used for a variety of purposes. For example, location information can be used to plot well sites in a GIS, lithologic descriptions can be used to refine stratigraphic relations, depth information can be used to identify aquifers, and yield information can be used to help determine the suitability of various sites for development. The reliability of these subsequent activities depends on the completeness and accuracy of the information gathered by the driller.

Suggestions to improve drilling record data include the use of global positioning system (GPS) units to determine the well location in terms of latitude and longitude in addition to the legal description of the property that is presently required. A diagram of the finished well, including construction and completion data, would enhance the written description provided by the driller. Determination of actual rather than estimated yields would better characterize the availability of ground water in an area.

Typically, a drilling record represents all that is known about a well. A complete drilling record that includes geographical coordinates, a sketch showing well construction, and reliable yield information would benefit residents, developers, and local officials who make decisions based on the driller's information.

Use U.S. Geological Survey Data Bases for Storage and Retrieval of Information

The USGS National Water Information System (NWIS) provides a convenient method for the storage and retrieval of information. Components of the NWIS include (1) the Water-Quality System, commonly referred to as QWDATA, a water-quality data storage and retrieval system (Maddy and others, 1989); (2) the Ground-Water Site-Inventory (GWSI) System, a ground-water-site data storage and retrieval system (Mathey, 1989); and (3) the Automated Data Processing System (ADAPS), developed for the processing, storage, and retrieval of water data (Dempster, 1990). These data bases, developed by the USGS, provide for entry of new sites and updates of existing sites within the local system. Placing the additional information gained through studies and activities described in this report in QWDATA, GWSI, or ADAPS would be useful.

STATE ENGINEER OFFICE

WELL RECORD

Section 1. GENERAL INFORMATION

(A) Owner of well____Owner's Well No.______________
Street or Post Office Address____
City and State____

Well was drilled under Permit No.______________________and is located in the:

a. ______1/4______1/4______1/4______1/4 of Section______Township______Range______N.M.P.M.

b. Tract No.___________of Map No.___________of the________________________________

c. Lot No.__________of Block No.________________of the______________________________
Subdivision, recorded in__________________________County

d. X =___________feet, Y=___________feet, N.M. Coordinate System__________________Zone in the____Grant.

(B) Drilling Contractor______________________________________License No.________________

Address____

Drilling Began________________Completed_______________Type tools__________Size of hole________in.

Elevation of land surface or______________________at well is_________ft. Total depth of well___________ft.

Completed well is shallow artesian. Depth to water upon completion of well___________ft.

Section 2. PRINCIPAL WATER-BEARING STRATA

Depth in feet		Thickness in feet	Description of water-bearing formation	Estimated yield (gallons per minute)
From	To			

Section 3. RECORD OF CASING

Diameter (inches)	Pounds per foot	Threads per in.	Depth in feet		Length (feet)	Type of shoe	From	To
			Top	Bottom				

Section 4. RECORD OF MUDDING AND CEMENTING

Depth in feet		Hole diameter	Sacks of mud	Cubic feet of cement	Method of placement
From	To				

Figure 16.--Well record form used by the Office of the State Engineer.

Section 5. PLUGGING RECORD

Plugging contractor____________________
Address____________________
Plugging method____________________
Date well plugged____________________
Plugging approved by____________________
State Engineer Representative

No.	Depth in feet		Cubic feet of cement
	Top	Bottom	
1			
2			
2			
4			

FOR USE OF STATE ENGINEER ONLY

Date Received

Quad__________FWL__________FSL__________

File No.____________________Use__________Location No.__________

Section 6. LOG OF HOLE

Depth in feet		Thickness in feet	Color and type of material encountered
From	To		

Section 7. REMARKS AND ADDITIONAL INFORMATION

The undersigned herby certifies that, to the best of his knowledge and belief, the foregoing is a true and correct record of the above described hole.

____
Driller

INSTRUCTIONS: This form should be executed in triplicate, preferably typewritten, and submitted to the appropriate district office of the State Engineer. All sections, except Section 5, shall be answered as completely and accurately as possible when any well is drilled, repaired, or deepened. Then this form is used as a plugging record, only Section 1(a) and Section 5 need be completed.

Figure 16b.--Well record form used by the Office of the State Engineer--Concluded.

Update "Ground Water in the Sandia and Northern Manzano Mountains, New Mexico" (Titus, 1980)

Frank Titus (oral commun., 1997) has suggested updating his 1980 report "Ground water in the Sandia and northern Manzano Mountains, New Mexico," a NMBMMR publication. Although most of the information contained in the report is useful today, the potentiometric surface Titus described (1980, fig. 4), which was based on water-level data collected in 1962-63, needs to be updated and the ground-water flow lines at the potentiometric surface need to be adjusted.

