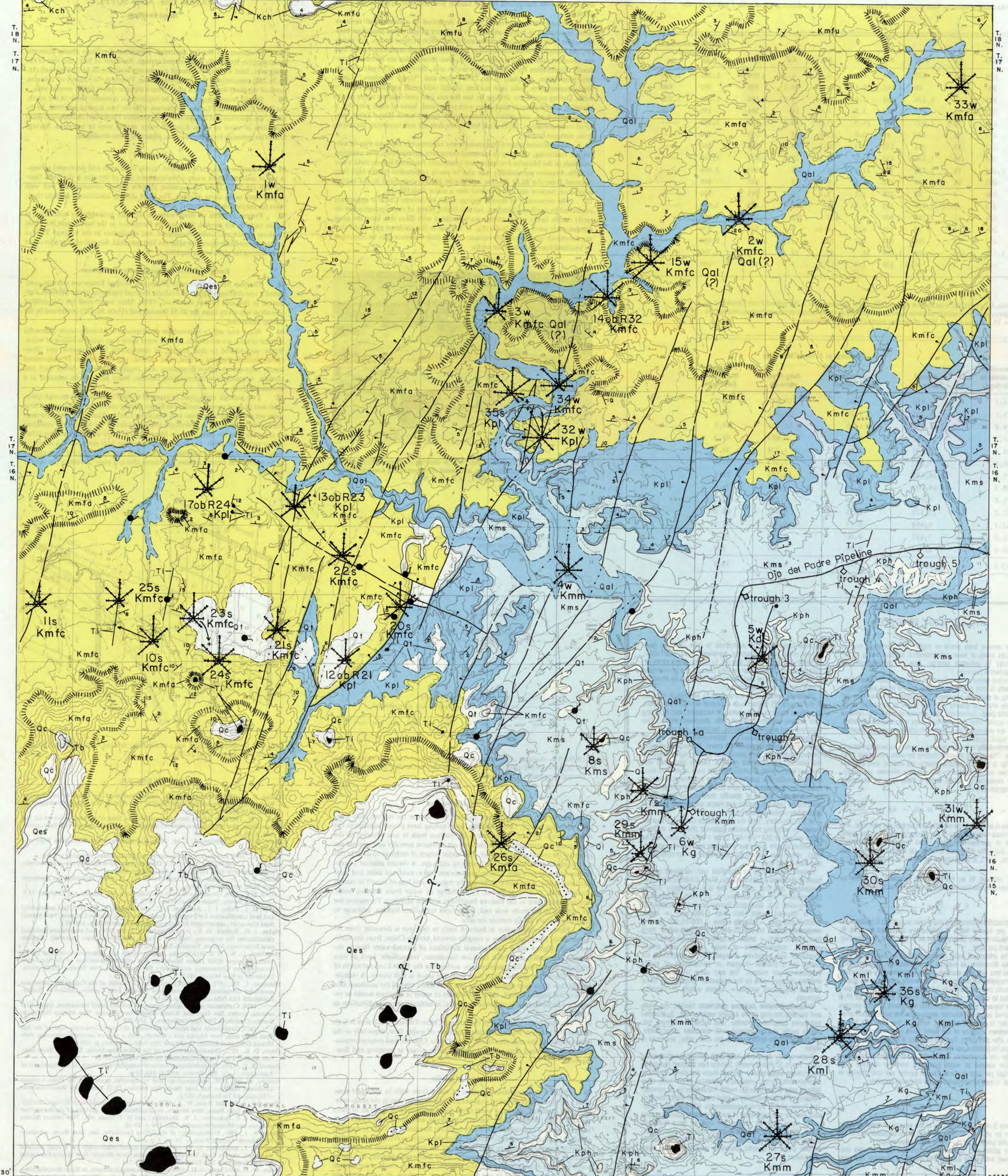
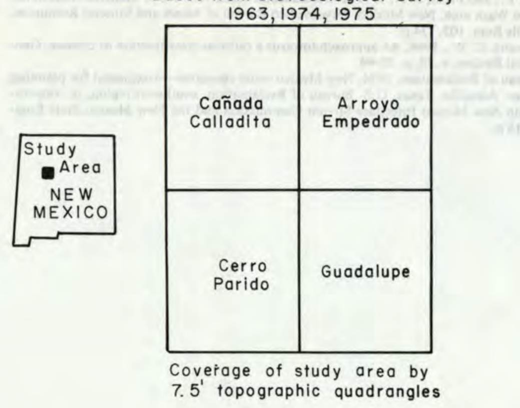


Cartography by Russell Wood

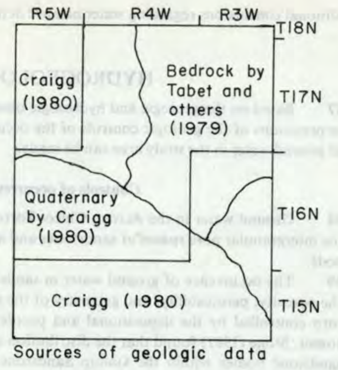
Bases from U.S. Geological Survey 1963, 1974, 1975



Coverage of study area by 7.5' topographic quadrangles

FIGURE 1—HYDROGEOLOGIC MAP OF ARROYO CHICO–TORREON WASH AREA

SCALE 1:62,500



Sources of geologic data

Approximate Mean Declination 1980

Geologic units

Quaternary

Qal — **alluvium***

Qes — **eolian sand:** light-brown, fine- to medium-grained; 0–3(?) ft thick

Qc — **colluvium:** poorly sorted deposits of locally derived basalt, sandstone, shale, and sand on slopes; may include small outcrops of Menefee Formation; 0–3(?) ft thick

Qt — **terrace deposits:** poorly sorted deposits of basalt and sandstone fragments, quartzite pebbles, and silty sand on gently sloping surfaces; 0–3(?) ft thick

Tertiary

Tb — **basalt:** thick sequence of flows capping Mesa Chivato; maximum aggregate thickness approximately 200 ft

Ti — **intrusions:** volcanic necks and dikes of basaltic composition

— **dikes**

Cretaceous

Kch — **Cliffhouse Sandstone:** light-brown, planar-bedded, massive, or cross-bedded, fine- to medium-grained sandstone of marine-shorezone origin; maximum thickness approximately 180 ft

Kmfu — **"Upper Member," Menefee Formation** *

Kmfa — **Allison Member, Menefee Formation** *

Kmfc — **Cleary Coal Member, Menefee Formation** *

Kpl — **Point Lookout Sandstone, main body***

Kms — **Satan Tongue, Mancos Shale***

Kph — **Hosta Tongue, Point Lookout Sandstone:** yellowish-gray, planar-bedded, massive, or cross-bedded, fine-grained sandstone of marine-shorezone origin; approximately 200 ft thick

Kmm — **Mulatto Tongue, Mancos Shale***

Kg — **Gallup Sandstone***

Kml — **Mancos Shale, lower part***

*See text for description of these units

Water-yielding characteristics

Aquifer

Locally an aquifer

Aquitard

Poorly known or above regional water table

Symbols

Water well, not sampled

Water well, sampled

Spring, not sampled

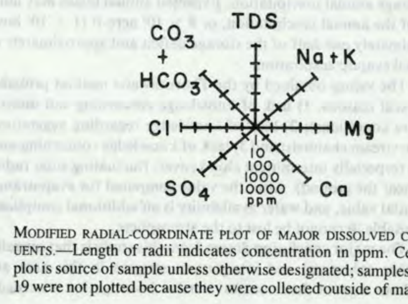
Spring, sampled

35s Kpl

35 = Sample number (tables 2, 3, 4, and 5); w indicates well, s indicates spring, ob indicates observation well; Kpl = aquifer

Gradational geologic contact

Ground-water chemistry



MODIFIED RADIAL COORDINATE PLOT OF MAJOR DISSOLVED CONSTITUENTS.—Length of radii indicates concentration in ppm. Center of plot is source of sample unless otherwise designated; samples 18 and 19 were not plotted because they were collected outside of map area.

Abstract

The Arroyo Chico–Torreon Wash area is located approximately 50 mi (80 km) northwest of Albuquerque in the southeast part of the San Juan Basin, a structural depression (Laramide) covering northwest New Mexico. The area is sparsely populated and used mainly for grazing; however, sizable reserves of coal occur in the area. Because the climate is semiarid and local streams are ephemeral or intermittent, ground water is the main source of water. Principal aquifers include alluvium of Quaternary age and the Menefee Formation, the Point Lookout Sandstone, sandstones in the Mancos Shale, the Gallup Sandstone, and the Dakota Sandstone, all of Cretaceous age. Occurrence of ground water is controlled mainly by the porosity, permeability, and geometry of the sandstone aquifers. These factors are in turn controlled by the continental and marine-shorezone origins of the sandstones. Aquifers are recharged mainly by transmission loss from streams crossing outcrops. Although only 1.9 percent of the average annual precipitation is represented by the average annual discharge, the portion of this water loss that becomes recharge is unknown but probably is small. Ground water flows generally toward Arroyo Chico from both the north and south. This movement is controlled partly by topography and partly by geologic structure. Yields of wells and springs are generally low: 1.0 gpm (0.064 L/s) or less. One exception is a flowing well completed in the Gallup Sandstone. This well originally flowed at 400 gpm (26 L/s); flow is now controlled at approximately half this rate. Quality of water from the alluvium is poor; quality of water from bedrock aquifers is best south of Arroyo Chico (328–4,770 ppm) and deteriorates northward (750–10,272 ppm). The major controls of quality are residence time and the abundance of shale in the stratigraphic column. Future supplies of water for domestic, livestock, and energy-resource development should be available from the Cretaceous sandstone aquifers, but the potential of the Westwater Canyon Member of the underlying Morrison Formation (Jurassic) should also be tested.

PREFACE

1 The specific objectives of this New Mexico Bureau of Mines and Mineral Resources series are to provide a single outlet for water-resource studies of small areas, to present results in a condensed and convenient style with emphasis on illustrations, and to make basic water-resource information for small areas available at less cost than is possible for the Bureau's Hydrologic Reports. On these sheets, paragraphs are numbered to facilitate citation.

2 Technical terms used are explained in the section on hydrogeologic principles (found on the back of this sheet). Most quantitative information is given in English units, followed by metric units in parentheses. Chemical concentrations are given only in English units (ppm—parts per million). For concentrations less than 7,000 ppm, metric and English values are about the same. Estimated or generalized values are rounded to the nearest hundred units; metric equivalents for such values are rounded to the nearest five units. Where the English values are small or obviously precise, metric equivalents are similarly precise. Metric equivalents were calculated by multiplying English units by conversion factors as follows:

English unit ×	Conversion factor =	Metric unit
acres (not abbreviated)	0.4047	hectares (ha)
acre-feet (acre-ft)	0.0012335	cubic hectometers (hm^3)
feet (ft)	0.3048	meters (m)
square feet per day (ft^2/d)	0.0929	square meters per day (m^2/d)
gallons (gal)	0.00379	cubic meters (m^3)
gallons per minute (gpm)	5.45	cubic meters per day (m^3/d)
gallons per minute (gpm)	0.0639	liters per second (L/s)
gallons per day (gpd)	0.003785	cubic meters per day (m^3/d)
inches (not abbreviated)	25.4	millimeters (mm)
miles (mi)	1.6093	kilometers (km)
million gallons per day (mgd)	0.044	cubic meters per second (m^3/s)
square miles (mi^2)	2.59	square kilometers (km^2)

An additional conversion used is 1 darcy equals 1.06×10^{-11} ft^2 or 9.87×10^{-9} cm^2.

