Hydrogeology and water resources of San Juan Basin, New Mexico

HYDROLOGIC REPORT 6 New Mexico Bureau of Mines and Mineral Resources 1983

A DIVISION OF

NEW MEXICO INSTITUTE OF MINING & TECHNOLOGY

TABLE 14—SUMMARY OF GEOLOGIC AND HYDROLOGIC CHARACTERISTICS OF MAJOR AQUIFERS IN THE SAN JUAN BASIN.

Unit (age)	Brief description	Thickness (ft)	Depth (ft)	Transmissivity (ft^2/d)	Specific conductance (μmhos/cm)
Valley fill (Quaternary)	unconsolidated fluvial, colluvial, eolian deposits	generally <100	at surface	<1,000->15,000	<1,000->7,000
Chuska Sandstone (Eocene/Oligocene)	eolian sandstone, lacustrine mudstone	700–1,800	at surface	unknown	<500
San Jose Formation (Eocene)	alluvial sandstone, mudstone	<200–2,700	at surface	two tests give 40 and 120	320–3,000 (2,000 average)
Nacimiento/Animas Formations (Paleocene)	alluvial and fluvial sandstone and mudstone	418–2,232	0–2,660	no data, but up to 100 expected for coarser sandstones	>2,000
Ojo Alamo Sandstone (Paleocene)	alluvial sandstone, minor mudstone	72–315	0–2,645	50–250 within 25 mi of outcrop	<1,000 near outcrop; >9,000 at depth
Kirtland Shale–Fruitland Formation (Cretaceous)	fluvial sandstone, mudstone; coal measures	<100–>2,000	0–3,000	<10	>5,000
Pictured Cliffs Sandstone (Cretaceous)	marine sandstone	25–281	0–4,130	0.001–3	>2,000 even near outcrop; <41,000 at basin center
Cliff House Sandstone (Cretaceous)	marine sandstone	20–245	0–6,150	<10–>60	2,000 near outcrop; >30,000 at depth
Menefee Formation (Cretaceous)	coal measures	400–1,000	0–6,262	<50	<3,000 south of Chaco River; no data in north
Point Lookout Sandstone (Cretaceous)	marine sandstone	40–415	0–6,400	240 (north of Crownpoint); 2 or less elsewhere	>1,500 (59,000 in basin center)
Crevasse Canyon Formation (Cretaceous)	coal measures, marine sandstone	420–700	0–3,200	probably <50	<2,000 near outcrop; greater elsewhere
Gallup Sandstone (Cretaceous)	marine sandstone	93–700	0–4,300	up to 400 in southwest; 100 or less in northeast	<1,000 near outcrop; 4,000 at northeast limit
Dakota Sandstone (Cretaceous)	marine sandstone, coal measures	200–350	0–8,500	variable; up to 100 locally	<2,000 near outcrop; >10,000 at depth
Morrison Formation (Jurassic)	alluvial and fluvial sandstone, mudstone	420–900	0–8,900	up to 500 in south; decreases northward	<1,000 in south and west; >10,000 at depth
Bluff–Cow Springs Sandstones (including Summerville Formation) (Jurassic)	eolian sandstone	60–200	0–9,000	probably <50	<2,000 near outcrop; greater at depth
Entrada Sandstone	eolian sandstone	130–740	0–9,310	<50 near outcrop; >100 at depth	<1,500 near outcrop; >10,000 at depth

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HYDROGEOLOGY AND WATER RESOURCES OF SAN JUAN BASIN, NEW MEXICO

FRONT COVER—CHETRO KETL RUINS at Chaco Canyon National Monument with Cliff House Sandstone in background (see fig. 41, p. 33).

FRONTISPIECE—LANDSAT MOSAIC OF NORTHWEST NEW MEXICO; study area indicated by outline. Note limited extent of active vegetation (red), extensive dissection by the San Juan River and its tributaries (upper left), Navajo Reservoir (black, just below Colorado border at upper right center), and encirclement of San Juan Basin by mountains. Source: *Satellite photomap of New Mexico,* New Mexico Bureau of Mines and Mineral Resources, Resource Map 12 (color), 1980.

Hydrologic Report 6

New Mexico Bureau of Mines & Mineral Resources

A DIVISION OF
NEW MEXICO INSTITUTE OF MINING & TECHNOLOGY

Hydrogeology and water resources of San Juan Basin, New Mexico

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Preface

In 1972, the New Mexico Bureau of Mines and Mineral Resources undertook a study of the availability of ground water for coal surface mining in the San Juan Basin. Funding for the study was provided in part by a grant from the New Mexico Water Resources Research Institute and by contributions from El Paso Natural Gas Company, Peabody Coal Company, and Western Coal Company. The study was expanded in 1974 to include the rest of the New Mexico portion of the basin and the potential water-resource problems and impact of other energy-development activities in the region. The expanded study was designed as a 5-yr cooperative effort of the Bureau, the U.S. Geological Survey, and the New Mexico State Engineer (now Water Resources Division, Natural Resources Department). Results of the initial study were presented by Shomaker and Stone (1976); this report is the final product of the expanded 5-yr study.