Involve Neighborhood Associations and Residents with Data Collection

The quantity and quality of water supplies in the east mountain area are issues of great interest and concern among residents. Ground water is commonly stored in large plastic or metal tanks; elaborate systems for the collection and storage of precipitation, used to supplement ground-water supplies, are not uncommon. Some residents measure ground-water levels in their well and gage rainfall on a regular basis. Involving neighborhood associations with certain types of data collection could be useful. Properly trained and equipped, residents could collect water-level and precipitation data. These data would be tagged for inclusion in the appropriate data base.

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SUPPLEMENTAL INFORMATION

Activities and information needed to define the hydrogeologic characteristics of the Madera Limestone in the east mountain area.

Modified from minutes of the meeting held in Albuquerque, New Mexico, December 2-3, 1997

Needs and Concerns

Water Budget

1. Watershed modeling.
2. Basic data collection.
3. Geohydrologic modeling.
4. Isotope studies relating to ground-water chemistry.
5. Spring inventory with discharge and water-quality information.
6. Flow and water quality of streams.
7. Quantification of recharge.
8. Determination of septic-system return flow.
9. Determination of domestic pumpage.
10. Quantification of imported water.
11. Water-level monitoring.
12. Determination of sources and sinks.
13. Ground-water flow.
14. Contamination transport.
15. Evaluation of water budgets according to geologic units.
16. Isotope analysis for all parts of the hydrologic cycle.
17. Chlorofluorocarbon (CFC) sampling.
18. Precipitation data (rainfall, snowfall, weather observers, radar).
19. Development of a small test area.
20. Definition of geohydrologic processes.

GIS Coverages / Applications

1. Faults.
2. Surficial geology.
3. Wells (including location and completion data).
4. Septic tanks (including location and density data).
5. Roads.
6. Residential developments.
7. Aquifer/pump tests.
8. Water-quality analysis.
9. Land use.
10. Soil types.
11. Topography.
12. Drainages/streams.
13. Land cover.
14. Compilation of reasonable coverages.

Data Consolidation

1. Well locations.
2. Water-level data.
3. Water-quality data.
4. Hydraulic property data.
5. Geohydrologic data.

Geology / Matrix / Framework

1. Determination of the depth of the base of the Madera Limestone.
2. Determination of the thickness of the Madera Limestone.
3. Development of site-selection criteria for dedicated monitoring wells and nested piezometers.
4. Installation of dedicated monitoring wells and nested piezometers.
5. Better geologic records on drilling.
6. Detailed geologic mapping for small-scale hydrologic studies.
7. Identification of major fractures.
8. Determination of fracture density.
9. Development of geologic cross sections.
10. Geologic mapping by NMBMMR.
11. Geophysical borehole logging.
12. Surface geophysics.

Recharge / Discharge

1. Determination of spatial and temporal distribution of rainfall.
2. Determination of spatial and temporal distribution of snowfall.
3. Determination of septic-system return flow.
4. Determination of return flow from imported water.
5. Measurement of discharge in drainages.
6. Determination of evaporation and ET.
7. Inventory of springs.
8. Measurement of discharge from springs.
9. Determination of domestic pumpage.

Water Levels

1. Water-level monitoring in domestic wells.
2. Water-level monitoring in University of New Mexico/BCEHD piezometers.
3. Water-level monitoring in unused wells.
4. Water-level monitoring in additional dedicated wells.

Water Quality

1. Determination/modification of criteria for selection of sampling sites.
2. Water-quality sampling from drainages.
3. Water-quality sampling from springs.
4. Water-quality sampling from domestic wells.
5. CFC/isotope sampling from selected wells.
6. Water-quality sampling in areas unaffected by domestic sewage.
7. Water-quality sampling from University of New Mexico/BCEHD piezometers.
8. Development of a three-dimensional perspective of nitrate contamination and migration.
9. Isotope analysis for all parts of the hydrologic cycle.
10. Compilation and evaluation of existing water-quality data.

Aquifer Parameters and Characteristics

1. Determination of permeability distribution (including fractures and solution channels).
2. Tracer tests to determine fracturing.
3. Installation of dedicated monitoring wells for aquifer testing.
4. Determination of storage coefficient.
5. Investigation of the hydraulic significance of fault zones.
6. Evaluation of aquifer-test analysis methods in different geologic units.
7. Pump tests.
8. Slug tests as initial aquifer tests (prior to aquifer testing).
9. Evaluation of specific-capacity data for initial T values, then determination of spatial distribution.
10. Aquifer characterization.

Miscellaneous

1. Early modeling.
2. Possible development and management of data bases.
3. Update of 1980 Titus report ("Ground water in the Sandia and northern Manzano Mountains, New Mexico").
4. Satellite imagery and (declassified) intelligence products.
5. Adjustment of boundaries of study area.
6. Incorporation/use of NMOSE model.
7. Suggested NMBMMR mapping priorities.
8. Involvement of neighborhood associations with data collection (water levels, well locations, and septic systems).

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