3 All wells, springs, and samples are identified in the tables by two numbers. The first is a field accession number. The other system of numbering is that used by the New Mexico State Engineer and is based on the township, range, and section land grid. In this system, each well or spring has a unique location number consisting of four parts separated by periods as shown in fig. 14 (on back). If the location of a well or spring cannot be determined to quarter-quarter or quarter-quarter-quarter section, a zero is used in the appropriate position in the number. Because all townships are N. and all ranges are W., compass directions are omitted in location numbers.

INTRODUCTION

4 The Arroyo Chico–Torreon Wash area is located approximately 50 mi (80 km) northwest of Albuquerque and 25 mi (40 km) south of Cuba. This area, the size of a 15-minute quadrangle, straddles the McKinley–Sandoval County line (fig. 1). Approximately 5% of the land is federally owned and controlled by the U.S. Bureau of Land Management (BLM). The remainder of the land is either state, Indian, or privately owned.

5 The study area is sparsely populated, and land use is dominated by the grazing of beef cattle on lands leased from the BLM. Sheep and goats are tended by Navajos in the north. In the southwest, on Mesa Chivato, the BLM supervises a firewood-cutting area. The only agriculture at present is at Guadalupe in the south, where the sole resident maintains a garden irrigated by a developed spring, and in the north, where Navajos tend small gardens near their hogans. Sizable reserves of coal occur at strippable and greater depths in the study area (Tabet and Frost, 1979).

6 Like most of the semiarid northwest part of the state, the Arroyo Chico–Torreon Wash area lacks adequate supplies of surface water and thus relies upon ground water. In order to evaluate the availability of water for and potential impact of energy-development activities in northwest New Mexico, the New Mexico Bureau of Mines and Mineral Resources, the U.S. Geological Survey, and the Office of the State Engineer (now Water Resources Division) undertook a cooperative study of the hydrogeology and water resources of the San Juan Basin. Although the study was necessarily regional in scope, some appreciation of local water-resource conditions was provided by detailed studies of selected smaller areas. The Arroyo Chico–Torreon Wash area was selected to provide details concerning the hydrogeology of an area of potential coal extraction and a regional discharge area in the southeast part of the San Juan Basin. This area was especially appropriate for study because the Bureau was simultaneously conducting a coal-drilling program here, and selected exploration holes could be converted to ground-water observation wells (Stone and Craigg, 1979). The purposes of this report are: 1) to characterize the water-resource situation in a typical coal-resource area in the San Juan Basin and 2) to summarize the hydrogeology and ground-water potential of a presumed discharge area.

7 ACKNOWLEDGMENTS—We wish to thank David Tabet, formerly coal geologist with the Bureau (now with ARCO, Denver), for assistance in the completion of the observation wells and for use of geologic data from the Bureau's coal-drilling program. Chemical analyses of water samples were made under the supervision of Lynn Brandvold, Bureau chemist. Kim Ong, chemist, U.S. Geological Survey, Albuquerque, provided well-swabbing equipment and useful discussions of well-completion techniques. Scott Anderholm, formerly graduate student at New Mexico Tech (now hydrologist, U.S. Geological Survey, Albuquerque) assisted with measurement of stratigraphic sections as well as cleaning and testing of observation wells.

FIGURE 2—TERTIARY VOLCANIC NECK (CERRO DE GUADALUPE) intruded through Upper Cretaceous strata (Mulatto Tongue of Mancos Shale); abandoned windmill along Abra de los Cerros (view to southwest from NW¼ sec. 35, T. 16 N., R. 3 W.).

REGIONAL SETTING

8 Topography in the northern and southeast parts of the area is generally characterized by mesas and buttes formed of soft shale capped by erosion- resistant sandstone. Badlands topography is characteristic of areas where soft, easily erodable mudstones (used here as a general term for fine-grained sedimentary rocks) of the Menefee Formation lie at the surface. Topography in the southeast quadrant is dominated by Tertiary volcanic necks that have intruded the nearly horizontal Cretaceous strata (fig. 2). The tops of these necks commonly stand 600–1,000 ft (180–300 m) above the eroded lowlands. The southwest part of the study area is dominated by an extensive upland known as Mesa Chivato. This feature is capped by a thick sequence of lava flows. Mesa Chivato stands 1,800–2,000 ft (500–600 m) above the surrounding lowlands.

9 Most of the area is drained by Arroyo Chico. Drainage is southeasterly toward the Rio Puerco, the master stream for this area. Torreon Wash drains the northern part and enters Arroyo Chico near the center of the area. Streams are ephemeral, except locally, where spring discharge results in intermittent flow. Arroyos are deeply entrenched into alluvium and shale; erosion is presently being accomplished by bank caving.

10 The climate is arid to semiarid with an average annual precipitation of 10–12 inches (250–300 mm; U.S. Bureau of Reclamation, 1976). As much as 75% of the annual precipitation may occur during the summer rainy season (July through September). This period is characterized by intense, afternoon thunderstorms that generate large volumes of runoff. Potential gross annual lake evaporation is large, amounting to 50 inches (1,270 mm), or nearly five times the average annual precipitation (U.S. Bureau of Reclamation, 1976).

11 Five soil associations have been recognized in the area (Maker and others, 1971, 1974): the Christianberg–Navajo, Basalt–Rockland–Cabezon–Torreon, Persayo–Billings–Badlands, Las Lucas–Litle–Persayo, and Travesilla–Persayo–Rockland associations. Use as irrigated cropland is limited in all these soils for several reasons, including gullying, bank slumping, high stone content, shallow soil depth, low water-holding capacity, and the small sizes and irregular shapes of the areas of occurrence.

12 The study area lies in the southeast part of the San Juan Basin, a northwest-trending, asymmetrical, Laramide depression. Structural relief is approximately 6,000 ft (1,800 m). Strata have steeper dips near the uplifts forming the eastern margin of the basin. A thick sequence of sedimentary deposits, ranging in age mainly from Pennsylvanian through Quaternary, occurs in the basin. Maximum thickness of these deposits exceeds 14,000 ft (4,270 m) in the central part of the basin near Gobernador.

13 The general structural framework of the Arroyo Chico–Torreon Wash area is dominated by a gently northwest-dipping block. Regional strike of the rocks is northeast; dips vary from 0° to 10° northwest. The area lies along the western edge of the Rio Puerco fault zone, and the strata are offset by a series of northeast-trending, high-angle, normal faults, usually downdropped on the west (fig. 1). Maximum displacements along these faults rarely exceed 50 ft (150 m). Several basaltic dikes are associated with the dominant northeast-trending fracture set.

14 Strata in the area consist mostly of Upper Cretaceous marine and nonmarine deposits (figs. 1 and 3). Molenaar (1977) summarized the depositional history of many of these deposits in the San Juan Basin. In ascending order, these strata include the lower Mancos Shale, consisting of offshore marine deposits; the Gallup Sandstone, a regressive beach deposit; the Mulatto Tongue of the Mancos, an offshore marine deposit; the Hosta Tongue of the Point Lookout Sandstone, a transgressive beach deposit; the Satan Tongue of the Mancos, an offshore marine deposit; the Point Lookout Sandstone (main body), a regressive beach deposit; the Menefee Formation, consisting of continental deposits of sandstone, shale, claystone, siltstone, and coal; and the Cliff House Sandstone, a transgressive beach deposit. In the southern part of the area, these strata are intruded and overlain by Tertiary volcanic rocks. Quaternary deposits include alluvium, eolian sand, colluvium, terrace deposits, and landslide debris.

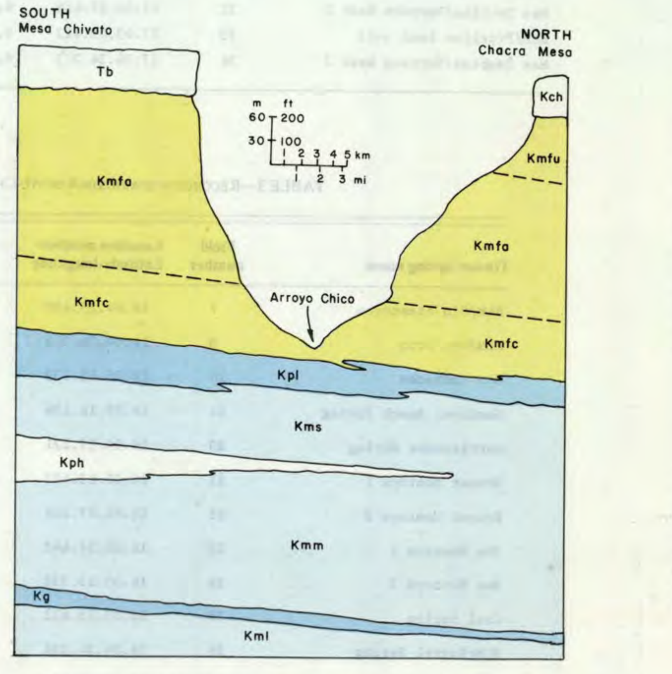


FIGURE 3—DIAGRAMMATIC CROSS SECTION THROUGH ARROYO CHICO–TORREON WASH AREA showing relationship between major stratigraphic units (modified from Tabet and Frost, 1979, fig. 2). Abbreviations for units same as on fig. 1.

AQUIFERS

15 The following discussion is restricted to geologic units presently utilized for water (table 1). The Tertiary igneous rocks, Cliff House Sandstone, Hosta Tongue of the Point Lookout Sandstone, and the Morrison Formation are omitted because 1) no wells are known to be completed in these units, 2) little is known of their hydrologic properties, and 3) suitable supplies of water can generally be obtained from other aquifers. The probable water-bearing characteristics of the omitted units were summarized by Craigg (1980) and Shomaker and Stone (1976).

Alluvium (Quaternary)

16 Alluvium in this area occurs mainly in and adjacent to ephemeral stream channels. These deposits consist of light-brown, clayey, silty, very fine to medium-grained sand. Drillers' logs in U.S. Geological Survey (Albuquerque) files indicate possible thicknesses of 40–80 ft (12–24 m). These thicknesses are for channel alluvium, the only alluvial deposit with aquifer potential in the area.

17 Water levels in wells completed in alluvium range from 0.7 to 33.0 ft (0.2–10.0 m). Yields from these wells are small. One well in Torreon Wash, north of the area in NE¼ sec. 22, T. 18 N., R. 4 W., was reportedly tested at a rate of 23.0–38.0 gpm (1.5–2.4 L/s) for 6.75 hrs, with 26.0 ft (8.0 m) of drawdown (U.S. Geological Survey files, Albuquerque). No recovery data are available, but specific capacity of the well would be 1.2 gpm/ft (0.25 L/s/m), assuming an average discharge of 30.5 gpm (2.0 L/s).

18 Water from alluvium generally is slightly to moderately saline. Three wells in the study area are partially completed in alluvium, but the Menefee Formation may be the principal aquifer (17.03.18.242, 17.04.22.331, and 17.04.23.224). Specific conductances of water from these wells are 4,000, 1,200, and 8,000 μmhos; dissolved-solids contents are 4,185, 750, and 10,272 ppm, respectively (table 4). Two wells north of the area along Torreon Wash, in NW¼ sec. 22, T. 18 N., R. 4 W., and SE¼ sec. 23, T. 18 N., R. 4 W., are completed in alluvium. Specific conductances of water from these wells are 3,680 and 9,280 μmhos, respectively (U.S. Geological Survey files, Albuquerque).

Menefee Formation (Cretaceous)

19 The Menefee Formation crops out mainly in the northern half of the study area and along the slopes around Mesa Chivato (figs. 1 and 3). The Menefee conformably overlies the Point Lookout Sandstone and is conformably overlain by the Cliff House Sandstone. Intertonguing occurs locally at both contacts. In general, this unit consists of interbedded, light-brown to gray, thick- to very thick bedded, fine- to medium-grained, poorly sorted sandstones (lithic arkoses by classification of Folk, 1974); yellowish-gray to olive-gray, medium- to thick-bedded siltstones; light-brownish-gray, thick- to very thick bedded, barren (noncarbonaceous) shales and claystones; and coal beds of variable thickness (Craigg, 1980, appendices A and C).