Like the study, preparation of this report also was a cooperative effort. The contributions of the various coauthors are given below; titles and affiliations are as of August 1980. In addition to integrating the various parts of the report, I prepared the abstract, introduction, and index; the chapters on regional setting and hydrogeology; the introductory remarks and geologic characteristics sections under aquifers in the chapter on ground-water resources; the introductory remarks and coal section in the chapter on water for energy development; and the introductory remarks and municipal supply sections in the chapter on water for other uses. F. P. Lyford and P. F. Frenzel, hydrologists, U.S. Geological Survey, provided the chapter on surface-water resources; the introductory remarks, overview, and hydrologic properties and water-quality sections under aquifers in the chapter on ground-water resources; the uranium and petroleum sections in the chapter on water for energy development; and the irrigation section in the chapter on water for other uses. N. H. Mizell, geologist, New Mexico Bureau of Mines and Mineral Resources, compiled the subsurface stratigraphic information and, working with me, prepared the subsurface maps and cross sections. E. T. Padgett, hydrologist, U.S. Geological Survey, compiled the well records and water-quality tables. F. P. Lyford, P. F. Frenzel, and I contributed jointly to the summary and conclusions, references, and glossary. These contributions are itemized merely for information; it is not necessary to cite individuals when referencing their portions of the report.

A few explanatory remarks are appropriate concerning organization, terminology, units of measurement, documentation of facts, and suggested approaches to finding information of interest. This report is organized into four parts: background information (introduction and regional setting), basic water-resource information (surface-water resources and ground-water resources), interpretation of geologic controls on the hydrologic system (hydrogeology), and evaluation of the role of water in the growth of northwest New Mexico (water for energy development and water for other uses). All technical terms used are defined in the glossary at the end of the report. Measurements are reported in English units with the exception of dissolved-solids concentrations for which the common metric unit, milligrams per liter (mg/L) is used. A table for converting English units to metric units with a key to abbreviations is given below. Facts in the text are often documented by reference to various types of summary diagrams, generalized maps, or schematic cross sections. Sheets 5, 6, and 7 (pocket, inside back cover) contain 48 figs. that refer to various parts of the text. More detailed information is provided elsewhere by means of tables or figures; consult the table of contents to identify the location of such additional information. In the interest of saving space and cost, the more lengthy tables (1, 2, 5, 6, 7, and 11) are presented in microform (pocket, inside back cover). To find information about a given aquifer, regardless of the area, see ground-water resources. To learn about the water resources of a given area, with or without respect to a given aquifer, scan the well records (table 1) and chemical analyses (table 6) using the location of interest. A summary of geologic and hydrologic characteristics of aquifers is given in table 14 (inside front cover). Consult the index for the location of other information.

English-to-metric conversion factors

Multiply English units	by	to obtain metric units
acres (not abbreviated)	0.4047	hectares (ha)
acre-feet (acre-ft)	1.2334	cubic meters (m^3)
barrels of oil (bbls)	0.1589	cubic meters (m^3)
cubic feet (ft^3)	0.02831	cubic meters (m^3)
darcies	9.66×10^{-6}	meters per second (m/s)
feet (ft)	0.3048	meters (m)
feet per day (ft/d)	0.3048	meters per day (m/d)
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)	0.06309	liters per second (L/s)
gallons per minute per foot (gpm/ft)	0.2072	liters per second per meter [(L/s)/m]
inches (not abbreviated)	2.54	centimeters (cm)
miles (mi)	1.609	kilometers (km)
square miles (mi^2)	2.590	square kilometers (km^2)
ton (short)	1.13267	cubic meters (m^3)

ACKNOWLEDGMENTS—The assistance of Scott Anderholm, Dan Brown, Bob Brod, and Steve Craigg, former graduate research assistants under my supervision at New Mexico Tech, in expanding the geologic data base for the parts of the San Juan Basin adjacent to their thesis study areas is gratefully acknowledged. Chemical analyses of water samples collected during these thesis studies were obtained under the direction of Lynn Brandvold, Bureau chemist. Frank Campbell, Bureau coal geologist, clarified coal reserves and current mining activity in the San Juan Basin. Thanks are also due the following U.S. Geological Survey personnel for assistance in the preparation of many of the tables and figures presented here: Craig Condon, Jesse Cosby, Steve Craigg, Gary Levings, Henry Lopez, Catherine McCutcheon, Raphael Padgett, John Rote, and April Warner. Energy-resource companies and their consultants, too numerous to list here, have kindly made their hydrologic data available; specific contributions are identified in the text. Also, the Technical and Engineering

Services Department of the Navajo Tribe, the U.S. Bureau of Indian Affairs, and the U.S. Public Health Service have furnished chemical analyses and records for numerous wells. The granting of access to private lands by landowners throughout this project is most appreciated. Finally, special gratitude is extended to John Shomaker, consultant, who conducted the initial study for the Bureau, for useful discussions and the large amount of information he so generously provided.