20 Three members of the Menefee Formation have been recognized in this area based on the presence or absence of coal (Tabet and Frost, 1979). In descending order, these are the coal-bearing "Upper member," the barren Allison Member, and the Cleary Coal Member (fig. 3).

21 The "Upper member" is approximately 650 ft (200 m) thick and consists of local sandstone lenses up to 40 ft (12 m) thick, siltstones, barren shales and claystones, and an abundance of carbonaceous shales and coals. This unit is more sandy in the lower part, near the gradational contact with the Allison Member, and more carbonaceous in the upper part, near the contact with the Cliff House Sandstone.

22 The thickness of the Allison Member ranges from approximately 400 to 550 ft (120–170 m). This unit consists predominantly of sandstones up to approximately 50 ft (15 m) thick, siltstones up to 3 ft (1 m) thick, and barren shales and claystones. Thin, carbonaceous shales and coals occur locally. In the lower part, just above the contact with the Cleary Coal Member, the Allison forms steep cliffs approximately 200 ft (60 m) high which consist of vertically stacked sequences of sandstone bodies. Individual sandstones are lenticular in cross section and have scoured bases.

23 The thickness of the Cleary Coal Member ranges from approximately 200 to 300 ft (60–90 m). This unit consists of local sandstones, barren shales and claystones, and abundant carbonaceous shales and coals. The Cleary Coal Member is more carbonaceous in the lower part, near the contact with the Point Lookout Sandstone, and more sandy in the upper part, near the gradational contact with the Allison Member.

24 The three members of the Menefee Formation represent the gradual succession of continental depositional environments ranging from a coastal swamp and lower floodplain associated with the regressing Point Lookout shoreline (Cleary Coal Member), to an upper floodplain (Allison Member), and back to a coastal swamp and lower floodplain associated with the transgressing Cliff House shoreline ("Upper member"; Tabet and Frost, 1979). The lenticular sandstone bodies are fluvial deposits; siltstones represent crevasse-splay or levee deposition; barren shales and claystones were deposited in a well-drained floodplain environment; and carbonaceous shales and coals were deposited in a poorly drained swamp environment (Mannhard, 1976).

25 Two observation wells have been completed in coal beds of the Menefee Formation (Craigg, 1980, appendices F and G). Well R32 (17.04.23.243 has been completed in a 5.0-ft (1.5 m)-thick coal bed in the Cleary Coal Member. Transmissivity has been calculated to be 1.0×10^{-4} ft^2/d (9.3×10^{-6} m^2/d). Well C1 (18.03.20. 311 has been completed in a 13.7-ft (4.2-m)-thick coal bed in the "Upper member." Transmissivity has been calculated to be 20 ft^2/d (1.9 m^2/d).

26 Two core samples from sandstones in the Cleary Coal Member were analyzed commercially for porosity as well as horizontal and vertical permeability (air). Values for porosity were 26.4 and 26.3 percent. Values for horizontal permeability were 210 and 163 millidarcies (2.23×10^{-12} and 1.73×10^{-12} ft^2; 2.07×10^{-9} and 1.61×10^{-9} cm^2), whereas the values for vertical permeability were 98 and 314 millidarcies (1.04×10^{-12} and 3.33×10^{-12} ft^2; 9.67×10^{-10} and 3.10×10^{-9} cm^2) (Craigg, 1980, appendix L).

27 Seven other wells completed in the Menefee were inventoried (table 2). Yields from the pumping wells are small, 1.0 gpm (0.064 L/s), or less. Nine springs that were inventoried issue from the Menefee (table 3). All of these springs are located south of Arroyo Chico; most of these springs are associated with the dominant northeast-trending fracture system in this area (fig. 1). Yields from the springs are small, estimated at 0.5–1.0 gpm (0.032–0.064 L/s). The potentiometric surface for the Menefee Formation is shown in fig. 4.

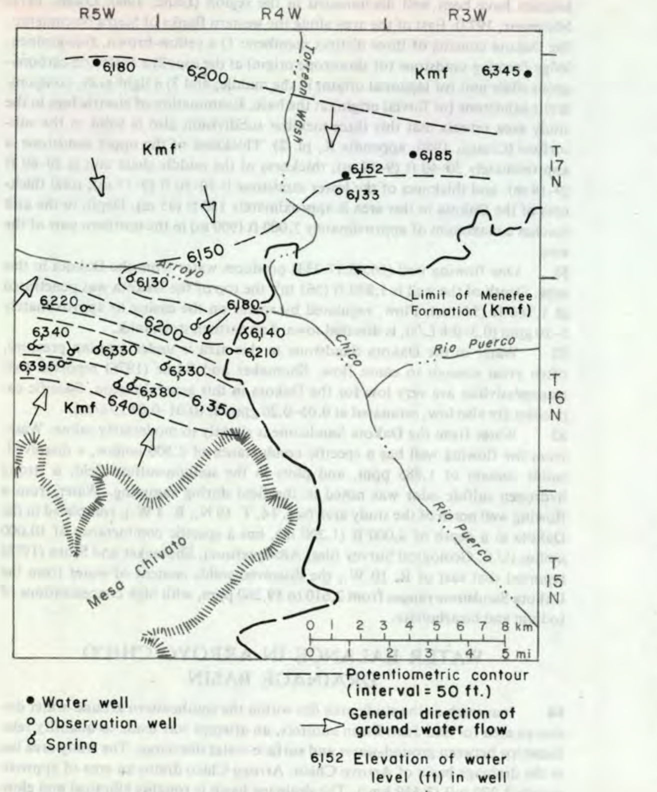


FIGURE 4—POTENTIOMETRIC SURFACE FOR GROUND WATER IN MENEFEE FORMATION.

28 Quality of water from the Menefee Formation ranges from fresh to moderately saline. Specific conductance ranges from 350 to 8,000 μmhos and dissolved-solids contents range from 386 to 10,272 ppm (fig. 5). Available data indicate that the quality of water in the Menefee generally is better south of Arroyo Chico (fig. 7). The averages of both well and spring waters plot in the sodium-bicarbonate-sulfate field on the Piper diagram (fig. 6).

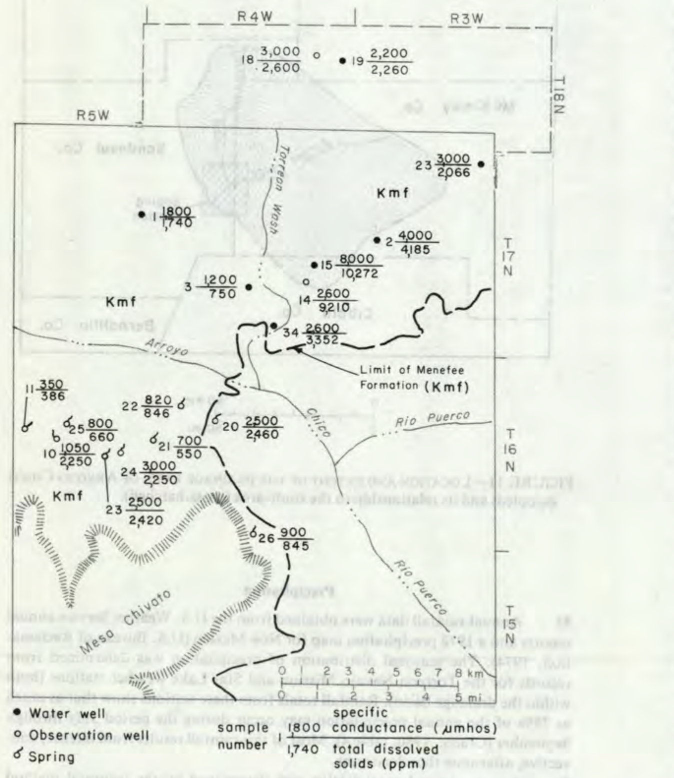


FIGURE 5—CHEMICAL QUALITY OF WATER IN MENEFEE FORMATION. (See tables 2, 3, 4, and 5 for additional information.)

Point Lookout Sandstone (Cretaceous)

29 The main body of the Point Lookout Sandstone crops out with an east-west trend on Mesa San Luis and with a north-south trend along the eastern slopes of Mesa Chivato (fig. 1). Surface exposures commonly form steep, vertical cliffs. The Point Lookout conformably overlies the Satan Tongue of the Mancos Shale; the contact is characterized by a distinct, alternating sandstone-shale transition zone. The Point Lookout is conformably overlain by the Cleary Coal Member of the Menefee Formation, with which it intertongues locally.

30 The Point Lookout is characterized by upward-coarsening sequences of light-olive-gray to yellowish-gray, thick- to very thick bedded, very fine to medium-grained, poorly to moderately sorted, bioturbated sandstones (arkose-lithic arkose). These sandstones locally contain the trace fossil *Ophiomorpha*. Dark-greenish-yellow to moderate-brown, thin- to thick-bedded shales are interbedded with the sandstones, especially in the lower part of the unit. The upper few meters consist of light-gray, distinctly laminated sandstone (Craigg, 1980, appendices A and C).

31 Thickness of the Point Lookout in this area (not including the transition zone) ranges from approximately 75 to 260 ft (23–79 m). Thickness varies systematically, forming a series of northwest-trending, relatively thicker ridges and thinner troughs (fig. 7). Depth to the top of the unit ranges from 0 to 1,200 ft (0–370 m). Depth increases toward the north, mainly because of dip, but also because of higher surface elevations (fig. 8). Depth of the Point Lookout beneath Mesa Chivato probably ranges from approximately 900 to 1,200 ft (275–370 m).

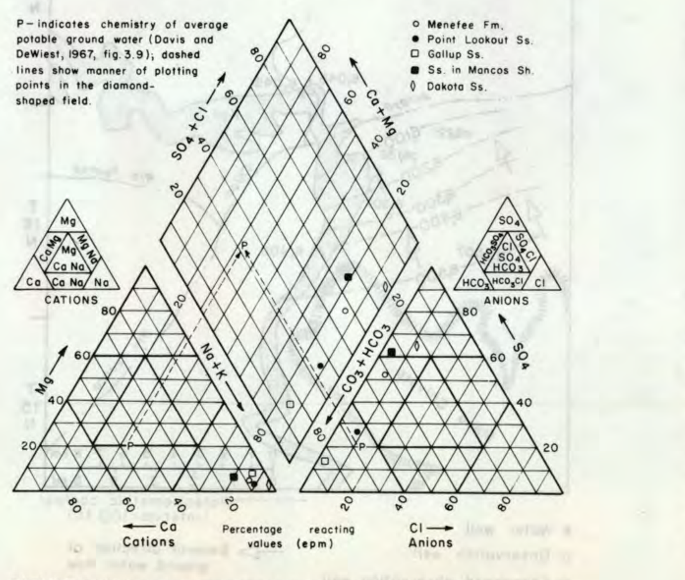


FIGURE 6—TRILINEAR PLOT OF AVERAGE CONCENTRATIONS OF MAJOR DISSOLVED CONSTITUENTS in ground waters of the Arroyo Chico–Torreon Wash area. (See tables 4 and 5 for complete analyses.)

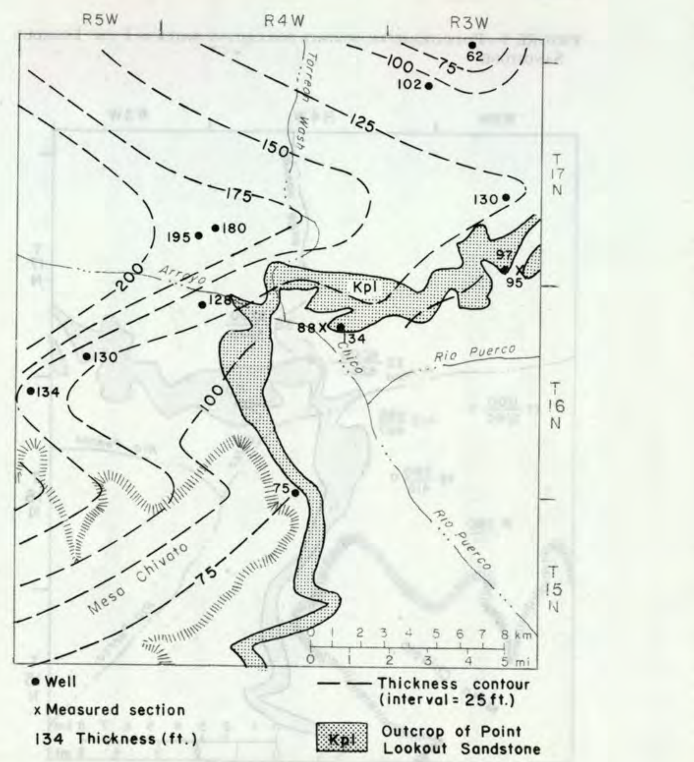


FIGURE 7—THICKNESS OF POINT LOOKOUT SANDSTONE (modified from Tabet and Frost, 1979, fig. 4).

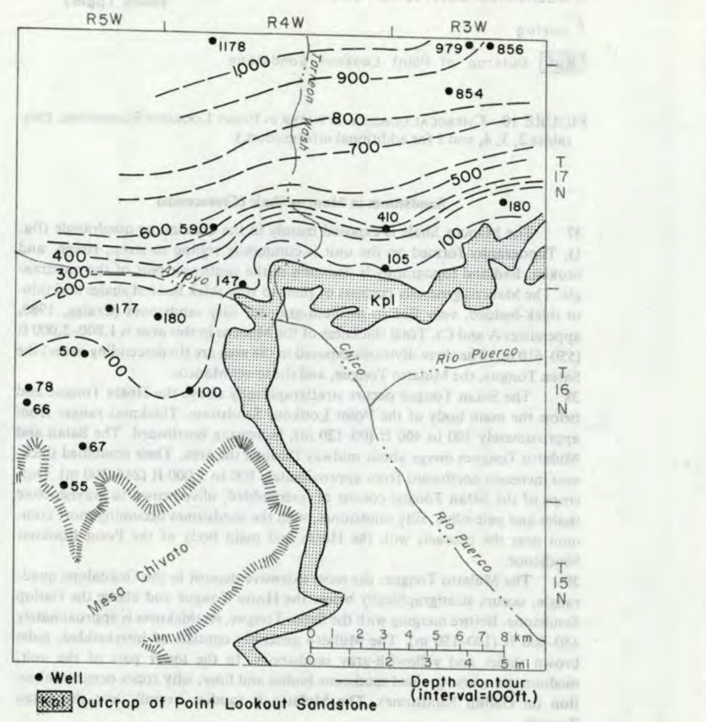


FIGURE 8—DEPTH TO TOP OF POINT LOOKOUT SANDSTONE (based on drill-hole data, Craigg, 1980, appendix K).

32 The Point Lookout is a regressive, marine-shoreline deposit. Shetiwy (1978) recognized three major sedimentary facies in the unit which represent (in ascending order) a shoreface, foreshore/backshore, and an estuarine/beach environment.

33 The potentiometric surface for the Point Lookout is shown in fig. 9. Analysis of three aquifer tests performed on observation wells R21, R23, and R24 (16.04.18.444, 16.04.06.331, and 16.05.02.444; Craigg, 1980, appendices F and G), all completed in the Point Lookout, indicate that transmissivity is low. Calculated values range from 1×10^{-2} to 1×10^{-1} ft^2/d (9×10^{-4} to 9×10^{-3} m^2/d). However, none of the wells fully penetrate the unit; thus, the transmissivities are not maximum values.

34 Three core samples from sandstones in the Point Lookout were analyzed commercially. Porosity ranged from 18.2 to 21.3 percent. Horizontal permeability (air) ranged from 0.81 to 8.9 millidarcies (8.59×10^{-15} to 9.43×10^{-14} ft^2; 7.99×10^{-12} to 8.78×10^{-11} cm^2), whereas vertical permeability (air) ranged from 0.72 to 5.4 millidarcies (7.63×10^{-15} to 5.72×10^{-14} ft^2; 7.11×10^{-12} to 5.33×10^{-11} cm^2; Craigg, 1980, appendix L).

35 One windmill and one spring, both on the south bank of Torreon Wash, were inventoried. The well (17.04.34.213) has a pumping yield of 0.5 gpm (0.03 L/s), and a completed depth of 111 ft (34 m). Yield from the spring (17.04.34.213) could not be measured because the source is at the base of a deep pool in the arroyo bottom.

36 Quality of water from the Point Lookout in the study area ranges from fresh to moderately saline. Specific conductance ranges from 380 to 5,000 μmhos; dissolved-solids contents for waters analyzed range from 415 to 6,290 ppm (fig. 10). Available data indicate that water quality is good south of Arroyo Chico, but deteriorates near and north of that stream. The average of five analyses of waters from the Point Lookout plots in the sodium-bicarbonate-sulfate field (fig. 6).

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Hydrogeology of Arroyo Chico–Torreon Wash area, McKinley and Sandoval Counties, New Mexico

Steven D. Craigg and William J. Stone

1983

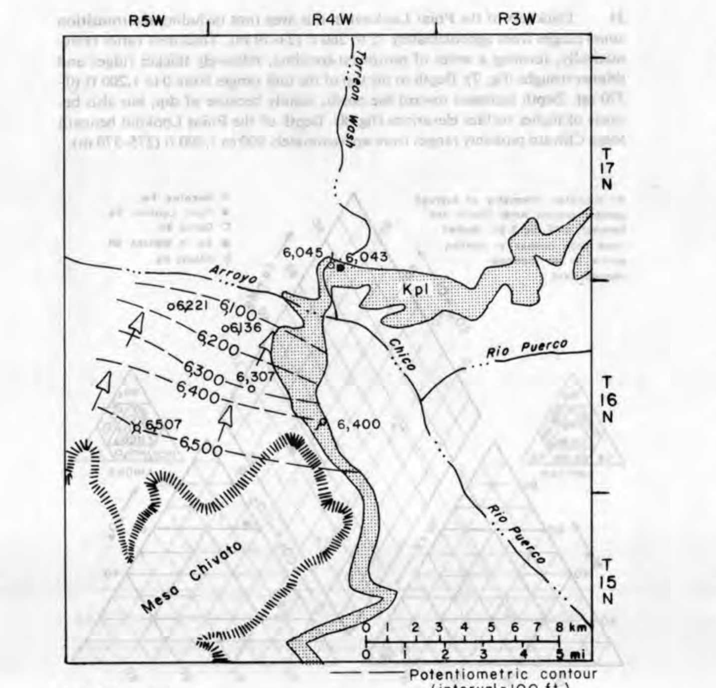

FIGURE 9—POTENTIOMETRIC SURFACE FOR GROUND WATER IN POINT LOOKOUT SANDSTONE.

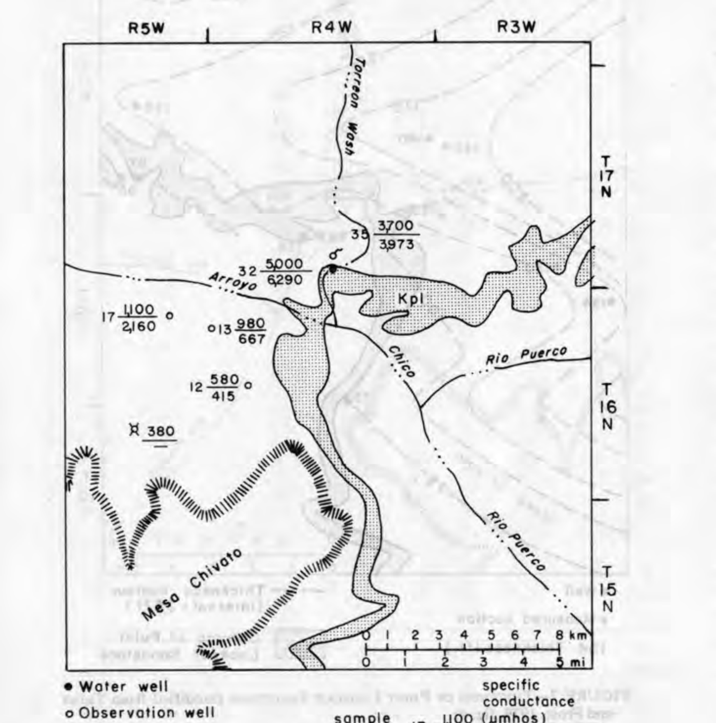

FIGURE 10—CHEMICAL QUALITY OF WATER IN POINT LOOKOUT SANDSTONE. (See tables 2, 3, 4, and 5 for additional information.)

Sandstones in Mancos Shale (Cretaceous)

37 The Mancos Shale is exposed mainly in the Guadalupe quadrangle (fig. 1). Topography formed on the unit is commonly rolling to steep, rough, and broken. Badland topography is common in the southwest part of the quadrangle. The Mancos generally consists of thin- to very thick bedded shales and thin- to thick-bedded, very fine to medium-grained, silty sandstones (Craigg, 1980, appendices A and C). Total thickness of the Mancos in this area is 1,800–2,000 ft (550–610 m). The three divisions exposed in the area are (in descending order) the Satan Tongue, the Mulatto Tongue, and the lower Mancos.

38 The Satan Tongue occurs stratigraphically above the Hosta Tongue and below the main body of the Point Lookout Sandstone. Thickness ranges from approximately 300 to 400 ft (90–120 m), increasing northward. The Satan and Mulatto Tongues merge about midway through the area. Their combined thickness increases northward from approximately 800 to 1,000 ft (245–300 m). Outcrops of the Satan Tongue consist of interbedded, olive-brown to grayish-olive shales and pale-olive, silty sandstones, with the sandstones becoming more common near the contacts with the Hosta and main body of the Point Lookout Sandstone.

39 The Mulatto Tongue, the most extensive deposit in the Guadalupe quadrangle, occurs stratigraphically below the Hosta Tongue and above the Gallup Sandstone. Before merging with the Satan Tongue, its thickness is approximately 450–500 ft (140–150 m). The Mulatto generally consists of interbedded, pale-brown shales and yellowish-gray sandstones. In the lower part of the unit, medium- to coarse-grained sandstone bodies and limy, silty zones occur (see section on Gallup Sandstone). The Mulatto is sandier overall than the Satan Tongue.

40 The lower Mancos, exposed only in the vicinity of Guadalupe and southward, is conformably overlain by the Gallup Sandstone and separates the Gallup from the Dakota Sandstone below. Thickness in the subsurface is approximately 1,000 ft (300 m). Surface exposures consist of interbedded, dusky yellow to pale-green shales and light-brown to yellowish-green sandstones.

41 Two wells completed in the unit were inventoried. Well 16.04.11.312 was pumping at a rate of 2.0 gpm (0.13 L/s) when visited; depth of the well and water level could not be measured. An abandoned well (16.03.35.131) was found to have a depth of 47.2 ft (14.4 m) and a water-level depth of 36.4 ft (11.1 m).

42 Four springs issuing from the Mulatto were inventoried. Two of these, Ojo Atascoso and Ojo de los Jaramillos (16.04.25.433 and 16.03.33.342), are developed with enclosed catchment/storage structures that feed water to stock tanks. The other two springs (16.04.36.332 and 15.03.20.133) occur in arroyo bottoms and are undeveloped. Yield of the springs is small, ranging from 0.5 to 2.0 gpm (0.032 to 0.13 L/s).