Socorro, New Mexico
January 1981

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New Mexico Bureau of Mines & Mineral Resources

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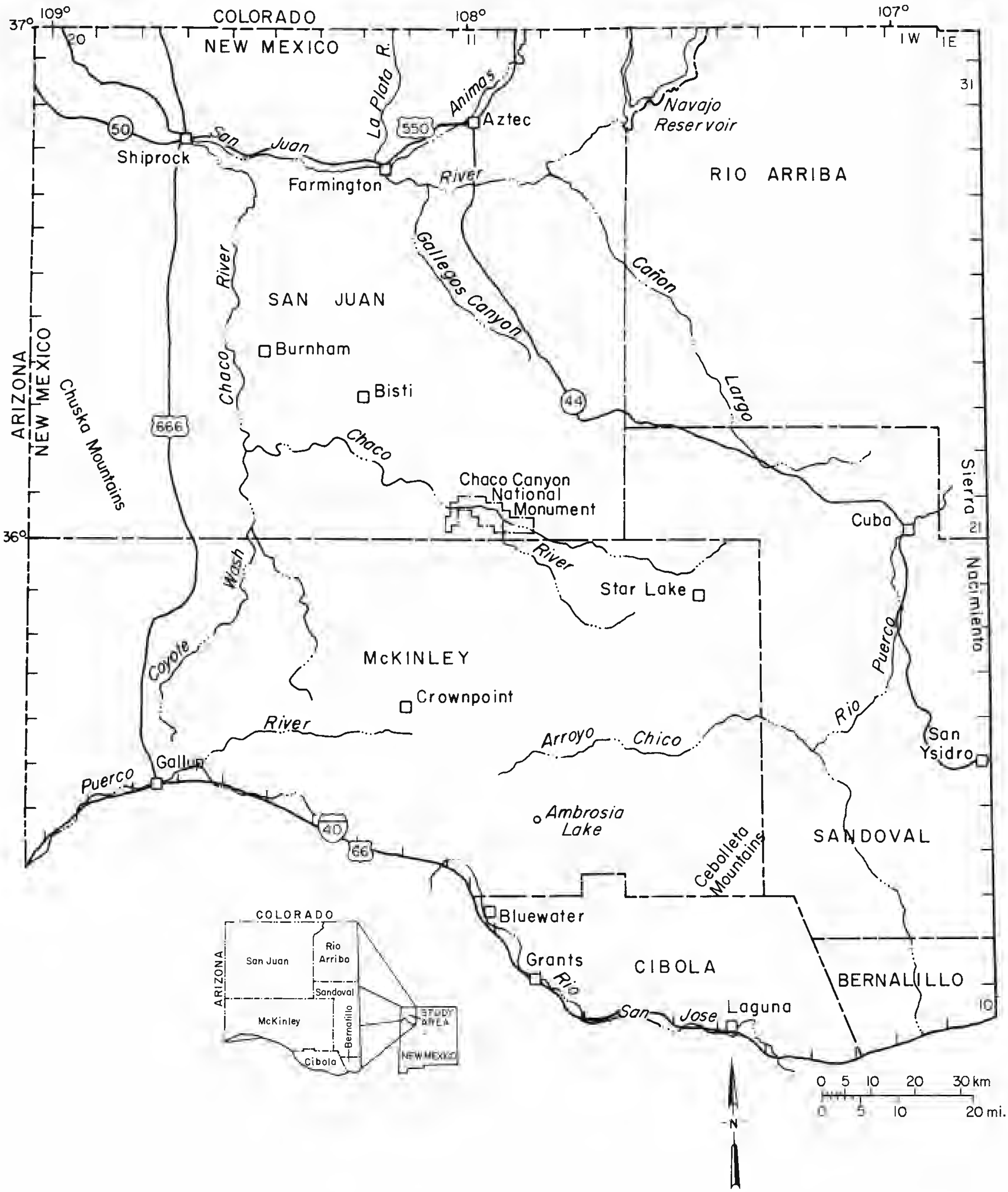


Figure 1—PLACES AND FEATURES OF REFERENCE IN AREA COVERED BY THIS STUDY.

Abstract

The San Juan Basin of northwest New Mexico contains a wealth of energy resources. Although petroleum reserves are nearly depleted, vast reserves of uranium and coal remain to be extracted. In this arid to semiarid region, surface-water resources are limited and fully appropriated. New water supplies for energy development and growing municipalities must, therefore, be derived from negotiated surface water or ground water. Major aquifers include Quaternary valley fill and sandstones of Tertiary, Cretaceous, Jurassic, and Triassic age. Ground water in these aquifers is generally confined, but some interaquifer leakage occurs; transmissivities between 100 ft^2/d and 200 ft^2/d are characteristic. Specific conductance of ground waters is variable (less than 500 μmhos to more than 30,000 μmhos). Regional flow is from elevated recharge areas on the basin margin toward discharge areas along the San Juan River in the northwest and along the Rio Puerco in the southeast. Occurrence, movement, and quality of ground water are subject to considerable geologic control provided by the distribution and characteristics of the sandstone aquifers, geologic structure, and regional stratigraphy. The principal uranium orebody is also a regional aquifer. Uranium-mine dewatering has caused water-level declines; greater declines will accompany construction of deeper mines. Post-mining persistence of toxic substances is unknown, but such material may remain near the mine cavity because of local geochemical conditions. Water is not generally encountered in strip mining; supply is the major water problem in coal development. Potential sources of water include deep aquifers, excess uranium-mine effluent, and Tertiary sandstone aquifers in areas adjacent to the coal belt. Impacts of return flow from the Navajo Indian Irrigation Project on San Juan River quality may be difficult to distinguish from impacts of energy development and municipal activities. Irrigated acreage in river valleys is expected to decrease as water rights are transferred to other uses, such as energy development. Future water needs of municipalities, growing in response to energy development, may be met in some areas by tapping deeper aquifers and in others by obtaining uranium-mine effluent. Water treatment may be required in both cases.

Introduction

The San Juan Basin of northwest New Mexico (fig. 1) encompasses many of the peoples, places, and products for which the state is known. The area is home to the Jicarilla Apache, Laguna, Navajo, and Ute Mountain Indians. It is the land of Chaco Canyon National Monument, the Four Corners, Navajo Lake, and Ship Rock. The familiar towns of Aztec, Bloomfield, Crownpoint, Cuba, Dulce, Farmington, Grants, Gallup, and Thoreau range in character from sleepy villages to booming energy towns. The San Juan Basin is also the site of major oil and gas fields whose names reflect their colorful setting: Cha-Cha, Devil's Fork, Horseshoe, Many Rocks, and Rattlesnake. The Navajo mine and Four Corners powerplant west of Farmington constitute the world's largest contiguous coal mine and electric-power-generating complex. The Grants uranium region, spanning the southern edge of the basin, has generally led the nation in uranium production since the early 1950's.

Developing this wealth of energy resources has been the major activity in the region for the past 30 yrs. Because of the arid setting, water plays a key role in this development. In response to concern about the availability of water for coal extraction and the potential impacts of dewatering of uranium mines on regional water resources, the New Mexico Bureau of Mines and Mineral Resources, the U.S. Geological Survey, and the New Mexico State Engineer entered into a cooperative hydrogeologic study in 1974 centering on the post-Triassic sequence of the San Juan Basin. The main objective of this report is to present the results of the cooperative 5-yr study.

Approach and methods

In the San Juan Basin study, the New Mexico Bureau of Mines and Mineral Resources was responsible for compiling the basic geologic data, and the U.S. Geological Survey was responsible for compiling the basic hydrologic data. To accomplish their task, Bureau workers compiled stratigraphic and petrographic information through field and laboratory studies. From these studies, structure, depth, and thickness maps, as well as textural and mineralogic classifications, were obtained for the major aquifers in the post-Triassic sequence of the basin (Stone and Mizell, 1978; Stone, 1971a, b). A basinwide geologic map was compiled (sheet 1, in pocket), and regional geologic cross sections (sheets 2–4, in pocket) were constructed. The distribution of regional sandstone bodies within the Gallup Sandstone was also mapped (Mizell and Stone, 1979).

The Survey compiled existing data (largely published) from numerous well records, aquifer tests, and water analyses. The stratigraphic information compiled by the Bureau was used to identify aquifers penetrated by wells for which depths were reported but not the aquifer. Water-level, transmissivity, and water-chemistry maps were then prepared for each major aquifer (Lyford, 1979).

Because the study was regional in scope, some appreciation of local conditions and problems in several key areas of the basin was needed. Such local detail was provided by four masters thesis studies at New Mexico Institute of Mining and Technology, sponsored by the Bureau of Mines and Mineral Resources. These involved study of the hydrogeology and water resources of four 15-minute-quadrangle-sized areas (fig. 1): The Aztec quadrangle (Brown, 1976; Brown and Stone, 1979), the Ambrosia Lake–San Mateo area (Brod, 1979; Brod and Stone, 1981), the Cuba quadrangle (Anderholm, 1979; Anderholm and Stone, in preparation), and the Arroyo Chico–Torreon Wash area (Craigg, 1980; Craigg and Stone, in press). The Aztec quadrangle in San Juan County was selected because it is an area heavily dependent on surface water, the availability of which might be diminished with increasing coal development in the region. The Ambrosia Lake–San Mateo area provided insight into water-resource problems of an active uranium mining area in Cibola and McKinley Counties. The Cuba quadrangle (Rio Arriba and Sandoval Counties) afforded an opportunity to study an area which straddles the basin margin and to evaluate the water resources of a potential boom town (Cuba) for coal development in the southeast part of the basin. The Arroyo Chico–Torreon Wash area (McKinley and Sandoval Counties) provided an opportunity to assess the water-resource situation in an area of potential coal development.

Previous work

This study was facilitated by the vast amount of previous work on the area. Many geologic reports have been prepared on the San Juan Basin because of its wealth of energy resources. Similarly, a great deal of hydrologic information has been previously compiled. Although it is beyond the scope of this section to list all of these, it is useful to identify some of the classical or more comprehensive works; these in turn give additional references. Other works are cited at appropriate places in the text.