43 No wells are known to produce water from the Satan Tongue or the lower Mancos; only one spring from each unit was located: Ojo Frio (16.04.26.213), a developed spring issuing from the Satan Tongue at the base of a volcanic neck, yields 1.0 gpm (0.064 L/s); Guadalupe Springs, an undeveloped spring issuing from the lower Mancos in Guadalupe Canyon, yields less than 1.0 gpm (0.064 L/s).

44 Quality of water from the Mulatto Tongue ranges from fresh to moderately saline. Specific conductance ranges from 800 to 3,500 μmhos and dissolved-solids contents range from 740 to 4,195 ppm. The average of five analyses of waters from the Mulatto Tongue plots in the sodium-bicarbonate-sulfate field (fig. 6). Water from Ojo Frio in the Satan Tongue has a specific conductance of 560 μmhos, a dissolved-solids content of 328 ppm, and plots in the sodium-bicarbonate field. Water from Guadalupe Springs, in the lower Mancos, has a specific conductance of 4,000 μmhos, a dissolved-solids content of 4,270 ppm, and plots in the sodium-sulfate field.

Gallup Sandstone (Cretaceous)

45 The Gallup Sandstone, which crops out in the southeast part of the area (fig. 1), forms resistant escarpments and commonly weathers to a rounded, beehive appearance. Maximum thickness is about 60 ft (20 m). The Gallup Sandstone conformably overlies the lower Mancos Shale and is conformably overlain by the Mulatto Tongue of the Mancos. The Gallup extends northward from the outcrop area for only a few miles to a line roughly connecting Star Lake, Chaco Canyon, and Shiprock, beyond which the unit has been removed by a pre-Niobrara erosion event as described by Molenaar (1973).

46 The Gallup Sandstone generally consists of very light gray to pinkish-gray, medium- to thick-bedded, very fine to fine-grained, bioturbated arkose (Craigg, 1980, appendices A, B, and C). The main body of the Gallup in this area consists of the Gallego Sandstone Member, a regressive-shoreline deposit (Molenaar, 1974). Zones of locally discontinuous sandstone bodies or limy, silty intervals up to 20 ft (6 m) thick are associated with the Gallup in this area. These zones occur about 60 ft (20 m) or more above the top of the unit. The sandstones are commonly medium to coarse grained and bioturbated. The limy, silty intervals consist of thin-bedded siltstones and shales interbedded with discontinuous, wedge-shaped, fine-grained, silty sandstones up to approximately 10 ft (3 m) thick. Molenaar (1974) suggested that these zones may represent offshore bars.

47 One flowing well (16.04.36.232) is known to produce water from the Gallup Sandstone. This well, drilled in 1971 by Homestake Partners, was converted to a water well by the BLM. Total depth is 602 ft (184 m). Initially, the flow was 400 gpm (25 L/s) at a pressure of 95 psi (655 kN/m^2), but flow is now regulated by valves on the casing to approximately one-half this rate. Another flowing well, west of the study area in SW¼ sec. 19, T. 16 N., R. 5 W., also taps the Gallup. This well is a converted oil well drilled in 1962 to a depth of 1,251 ft (381 m). Flow is reportedly 120 gpm (7.7 L/s).

48 Ojo del Padre (15.03.09.444), a spring located in Guadalupe, has its source in the Gallup Sandstone. Although yield from the spring is small (measured at 1.0 gpm; 0.064 L/s), it is constant and reliable.

49 Water analyzed from the Gallup Sandstone is fresh. Water from the BLM flowing well has a specific conductance of 580 μmhos and dissolved-solids content of 390 ppm. Water from Ojo del Padre has a specific conductance of 600 μmhos and a dissolved-solids content of 626 ppm. Both waters plot in the sodium-bicarbonate field. Water from the flowing well west of the area had a specific conductance of 3,130 μmhos in 1962, with a strong hydrogen-sulfide odor reported (U.S. Geological Survey files, Albuquerque).

Dakota Sandstone (Cretaceous)

50 The Dakota Sandstone is not exposed in the area, but its geologic characteristics have been well documented in the region (Dane, 1960; Owen, 1973; Molenaar, 1977). East of the area along the western flanks of Sierra Nacimiento, the Dakota consists of three distinct members: 1) a yellow-brown, fine-grained, ledge-forming sandstone (of shorezone origin) at the top; 2) a shale and carbonaceous shale unit (of lagoonal origin) in the middle; and 3) a light-gray, conglomeratic sandstone (of fluvial origin) at the base. Examination of electric logs in the study area reveals that this three-member subdivision also is valid in the subsurface (Craigg, 1980, appendix K, pl. 2). Thickness of the upper sandstone is approximately 30–40 ft (9–12 m); thickness of the middle shale unit is 30–60 ft (9–18 m); and thickness of the lower sandstone is 30–50 ft (9–15 m); total thickness of the Dakota in this area is approximately 150 ft (45 m). Depth to the unit reaches a maximum of approximately 3,000 ft (900 m) in the northern part of the area.

51 One flowing well (16.03.17.333) produces water from the Dakota in this area. Depth of the well is 1,840 ft (561 m); the top of the Dakota was penetrated at 1,785 ft (544 m). Flow, regulated by valves on the casing to approximately 5–10 gpm (0.3–0.6 L/s), is directed toward an earthen stock tank.

52 Water in the Dakota Sandstone in this area is under artesian pressure, often great enough to cause flow. Shomaker and Stone (1976) reported that transmissivities are very low for the Dakota in this general region. Specific capacities are also low, estimated at 0.05–0.20 gpm/ft (0.01–0.04 L/s/m).

53 Water from the Dakota Sandstone is slightly to moderately saline. Water from the flowing well has a specific conductance of 2,500 μmhos, a dissolved-solids content of 1,885 ppm, and plots in the sodium-sulfate field; a strong hydrogen sulfide odor was noted in the field during sampling. Water from a flowing well north of the study area (sec. 14, T. 19 N., R. 3 W.), completed in the Dakota at a depth of 4,000 ft (1,200 m), has a specific conductance of 10,000 μmhos (U.S. Geological Survey files, Albuquerque). Shomaker and Stone (1976) reported that east of R. 10 W., the dissolved-solids content of water from the Dakota Sandstone ranges from 2,610 to 59,260 ppm, with high concentrations of sodium and bicarbonate.

WATER BALANCE IN ARROYO CHICO DRAINAGE BASIN

54 Inasmuch as the study area lies within the southeastern ground-water discharge area for San Juan Basin aquifers, an attempt was made to quantify relationships between ground-water and surface-water discharge. The study area lies in the drainage basin of Arroyo Chico. Arroyo Chico drains an area of approximately 1,370 mi^2 (3,550 km^2). The drainage basin is roughly elliptical and elongated in a northeasterly direction (fig. 11). Although the water-balance study was only partially successful, several useful things were learned: the relationship between average annual precipitation and average annual runoff, the sources of sustained flow, and the probable sources of water loss.

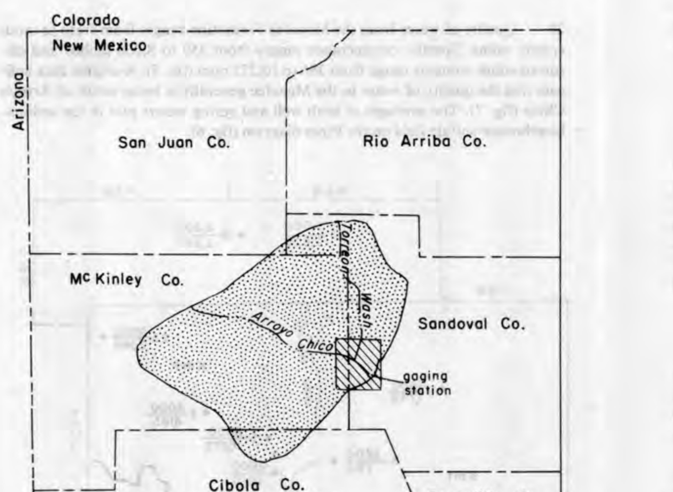

FIGURE 11—LOCATION AND EXTENT OF THE DRAINAGE BASIN OF ARROYO CHICO (stippled) and its relationship to the study area (cross-hatched).

Precipitation

55 Annual-rainfall data were obtained from the U.S. Weather Service annual reports and a 1972 precipitation map for New Mexico (U.S. Bureau of Reclamation, 1974). The seasonal distribution of precipitation was determined from records for the Torreon Navajo Mission and Star Lake weather stations (both within the drainage basin). Rainfall totals from these stations show that as much as 75% of the annual precipitation may occur during the period July through September (Craigg, 1980, table 4). Most of this rainfall results from intense, convective, afternoon thunderstorms.

56 Average annual precipitation was determined by the isohyetal method (Linsley and others, 1975) to be 11.5 inches (292 mm).

Runoff

57 Discharge data for the gaging station at the mouth of Arroyo Chico (fig. 12) were obtained from the U.S. Geological Survey, Albuquerque. The average annual discharge at this station (based on 35 consecutive yrs of record) is 15,432 acre-ft (19 hm^3).

58 Runoff volumes in Arroyo Chico vary widely, depending mainly on season (fig. 13). Peak volumes occur during the rainy season (July–September). During this period, afternoon thunderstorms may generate large volumes of runoff, and up to 99% of the annual discharge may occur (Craigg, 1980, table 4). The period from October through November is generally characterized by decreasing discharge in response to the drier autumn season. December through March is commonly a period of increasing flow, reflecting influence of the frontal storm systems that characterize winter. Runoff decreases from April through June because of depletion of snowmelt and a drier, spring-rainfall period. This strong seasonal control on runoff volumes was shown graphically by Craigg (1980, plate 4; figs. 28 and 29).

TABLE 1—SUMMARY OF WATER-RESOURCE INFORMATION, ARROYO CHICO-TORREON WASH AREA. **TDS**, total dissolved solids; **SC**, specific conductance.

Aquifers (maximum known thickness, ft)	Lithology	Maximum depth to top (ft)	Maximum known yield (gpm)	TDS in ppm (SC in μmhos)
Alluvium (80)	Very fine–medium clayey, silty sand	at surface	38	750–10,272 (1,200–9,280)
Sandstones in Menefee Fm. (50)	Fine–medium fluvial sandstone	surface–1,150	1	386–10,272 (350–8,000)
Point Lookout Ss. (200)	Very fine–medium marine sandstone	surface–1,200	1.4	415–6,290 (380–3,700)
Sandstones in Mancos Sh. (10)	Very fine–fine marine sandstone	surface–2,500	2	328–4,270 (560–4,000)
Gallup Ss. (70)	Very fine–fine marine sandstone	surface–2,000	400	390 (580–3,130)
Dakota Ss. (150)	Fine marine ss. at top; carbonaceous, paludal ss. in middle; conglomeratic, fluvial ss. at base	3,000	10	1,885 (2,500–10,000)

TABLE 2—RECORDS OF WELLS IN ARROYO CHICO-TORREON WASH AREA; see fig. 1 for locations. E, estimated; M, measured; R, reported (USGS, WRD files, Albuquerque); L, log value; S, stock; D, domestic; O, observation; U, unused; --, not measured. Abbreviations for aquifers same as in fig. 1.