The geology of the area has been mapped at a scale of 1:500,000 by Dane and Bachman (1965). Geology is also covered at a scale of 1:250,000 by four 1°×2° sheets: the Shiprock quadrangle (O'Sullivan and Beikman, 1963), the Gallup quadrangle (Hackman and Olson, 1977), the Albuquerque quadrangle (Wyant and Olson, 1978), and the Aztec quadrangle (Manley and others, 1978). The location of these maps is shown on sheet 1.

The geologic structure of the San Juan Basin has been discussed by Kelley (1950, 1951, 1963), Hunt and Dane (1954), and Baltz (1967). Classical stratigraphic works include those by Sears and others (1941), Harshbarger and others (1957), Hollenshead and Pritchard (1961), and Baltz and others (1966). References on specific stratigraphic units and energy resources are given in the text.

Comprehensive hydrologic studies include those by Gregory (1916), Waring and Andrews (1935), Berry (1959), and Cooley and others (1969). Jobin (1962) addressed the transmissive character of Colorado Plateau strata. Baltz and West (1967) and Brimhall (1973) evaluated the water-resource potential of the Tertiary strata in the central part of the San Juan Basin. Gordon (1961), Cooper and John (1968), Mercer and Cooper (1970), and Shomaker (1971) reported on the geology and ground water of the southern part of the basin.

Well numbering

Two systems of numbering water wells and springs are used in this report; both are based on location. The first is the system employed by the New Mexico State Engineer that makes use of the Public Land Survey System (township, range, and section). In this system, each well or spring has a unique location number consisting of four parts separated by periods: 21.07.28.213. The first part (on the left) refers to the township, the second designates the range, and the third identifies the section (fig. 2a). The fourth locates the well or spring within the section to the nearest 10-acre tract as follows: each section is divided into quarters which are assigned numbers such that the northwest quarter is number 1, the northeast quarter is number 2, the southwest quarter is number 3, and the southeast quarter is number 4. Each quarter section is then divided into quarters that are numbered in the same manner. Each quarter-quarter section is similarly divided and numbered. If the location of a well or spring cannot be determined to quarter-quarter section or quarter-quarter-quarter section, nothing is entered in the appropriate position in the right-hand or fourth part of the number. A well designated 21.07.28.213 is located in the SW¼NW¼NE¼ sec. 28, T. 21 N., R. 7 W. (fig. 2a). A spring located in the NW¼ sec. 31, T. 2 S., R. 1 W. would be numbered 2.1.31.1. All wells and springs in the study area are north of the New Mexico base line and west of the New Mexico principal meridian (table 1, microfiche pocket).

In land grants not surveyed by the Public Land Survey System, locations were approximated by projecting township, range, and section lines from adjacent areas.

A different numbering system, keyed to Bureau of Indian Affairs (BIA) quadrangles, is used for the main part of the Navajo Indian Reservation. This area has been divided into 15-minute quadrangles, each bearing a unique number. The well or spring number consists of three parts (for example, 32-3.65×17.05). The first part is the BIA quadrangle number, the second is the distance in miles west of the east line, and the third part is the distance in miles south of the north line. Thus, the well numbered 32-3.65×17.05 is located in BIA quadrangle 32, and lies 3.65 mi west of the east line and 17.05 mi south of the north line (fig. 2b).

In addition to these location numbers, the water wells have also been located by latitude and longitude coordinates (table 1).

Wells used in compiling subsurface stratigraphic data are shown on fig. 3 and are identified in table 2 (microfiche pocket). These wells were numbered sequentially as an aid in correlating fig. 3 with table 2.