Owner/well name	Field number	Location number	Ground elevation (ft)	Total depth (ft)	Water depth (ft)	Date	Principal aquifer	Aquifer thickness	Use	Yield (gpm)
Navajo Tribe/15B-32	1	17.05.12.423	6,422	343 R	-----	6/28/78	Kmfa	13.0 R	S	1.5 M
Arroyo Piedra Lumbre well	2	17.03.18.242	6,215	55 M	30.7 M	6/28/78	Kmfc (Qal?)	------	S	2.0 M
B.P. Hovey windmill	3	17.04.22.332	6,110	-----	-----	6/28/78	Kmgc (Qal?)	------	S,D	0.5 M
Arroyo Chico/Torreon Wash well	4	16.04.11.312	6,013	-----	-----	6/28/78	Kml	------		0.5 E
BLM/Converted oil test	5	16.03.17.333	6,130	1,840 R	flowing	6/28/78	Kd	55.0 R	S	5.0 E
BLM/Homestake well	6	16.04.36.232	6,150	602 R	flowing	6/28/78	Kg	11.0 R	S,D	200.0 R
NMBMMR/R21	12	16.04.18.444	6,395	250 R	102.2 M	7/27/78	Kpl	144.0 L	O	-----
NMBMMR/R23	13	16.04.06.331	6,235	250 R	93.3 M	8/31/78	Kpl	68.0 L	O	-----
NMBMMR/R32	14	17.04.23.243	6,175	240 R	41.5 M	9/29/78	Kmfc	5.0 L	O	-----
B.P. Hovey/abandoned well	15	17.04.23.224	6,140	45 R	13.5 M	9/29/78	Kmfc (Qal?)	-----	U	-----
NMBMMR/R24	17	16.05.02.444	6,310	250 R	120.3 M	6/04/79	Kpl	49.0 L	O	-----
NMBMMR/C1	18	18.03.20.311	6,530	170 R	106.2 M	6/27/79	Kmfu	13.7 M	O	-----
Navajo Tribe/15T-541	19	18.03.20.433	6,585	-----	-----	6/27/79	Kmfu		S	2.0 E
BLM/Abra de los Cerros	31	16.03.35.131	6,091	47 M	36.4 M	6/19/79	Kml	-----	U	-----
Max Tachias/Torreon Wash 1	32	17.04.27.444	6,084	-----	-----	6/21/79	Kpl		S	2.3 M
BLM/Pipeline Road well	33	17.03.03.422	6,411	247 M	66.0 M	6/21/79	Kmfa	-----	U	-----
Max Tachias/Torreon Wash 2	34	17.04.34.213	6,075	111 M	36.4 M	6/19/79	Kmfc	-----	S,D	0.5 M

TABLE 3—RECORDS OF SPRINGS IN ARROYO CHICO-TORREON WASH AREA. I, irrigation; other abbreviations same as in table 2.

Owner/spring name	Field number	Location number/ Latitude-longitude	Ground elevation (ft)	Principal source	Date visited	Use	Yield (gpm)	Remarks
BLM/Ojo Atascosco	7	16.04.25.433	6,085	Kmm	6/28/78	S	1.0 E	enclosed, stock tank
BLM/Ojo Frio	8	16.04.26.213	6,260	Kms	6/28/78	S	1.0 E	enclosed, stock tank
Ojo Azabache	10	16.05.15.233	6,085	Kmfc	7/20/78	S	0.5 R	inside rock house
Sandoval Ranch Spring	11	16.05.16.124	6,340	Kmfc	7/20/78	S	0.5 E	undeveloped
Rattlesnake Spring	20	16.04.17.221	6,210	Kmfc	6/11/79	S	very low	undeveloped
Ernest Montoya 1	21	16.05.13.422	6,320	Kmfc	6/11/79	S	0.5 M	enclosed, stock tank
Ernest Montoya 2	22	16.04.07.244	6,180	Kmfc	6/11/79	S	0.5 M	enclosed, stock tank
Joe Montoya 1	23	16.05.14.442	6,360	Kmfc	6/11/79	S	0.5 E	undeveloped
Joe Montoya 3	24	16.05.13.333	6,380	Kmfc	6/11/79	U	very low	enclosed, abandoned
Coal Spring	25	16.05.15.412	6,340	Kmfc	6/11/79	S	0.25 M	coal-sandstone contact
BLM/Barrel Spring	26	16.04.34.334	7,210	Kmfc	6/13/79	S	0.5 M	enclosed, stock tank
Cañon Salado	27	15.03.20.133	6,055	Kmm	6/13/79	S	1.0 E	undeveloped
Guadalupe Springs	28	35°31'50"N. 107°09'52"W.	5,960	Kml	6/13/79	S	1.0 E	undeveloped
BLM/Ojo de las Yeguas 1	29	16.04.36.332	6,220	Kmm	6/13/79	S	2.0 E	undeveloped
BLM/Ojo de los Jaramillos	30	16.03.33.342	6,000	Kmm	6/15/79	S	0.5 M	enclosed, 3 stock tanks
Max Tachias/Torreon Wash	35	17.04.34.213	6,050	Kpl	6/25/79	S	very low	undeveloped
Sanchez/Ojo del Padre	36	35°32'22"N. 107°09'10"W.	5,875	Kg	6/29/79	S,D,I	0.5 M	on-off valve

TABLE 4—RESULTS OF CHEMICAL ANALYSES (PPM) OF WATER FROM WELLS IN ARROYO CHICO-TORREON WASH AREA. Locations given in table 2 and fig. 1. **HCO_3**, bicarbonate; **Cl**, chloride; **SO_4**, sulfate; **Na**, sodium; **K**, potassium; **Mg**, magnesium; **Ca**, calcium; **TDS**, total dissolved solids. Precision as reported by laboratory.

Owner/well name	Field number	Analysis date	HCO_3	Cl	SO_4	Na	K	Mg	Ca	TDS	Specific conductance (μmhos) field	Specific conductance (μmhos) lab
Navajo Tribe/15B-32	1	10/78	960	220	72	530	2.2	0.25	2.7	1,790	1,800	2,040
Arroyo Piedra Lumbre well	2	10/78	564	15	2,274	1,150	4.4	53	123	4,185	4,000	4,440
B.P. Hovey windmill	3	6/79	363	15	146	168	2.6	5.2	38	750	1,200	-----
Arroyo Chico/Torreon Wash well	4	6/79	294	76	874	442	1.2	43.5	32.6	1,770	2,000	2,000
BLM/Converted oil test	5	10/78	336	98	789	620	2.7	1.4	3	1,855	2,500	2,730
BLM/Homestake Well	6	10/78	218	8	27	109.5	0.7	0.15	3.3	390	580	500
NMBMMR/R21	12	10/78	315	3.8	90	150	3.25	1.5	7.8	415	580	527
NMBMMR/R23	13	10/78	328	6.8	260	175	3.7	15.5	40.1	667	980	895
NMBMMR/R32	14	10/78	1,750	1,220	3,650	3,140	4.4	18.4	24.8	9,210	7,000	9,790
B.P. Hovey abandoned well	15	10/78	702	529	5,979	3,300	15.75	65.0	32	10,272	8,000	9,790
NMBMMR/R24	17	6/79	847	30	85	350	81.5	0.72	6.1	2,160	1,100	-----
NMBMMR/C1	18	6/79	616	13	1,116	820	9.6	1.6	9.0	2,600	3,000	-----
Navajo Tribe/15T-541	19	6/79	1,080	53	355	648	8.5	0.57	2.0	2,260	2,200	-----
BLM/Abra de los Cerros	31	6/79	343	56	1,842	1,020	35	4.9	4.5	4,195	3,500	3,500
Max Tachias/Torreon Wash 1	32	6/79	210	684	3,190	1,640	13.3	169	184	6,290	5,000	-----
BLM/Pipeline Road well	33	6/79	720	81	970	225	4	2.7	4.9	2,066	3,000	3,000
Max Tachias/Torreon Wash 2	34	6/79	1,807	255	302.5	920	2.9	33.5	5	3,352	2,600	2,600

59 Arroyo Chico flows intermittently throughout a short reach (4 mi; 6 km) between sec. 36, T. 17 N., R. 5 W. and sec. 9, T. 16 N., R. 4 W. The sources of this flow include discharge from a spring in the channel bottom (SE¼ SE¼ SE¼ sec. 36, T. 17 N., R. 5 W.) and input from other springs in tributary arroyos.

60 Most of the springs that discharge into Arroyo Chico issue from the Menefee Formation south of the stream, at the base of the slope around Mesa Chivato (fig. 1). The Point Lookout Sandstone, and possibly deeper units, also may contribute water to the intermittent flow. The major source of the spring flow, however, is believed to be the flanks of Mount Taylor to the southwest. Available water-quality data (figs. 5 and 10) corroborate such a source; ground water is generally fresher south of Arroyo Chico. No clear evidence of discharge from the deep, regional-flow system was found.

Water balance

61 In order to determine relationships between annual basin precipitation and runoff, theoretical runoff volumes were computed for 0.5, 1.0, 1.5, 2.0, 3.0, and 4.0% of the average annual basin precipitation of 11.5 inches (292 mm), and then compared to actual volumes at the gaging station (table 6). The 35-yr average discharge of 15,432 acre-ft (19 hm^3) represents 1.9% of the average annual precipitation. Runoff volumes for the water yrs 1966–1978 range from 0.3 to 4.1% of annual precipitation in the basin; the average runoff for this 13-yr period is 12,200 acre-ft (15 hm^3) and represents 1.5% of the average annual precipitation. These rainfall-runoff relationships compare favorably with those reported by Stone and Brown (1975).

62 Less than 4% of the average annual precipitation falling on the drainage basin reaches the mouth of the stream as runoff (table 6). Loss of water in the basin occurs in various ways including seepage into alluvium and bedrock before reaching the channel, loss during flow down the channel (transmission loss), and evapotranspiration. As noted by Renard (1970), transmission loss is the most significant of these factors in ephemeral streams. Some of the water that infiltrates into the alluvium is retained as interstitial moisture and becomes subject to evapotranspiration. The major effect of evapotranspiration is probably the reduction of recharge volumes, initially to alluvium, but ultimately to bedrock aquifers.

63 Gregory and Walling (1973) gave the following generalized water-balance equation for a drainage basin:

$$P = Q + E \pm s$$

where P = available precipitation
Q = runoff
E = evapotranspiration, and
s = change in storage.

For the purpose of this study, P is the average annual-basin precipitation and Q is the 35-yr average annual discharge. Potential evapotranspiration was computed by the Thornthwaite method (Thornthwaite, 1948) to be about 33 inches (840 mm) per year (Craigg, 1980, table 6); for the entire drainage basin, this amounts to approximately 2.3 × 10^6 acre-ft/yr (2.8 × 10^3 hm^3/yr). This value is almost three times the average annual precipitation in the basin, which is not surprising for a semiarid region.

64 Evaluating the storage term in the water-balance equation gives approximately 1.5 × 10^6 acre-ft/yr (1.8 × 10^3 hm^3/yr), a storage deficit of almost twice the average annual precipitation. Expected annual losses may amount to 96% or more of the annual precipitation, or 8 × 10^5 acre-ft (1 × 10^3 hm^3); this figure is approximately one-half of the storage deficit and approximately one-third of the potential evapotranspiration.

65 The values obtained by the Thornthwaite method probably are too large for several reasons: 1) lack of knowledge concerning soil moisture (antecedent moisture conditions); 2) lack of knowledge regarding vegetation density, especially in stream channels; and 3) lack of knowledge concerning meteorologic conditions (especially intermittent cloud cover, fluctuating solar radiation, and wind speed near the ground). Also, the value computed for evapotranspiration is only a potential value, and water availability is an additional complication. If water is not available, it cannot be lost to the atmosphere.

66 The major conclusion drawn from this study is that overall, Arroyo Chico and other ephemeral and intermittent streams in this area are losing water throughout most of their courses. Further investigation is needed before any additional conclusions regarding water balance in the drainage basin can be drawn.