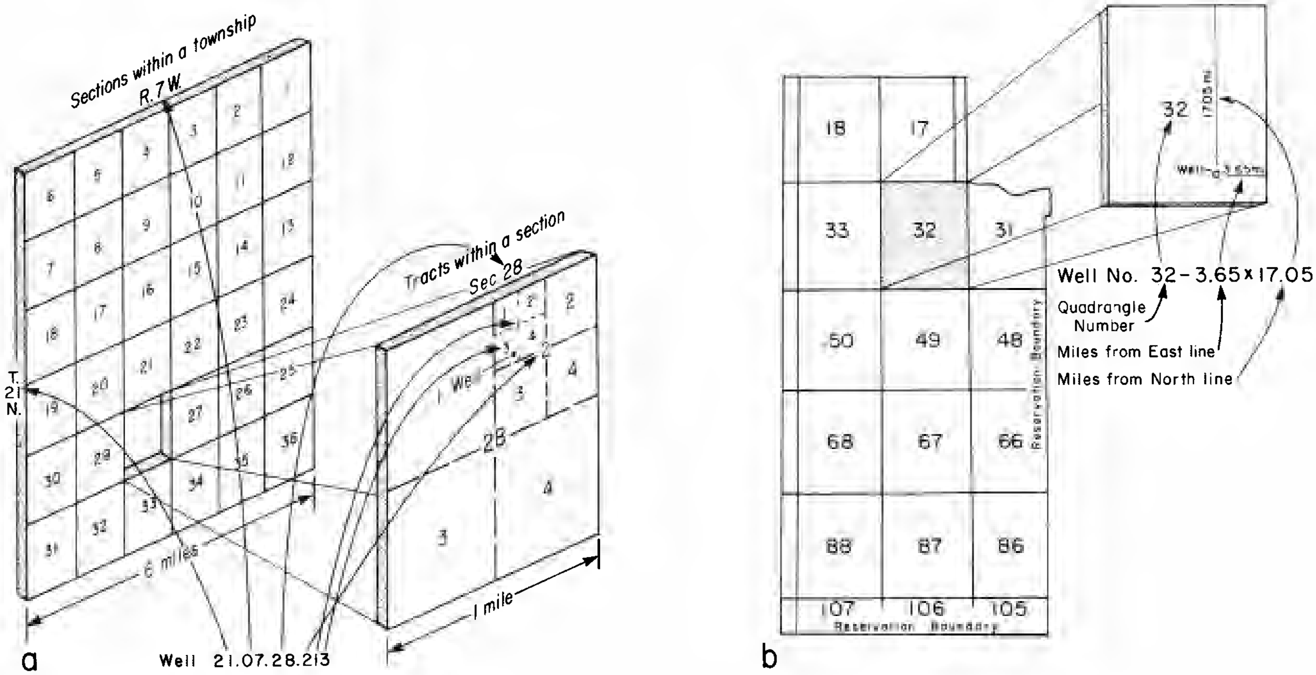


Figure 2—WELL-NUMBERING SYSTEMS USED IN THIS REPORT: a) system used in areas covered by public land grid, b) system used on Navajo Indian reservation.

Regional setting

The name San Juan Basin is applied to both the drainage basin of the San Juan River and the larger structural depression covering approximately 30,000 mi^2 of northwest New Mexico and southwest Colorado. As used in this report, the term refers to the structural basin unless "River" or "drainage" are included. Furthermore, this study was restricted to the New Mexico portion of the basin, excluding the Gallup sag, the Acoma embayment, and the Chama Basin. The study area encompasses all of San Juan County, all but the southwest part of McKinley County, and parts of Bernalillo, Rio Arriba, Sandoval, and Cibola Counties (fig. 1).

Physiography

The San Juan Basin accounts for half of the Navajo section of the Colorado Plateau physiographic province (Fenneman, 1931). The area is characterized by a wide range of land forms: broad uplands and wide valleys, deep canyons, badlands, volcanic plugs, mesas, buttes, and hogbacks. In areas away from canyons and mesas or buttes, local relief is generally low.

Areas of high elevation nearly encircle the basin: on the west are the Chuska Mountains (8,000 ft), the Lukachukai and Carrizo Mountains, just across the state line in Arizona (approximately 9,500 ft); on the south are the Zuni Mountains (8,000 ft) and Mount Taylor (11,389 ft); and on the east are the Sierra Nacimiento and San Pedro Mountains (10,624 ft). The San Juan Mountains, lying wholly in Colorado, complete the enclosure on the north. Maximum relief in the New Mexico part of the basin is approximately 6,580 ft, based on Mount Taylor as the highest point and the San Juan River at the Four Corners as the lowest point (approximately 4,800 ft).

Climate

The climate is generally arid to semiarid, but precipitation varies considerably across the region (table 3). As might be expected, a map of normal annual precipitation prepared by the Soil Conservation Service (U.S. Bureau of Reclamation, 1976) shows highest values are associated with mountainous areas: 30 inches at Mount Taylor, 25 inches in the San Pedro Mountains, and 20 inches in the Chuska Mountains. In the central part of the basin, annual precipitation is generally 10 inches; values as low as 8 inches occur along the San Juan River west of Farmington and along the north-flowing reach of the Chaco River. Reported extremes of precipitation include 4.00 inches in 24 hrs at Dulce (Maker and others, 1973a), 3.4 inches in 24 hrs at Regina (Maker and others, 1971), and 11.25 inches in a single month (February) at Ft. Wingate (Maker and others, 1974a).

Most precipitation (approximately 60% of the total) occurs during summer months as local, often intense, thunderstorms. Higher elevations also receive considerable winter precipitation. The source of summer moisture generally is the Gulf of Mexico; the source of winter precipitation is the Pacific Ocean. Mountain barriers and long distances lying between both of these