TABLE 5—RESULTS OF CHEMICAL ANALYSES (PPM) OF WATER FROM SPRINGS IN ARROYO CHICO-TORREON WASH AREA. Locations given in table 3 and fig. 1. Abbreviations same as in table 4.

Owner/spring name	Field number	Analysis date	HCO_3	Cl	SO_4	Na	K	Mg	Ca	TDS	Specific conductance (μmhos) field	Specific conductance (μmhos) lab
BLM/Ojo Atascosco	7	7/78	198	15	472	304	4.6	0.85	4.1	994	1,200	1,600
BLM/Ojo Frio	8	8/78	300	4	48	141.5	0.6	0.2	2.7	328	560	640
Ojo Azabache	10	8/78	335	27	1,270	759	1.85	0.65	5.01	2,250	1,050	1,250
Sandoval Ranch Spring	11	8/78	188	19	132	112	3.2	6.0	16	386	350	450
Rattlesnake Spring	20	6/79	632	38	1,003	692	25.3	23.3	38.3	2,460	2,500	-----
Ernest Montoya 1	21	6/79	243	8	133	89	3.9	15.5	31	550	700	-----
Ernest Montoya 2	22	6/79	233	13	351	155	3.3	24.5	54.7	846	820	-----
Joe Montoya 1	23	6/79	360	36	1,134	635	5.0	9.5	29.8	2,420	2,500	-----
Joe Montoya 3	24	6/79	1,700	74	1,134	700	27.5	35	351	4,060	3,000	-----
Coal Spring	25	6/79	233	18	106	196	1.4	0.6	5	660	800	-----
BLM/Barrel Spring	26	6/79	530	5	28	226	2.1	1.2	5.3	845	900	-----
Cañon Salado	27	6/79	315	0.51	1,854	325	0.24	59	512	3,105	3,000	-----
Guadalupe Springs	28	6/79	226	10	2,765	800	4.0	132	318	4,270	4,000	-----
BLM/Ojo de las Yeguas 1	29	6/79	304	8	57	129	4.7	0.41	3.7	740	800	-----
BLM/Ojo de los Jaramillos	30	7/79	457	46	709	435	4.7	28	41.6	1,740	2,000	-----
Max Tachias/Torreon Wash	35	7/79	1,580	255	920	1,090	26	25	24	3,973	3,700	-----
Sanchez/Ojo del Padre	36	7/79	407	2	54.8	136	1.2	17.5	9	626	600	-----

TABLE 6—PRECIPITATION AND DISCHARGE DATA FOR ARROYO CHICO DRAINAGE BASIN, 1966–1978. A water year is the period from October 1 of the previous year through September 30 of the given year. Percentage of basin rainfall is based on average annual drainage basin precipitation of 11.5 inches; 35-yr average annual discharge = 15,432 acre-ft, or 1.86% of average annual basin precipitation.

	Precipitation at Torreon Mission			Discharge at Arroyo Chico gage			
Water year	Annual (inches)	July–Sept. (inches)	Percentage of annual in July–Sept.	Annual (acre-ft)	Percentage of basin rainfall	July–Sept. (acre-ft)	Percentage of annual in July–Sept.
1966	9.32	4.35	46.7	14,910	1.80	10,622	71.2
1967	7.68	5.77	75.1	34,755	4.10	34,241	98.5
1968	9.28	3.69	39.8	11,514	1.40	11,352	98.6
1969	10.57	4.83	45.7	8,162	1.00	6,883	84.3
1970	11.11	4.63	41.7	13,988	1.65	5,338	38.3
1971	8.11	4.87	60.0	7,587	0.90	7,383	97.2
1972	10.78	7.85	72.8	16,497	2.00	15,106	91.6
1973	15.03	4.24	28.2	18,203	2.15	4,810	26.4
1974	7.43	3.79	51.0	3,025	0.35	2,783	92.0
1975	13.37	5.64	42.2	13,172	1.55	8,245	62.0
1976	5.79	2.47	42.7	6,468	0.75	6,393	98.9
1977	11.57	7.11	61.4	7,627	0.90	7,188	94.2
1978	11.56	2.18	18.9	2,717	0.32	196	7.2
Mean	10.12	4.72	45.0	12,200	1.45	9,273	73.9

HYDROGEOLOGIC PRINCIPLES

Hydrogeology is the science that applies geologic concepts and methods to the understanding of hydrologic phenomena. Hydrogeologists attempt to explain the role of the geologic framework in controlling the occurrence and quality of water resources.

The ultimate source of most surface and ground water is precipitation. In the arid Southwest, a small amount of the moisture from rain and snow runs off to major streams; much of it quickly soaks into the ground. Although the bulk of this moisture is soon returned to the atmosphere through evapotranspiration, some may move deeper and be stored as ground water.

Ground water occupies fractures or intergranular pores in saturated zones beneath the ground surface. All natural materials in the ground may be classed as one of the following:

aquifer—readily stores and transmits ground water;
aquitard (or aquiclude)—stores, but poorly transmits ground water;
aquifuge—neither stores nor transmits ground water.

Thus, the search for ground water is the search for aquifers.

Ground water in aquifers may be unconfined or confined. **Unconfined ground water** is in direct contact with the atmosphere and so is not under pressure. Unconfined water stands in wells at the same level where encountered in drilling. The surface characterizing the top of unconfined ground water is the **water table.** A water table map may be prepared by contouring water levels in wells tapping the unconfined aquifer.

Confined ground water (or **artesian ground water**) is restricted to an aquifer by the presence of aquifuges or aquitards at least above the aquifer and possibly also below it. The upper confining layer prevents direct contact with the atmosphere. Confined or artesian ground water is under pressure and will rise above the level where it is encountered in drilling, although not necessarily to the ground surface. The level to which artesian water rises in tightly cased wells is the **potentiometric surface.** A potentiometric surface map for a given artesian aquifer may be prepared by contouring water levels in wells open only to that aquifer.

Recharge, the process by which ground water is replenished, may be direct (from the surface itself) or indirect (from the surface by means of other geologic units). Recharge may be natural or artificial (induced by man). **Discharge,** the process by which ground water is depleted, similarly may be direct or indirect, natural or artificial. In some areas neither recharge nor discharge occurs.

Ground water moves from areas of recharge to areas of discharge. Movement occurs in **flow systems** of various sizes—ranging from small, local, mountain-to-valley systems to large regional systems covering entire counties or even states. Flow is through connected fractures or intergranular pores. Only in areas of underground caverns does ground water flow in distinct channels; the idea that ground water generally occurs in underground rivers is misleading. Movement is slow, averaging less than 5 ft/day. Higher flow rates occur in fractured rock and coarse, clean (not muddy) gravel.

Unconfined water moves from areas of higher water table toward areas of lower water table under the influence of gravity; flow is perpendicular to water table contours. Confined water moves from areas of higher potentiometric surface towards areas of lower potentiometric surface owing to differences in potential energy; flow is perpendicular to equipotential contours.

Several terms have evolved for specific aquifer properties. **Porosity** is that percentage of the volume of an aquifer consisting of pores or openings. The quantity of water that will readily drain by gravity from the pores of an aquifer is its **specific yield.** Conversely, the amount of water that remains in an aquifer after drainage by gravity is its **specific retention.** Both are expressed as a decimal fraction or percent; together they equal porosity.

Permeability is the capacity of a porous material to transmit water. The volume of water moving between two points in an aquifer is generally proportional to the vertical drop between the two points divided by the distance between the points. This relationship, called **Darcy's Law,** may be expressed mathematically as:

$$\frac{Q}{A} = K \times \frac{(h_1 - h_2)}{L} \quad \text{or} \quad Q = KA \times \frac{(h_1 - h_2)}{L},$$

where Q is the volume of water discharged per unit time, A is the cross-sectional area of the discharge site, K is the coefficient of permeability (also called **hydraulic conductivity**), $(h_1 - h_2)$ is the difference in height (or **head**) between the two points, and L is the distance between the points; $\frac{(h_1 - h_2)}{L}$ is also referred to as the **hydraulic gradient.** To solve for permeability the equation may be rewritten as follows:

$$K = \frac{Q}{A} \times \frac{L}{(h_1 - h_2)}$$

Permeability is commonly expressed as gpd/sq ft (gallons per day per square foot). If gallons are converted to cubic ft, permeability may be expressed as ft/d or m/d (feet per day; meters per day).

The amount of water flowing through an aquifer depends on its thickness as well as its permeability. **Transmissivity** takes this fact into account and is determined by multiplying permeability by thickness. It is usually expressed as gpd/ft (gallons per day per foot—of thickness). If gallons are converted to cubic ft, transmissivity may be expressed as ft^2/d (feet squared per day); the metric equivalent is m^2/d (meters squared per day). Another measure of the performance of an aquifer is **specific capacity,** which is the yield per foot of **drawdown** (decline of the water table or potentiometric surface after pumping). Specific capacity is expressed as gpm/ft or lps/m (gallons per minute per foot or liters per second per meter—of drawdown). **Storativity** is a dimensionless measure of the volume of water produced from (or injected into) storage per unit surface area of aquifer per unit change in head. It may be computed by the following equation:

$$S = \frac{v}{A\,(h_1 - h_2)},$$

where S is the storativity, v is the volume of water released from (or put into) storage, A is the cross-sectional area of the aquifer prism, and $(h_1 - h_2)$ is the change in head.

In addition to quantity, the hydrogeologist is also concerned with **water quality.** The quality or chemical character of water determines its usefulness to man. Specific quality/use criteria include salinity, hardness, taste, odor, color, turbidity, biological purity, and pH. In nature, water rarely occurs in a pure state; water moving through the environment picks up many natural and manmade substances as dissolved constituents or suspended matter.

Dissolved constituents come from 1) solution of minerals in the ground, 2) contact with industrial or municipal waste, 3) addition of agricultural waste and fertilizers, and 4) mixing with waters already charged with dissolved solids. This dissolved load determines salinity, hardness, and pH.

Dissolved-solids content is determined in the field by means of a **specific-conductance** meter. Although pure water conducts electricity very poorly and thus is highly resistive, the addition of dissolved material (which separates into charged **ions**) makes it conductive; the more material in solution the greater the conductance. The unit measurement of specific conductance is the mho (the inverse of ohm, the unit of resistance). Values of specific conductance are usually reported (in both the English and metric systems) in μmhos or **micromhos** (millionths of a mho).

In the laboratory, total dissolved-solids content is approximated by weighing the residue obtained after oven drying a water sample at 356° F (180° C) for 1 hour. Results may be presented as ppm (parts per million) or mg/l (milligrams per liter), which are numerically equivalent for concentrations less than 7,000 ppm.

Ground waters may be classified and compared on the basis of dissolved-solids contents. Many schemes have been suggested, but that used by the U.S. Geological Survey (Swenson, H. A., and Baldwin, H. L., 1965, A primer on water quality: U.S. Geological Survey Special Publication, 27 p.) is followed herein: less than 1,000 ppm = **fresh**; 1,000-3,000 ppm = **slightly saline**; 3,000-10,000 ppm = **moderately saline**; 10,000-35,000 ppm = **very saline**; more than 35,000 ppm = **brine.** To compare ground-water compositions, concentrations of major cations and anions (positively and negatively charged ions, respectively) are plotted on a trilinear diagram as percentages of epm's (equivalents per million). The epm value is calculated by dividing the ppm value by the equivalent weight of the ion of interest (equivalent weight = atomic weight ÷ chemical valence).

Suspended matter includes sediments flushed into wells and bacteria thriving in the aquatic environment. Suspended sediments determine turbidity, and bacteria determine biological purity. In combination with dissolved constituents, suspended matter contributes to the color, odor, and taste of water.