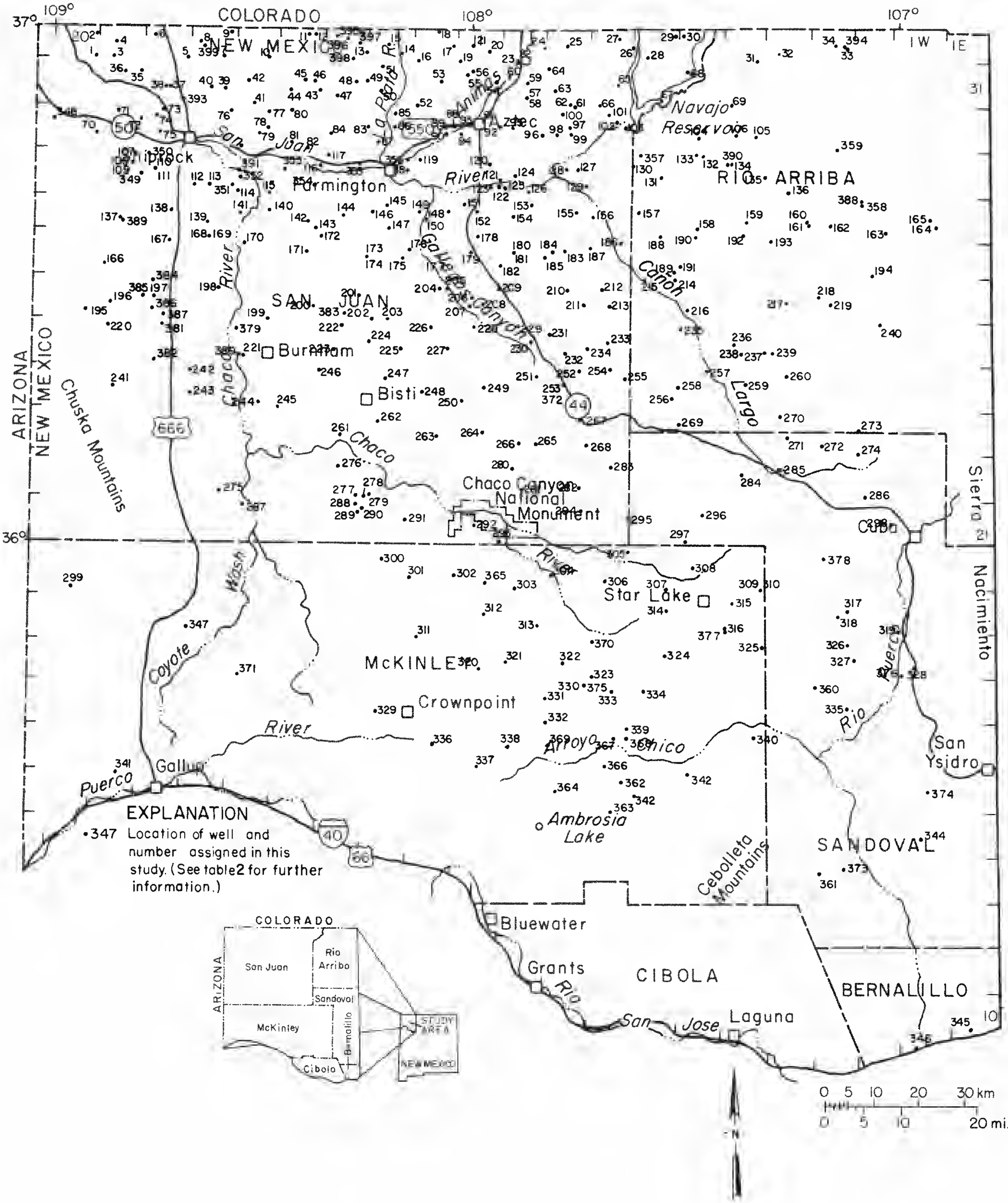


Figure 3—LOCATION OF WELLS USED IN COMPILING SUBSURFACE STRATIGRAPHIC DATA. See table 2 (microfiche pocket) for identification of wells used.

TABLE 3—Average annual temperature and precipitation at selected stations in the San Juan Basin. [1]Figures and letters indicate distance (mi) and direction from Post Office; [2]SJ = San Juan (Maker and others, 1973b), MK = McKinley (Maker and others, 1974a), SDV = Sandoval (Maker and others, 1971), RA = Rio Arriba (Maker and others, 1973a), V = Valencia (Maker and others, 1974b). Note: This part of Valencia County is now Cibola County.

Station	Elevation (ft)	Temperature Mean max. (°F)	Temperature Mean min. (°F)	Temperature Yrs of record	Precipitation Mean annual (inches)	Precipitation Yrs of record	County and source[2]
Aztec Ruins National Monument	5,640	68	35	30	9.33	59	SJ
Bloomfield (35E)[1]	5,794	68	35	51	8.46	60	SJ
Chaco Canyon National Monument	6,125	68	34	25	8.67	28	SJ
Crownpoint	6,978	64	38	41	10.48	47	MK
Cuba	6,945	64	29	20	14	22	SDV
Dulce	6,950	63	25	43	17.08	52	RA
Farmington Airport	5,494	67	37	19	8.12	20	SJ
Fruitland	5,165	69	36	47	6.96	55	SJ
Ft. Wingate	7,000	64	36	34	13.62	69	MK
Gallup	6,465	67	31	8	9.44	12	MK
Grants–Milan Airport	6,520	66	32	8	8.83	13	V
Laguna	5,815	69	38	42	9.86	48	V
Lybrook	7,160	62	34	8	12.01	9	RA
Newcomb	5,565	70	35	11	5.35	13	SJ
Regina	7,450	62	29	42	16.15	46	SDV
Shiprock (1E)[1]	4,974	70	37	29	7.04	32	SJ
Tohatchi	6,800	66	39	34	10.47	43	MK

sources and northwest New Mexico account for its aridity.