Water-quality standards have been defined for most water uses. The U.S. Public Health Service has adopted standards for drinking-water quality. Most of these standards consist of recommended limits; maximum allowable limits have been defined only where specific health hazards exist. A common measure of water potability is total dissolved-solids content. The Public Health Service recommends 500 ppm as a desirable limit for drinking water. Lacking suitable sources, many public water supplies exceed this limit by more than four times. Water-quality requirements for various industrial purposes have been established; similarly, the tolerance of various crops to specific dissolved constituents has been determined.

HYDROGEOLOGY

67 Based on the geologic and hydrologic observations given above, some interpretations of the geologic controls of the occurrence, movement, and quality of ground water in the study area can be made.

Controls of occurrence

68 Ground water in the Arroyo Chico-Torreon Wash area occurs mainly in the intergranular pore spaces of sandstones and alluvium and in fractures in coal beds.

69 The occurrence of ground water in sandstones is primarily controlled by the porosity, permeability, and geometry of the sandstones. These factors are in turn controlled by the depositional and postdepositional history of the sandstones. Stone (1981) found that the distribution and geometry of progradational sandstone bodies within the Gallup Sandstone are the major controls on its hydrologic behavior. The Point Lookout Sandstone, though varying in thickness locally (fig. 7), has a generally sheet-like geometry that results in a fairly uniform distribution of hydrologic characteristics throughout the area. However, the Point Lookout Sandstone had an origin similar to that of the Gallup Sandstone, and the controls recognized for the Gallup probably also apply to the Point Lookout.

70 Ground-water occurrence in units deposited in a continental environment, in addition to being controlled by geometry of individual sandstone bodies, is also controlled by the location and distribution of these bodies. For example, the Menefee Formation contains lenticular, channel-sandstone bodies that are commonly elongate in a northeast direction; these bodies are distributed randomly. Exploration for ground water in this unit, therefore, is largely a hit-or-miss proposition, especially in the Cleary Coal and "Upper members." Given ideal circumstances, units such as these should yield small amounts of water to wells. During recent test drilling by the Bureau into coal-bearing zones of the Menefee, several channel sandstones were penetrated. Some of these were dry, a few contained oil, and others contained poor-quality water (Dave Tabet, personal communication, 1979). Coal beds in the area are also lenticular, discontinuous, elongate bodies.

71 An additional control on ground-water ocurrence in this area may be subsurface fracturing, resulting in increased secondary permeability. For example, coal beds in the Menefee Formation are commonly fractured and do yield water to wells. Fracture permeability may also be partly responsible for the high flow reported from the BLM flowing well (16.04.36.232) completed in the Gallup Sandstone, because this well is located near a major fault (fig. 1).

72 The occurrence of several springs south of Arroyo Chico is apparently controlled by northeast-trending, normal faults. Many of these springs occur directly on the faults; other springs are associated with dikes that have the same northeasterly trend as the faults (fig. 1). Springs in the southeast part of the area are commonly associated with volcanic necks; their existence may be controlled by localized fracturing near the necks.

FIGURE 12—ARROYO CHICO GAGING STATION showing concrete control, stilling well and shelter for recording gage, and metal shed containing a sediment sampler; view to west in NE¼ sec. 30, T. 16 N., R. 3 W.

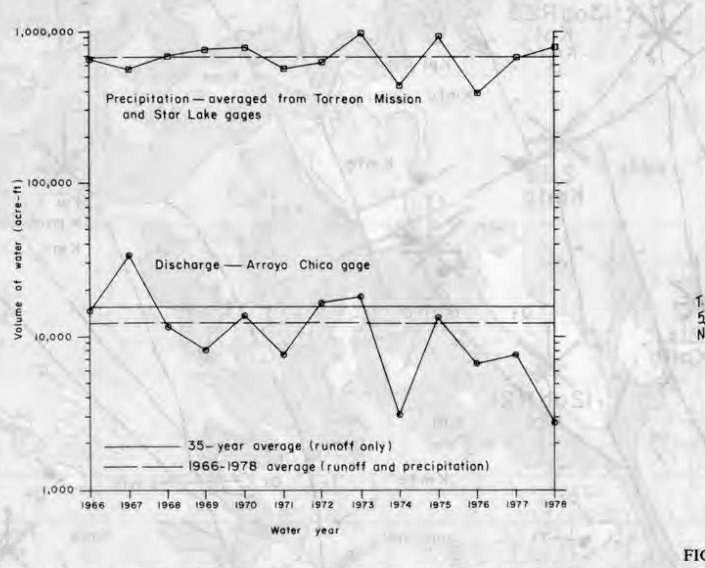

FIGURE 13—ANNUAL DISCHARGE AND PRECIPITATION AT ARROYO CHICO GAGING STATION FOR WATER YEARS 1966–1978; water year is October of previous year through September of given year.

Controls of movement

73 Recharge is enhanced where aquifers lie at or near the surface, thus readily intersecting runoff. Uplift, folding, and faulting have placed aquifers in the Arroyo Chico-Torreon Wash area at the surface both in and adjacent to the study area. Outcrop belts within the area are extensive laterally and provide the potential for considerable recharge. The major means of recharge to units in this area is transmission loss of runoff crossing outcrops. A certain amount of subsurface recharge probably also occurs between leaky, confined units and their confining layers. Alluvium is recharged by transmission loss of runoff in stream channels and, to a lesser extent, by discharge of water from bedrock units. Geologic units such as the Dakota Sandstone and the Morrison Formation are not exposed in the study area and, aside from subsurface leakage, recharge to these units occurs totally outside the area.

74 Flow of ground water in bedrock units in this area is downdip from recharge areas. Direction of flow is roughly toward Arroyo Chico, from the north and south. Figs. 4 and 9 show general directions of ground-water flow in the Menefee Formation and Point Lookout Sandstone, respectively. Lack of data precludes contouring the potentiometric surface for the Point Lookout north of Arroyo Chico, but ground-water flow from the south is well shown. A component of flow from deep aquifers in the San Juan Basin toward the southeast also exists in this region (Lyford, 1979). Movement of water in alluvium would be expected to be downslope in response to gravity, in basically the same directions as stream flow.

75 Ground-water discharge in the Arroyo Chico-Torreon Wash area is both natural and induced. Natural discharge consists of spring flow, especially in the southern part of the area around the base of Mesa Chivato, and evapotranspiration, especially along channels. Induced discharge occurs at pumping and flowing wells.

Controls of quality

76 Table 4 shows chemical analyses of water from wells in the study area; table 5 gives results of chemical analyses of water from springs in the study area. Dissolved materials in ground water come from dissolution of minerals in rocks through which the water flows, subsurface leakage, and mixing with waters from adjacent units. For example, the Point Lookout Sandstone is a leaky, confined aquifer. In areas of recharge, leakage from the overlying Menefee Formation probably occurs, resulting in deterioration of the quality of water in the Point Lookout. As ground water flows downdip, away from recharge areas, leakage of water from the Point Lookout into the Menefee Formation would occur because of greater hydraulic head in the Point Lookout. Leakage of water from the underlying Mancos Shale into the Point Lookout would also occur, probably causing deterioration of the quality of water in the Point Lookout. In alluvial aquifers, water quality may deteriorate downstream because of the contribution of poorer quality water by discharge from bedrock sources and subflow from tributaries.

77 Locally, lithology exerts a strong control on the quality of ground water. For example, the high sulfate content of waters from coal beds in the Menefee Formation probably is the result of dissolution of iron-sulfide minerals and the oxidation of organic materials. Calcium and carbonate in ground waters in the area probably result from dissolution of calcite cement. Ground water in the area is commonly of the sodium-sulfate or sodium-bicarbonate type (fig. 6). The source of much of the sodium in the waters may be clay minerals in the matrix of sandstones and subsurface leakage and mixing with waters from confining layers composed of semipermeable shales.

78 Quality of water from the Menefee Formation and Point Lookout Sandstone is generally better south of Arroyo Chico (figs. 5 and 10). This pattern is most obvious for the Point Lookout, in which the water quality gradually becomes worse toward Arroyo Chico from the south, and rapidly deteriorates north of the stream (Craigg, 1980, fig. 21). This quality difference probably results from mixing of waters moving toward Arroyo Chico from the north and south; waters from the south (Mount Taylor) may have a shorter residence time, resulting in better water quality south of Arroyo Chico.

WATER USE AND SUPPLY

Rural dwellings

79 Inhabitants of the few scattered, permanent dwellings obtain domestic water supplies from wells or developed springs. Residents of San Luis, east of the study area, haul water to their small community from the BLM flowing well (16.04.36.232) completed in the Gallup Sandstone. People in the vicinity of Torreon, north of the study area, obtain water from a pipeline that is fed by several wells.

80 Should future water supplies be required for domestic needs in the south, the Point Lookout and Gallup Sandstones offer the best aquifer potential. In the north, the alluvium and sandstones in the Menefee Formation should yield small quantities of water to wells, although water quality may be marginal. Springs also offer potential for water supplies, especially when developed.

Livestock

81 Water for stock use is obtained mainly from wells and developed springs. A major source of stock water in the southeast part of the area is the BLM flowing well (16.04.36.232). An extensive pipeline system connects this well with several stock tanks along its route. The BLM also has constructed earthen reservoirs for the catchment of runoff.

82 Present supplies of stock water in the area probably are sufficient. If future supplies are needed, the Menefee Formation in the north, and the Point Lookout Sandstone, Gallup Sandstone, and sandstones in the Mulatto Tongue of the Mancos Shale elsewhere offer the best potential. Several springs also could be developed for stock-water supplies.

Energy-resource exploration and development

83 The New Mexico Bureau of Mines and Mineral Resources recently completed a test-drilling program to evaluate the coal resources in the Menefee Formation in this area (Tabet and Frost, 1979). Most water used for this drilling operation was taken from the BLM flowing well (16.04.36.232) completed in the Gallup Sandstone.

84 Water also will be required for development of Menefee coals. Inasmuch as local streams are ephemeral, ground water is the only suitable source of water. Water uses related to coal mining, as summarized by Shomaker and Stone (1976), include washing of coal, dust control, and reclamation of strip-mined lands; mine-mouth power generation also requires water for boiler feed and cooling. If gasification is considered feasible, water also will be required as a processing fluid.

85 Two geologic units could be expected to yield water in large enough quantities and of good enough quality for future mining operations in this area. These units are the Gallup Sandstone and Westwater Canyon Member of the Morrison Formation. Although the hydrologic characteristics of the Morrison Formation in the study area are unknown, the Morrison is a major aquifer elsewhere (Shomaker and Stone, 1976). The Dakota Sandstone has little potential as a source of water for mining-related activities because of its low yields and the poor quality of its water. The Point Lookout Sandstone also is a poor candidate for similar reasons.

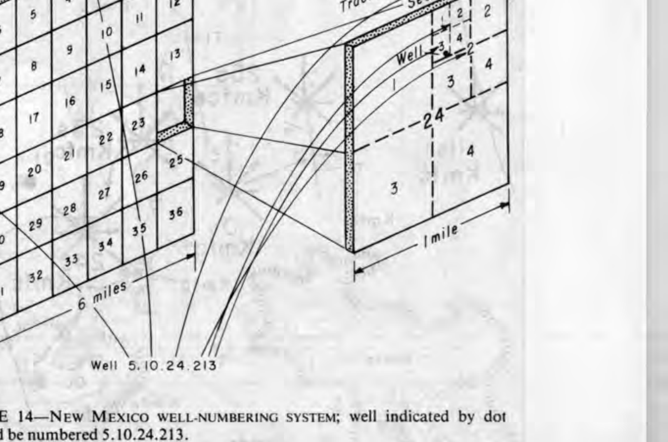

FIGURE 14—NEW MEXICO WELL-NUMBERING SYSTEM; well indicated by dot would be numbered 5.10.24.213.

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