Maximum temperatures generally occur in July; minima are obtained in January (table 3). The highest maximum temperatures are associated with the lower elevations, such as the valleys of the Chaco and San Juan Rivers; lowest minimum temperatures are associated with the higher elevations. Temperature extremes include a high of 110°F at Fruitland (Maker and others, 1973b) and a low of −48°F at Dulce (Maker and others, 1973a). Detailed (monthly) temperature data may be found in the sources cited in table 3.

Wind directions in the basin vary locally because of topography. Along the San Juan River, for example, easterly and westerly winds dominate, owing to the east-west orientation of the valley (Maker and others, 1973b). In Sandoval County, westerly and southwesterly winds predominate, but topography causes considerable local variation (Maker and others, 1971). Westerly winds are common in McKinley County (Maker and others, 1974a). Spring is the windiest season and spring wind velocities are strongest, averaging 10–12 mph, whereas summer winds average only 8 mph (Maker and others, 1973b).

Class-A-pan-evaporation data for the region are sparse. An annual average of 67.37 inches has been reported for a station 3 mi northeast of Farmington for the period 1948–1962; the highest monthly value, 10.50 inches, was observed in June and the lowest value, 0.74 inches, was observed in December (Cooper and Trauger, 1967, p. 190). The average evaporation during the period May through October is 46 inches at El Vado Dam (28 mi southeast of Dulce) and 52 inches at Gallup; annual values of 63 inches and 72 inches have been estimated for these two stations, respectively (Maker and others, 1973a and 1974a).

Vegetation and soils

Upper Sonoran through Canadian life zones have been recognized in the San Juan Basin (Bailey, 1913). Most of the basin lies in the upper Sonoran zone, marginal mountain slopes lie in the Transition zone, and highest parts of bordering mountains lie in the Canadian zone (Cooper and Trauger, 1967).

According to a map by the Soil Conservation Service (U.S. Bureau of Reclamation, 1976), most of the basin would be classified as grassland with yuccas and cacti. This includes the areas drained by the Chaco River and bordering the San Juan River west of Bloomfield. Next in abundance is land covered with piñon and juniper; such vegetation is characteristic of the lower piedmont slopes and the area lying generally northeast of a line connecting Aztec and Cuba. Some areas in the central part of the basin are classified as brushland (big sagebrush, rabbitbrush, gambel oak). The highest parts of the bordering mountains are covered primarily with ponderosa pine. Drainageways are dominated by riparian vegetation.

An area as large as the San Juan Basin contains a wide range of soils types. Detailed description of these soils is not possible within the scope of this report, but the following generalizations, based on a map prepared by the Soil Conservation Service (U.S. Bureau of Reclamation, 1976), should be useful. The northwest part of the basin, that part associated with the bulk of the drainage area of the Chaco and San Juan Rivers in San Juan County, is characterized by light-colored, cool, desertic soil types. The highest elevations, in mountains bordering the basin, are characterized by moderately dark to dark mountain soils. The area lying between these two zones is characterized by dark-colored, western plateau soils.

More specific soil information is available in one of two forms. General county soil maps, with descriptions of soil associations and characteristic vegetation as well as the irrigation potential and various engineering properties of the local soils, are available for all of the counties covered by the San Juan Basin (Maker and others, 1971, 1973a, b, 1974a, b). Detailed soil maps have been published for only Valencia (includes area of new Cibola County) and Bernalillo Counties. Detailed soil reports for other counties in the study area are in various stages of completion by the Soil Conservation Service.

General geology

The San Juan Basin is a Laramide (Late Cretaceous-Early Tertiary) depression lying at the eastern edge of the Colorado Plateau. Maximum structural relief was reported by Kelley (1950) as 10,000 ft. Several structural elements have been recognized in the basin (fig. 4). The most distinct type of structure in the Colorado Plateau is the monocline, and the San Juan Basin displays excellent examples (fig. 5). The largest, The Hogback monocline, forms a sharp boundary between the marginal platforms and the central basin.

The maximum stratigraphic thickness encountered is 14,423 ft, recorded in an oil well near the structural center of the basin. Sedimentary rocks of Jurassic and Cretaceous age crop out around the basin rim and over a broad area in the southern and western parts of the basin (sheet 1). Tertiary sedimentary rocks cover most of the central basin (northeast part of the area). Quaternary deposits are restricted mainly to major valleys. The time-stratigraphic nomenclature of the rocks involved in this study is best shown in a schematic cross section of the basin (fig. 6).

The Jurassic strata were deposited in various desert environments (dune fields, playas, saline lakes, and wet alluvial aprons). Alluvial or fluvial deposition continued, at least locally, into Early Cretaceous time; however, the record is spotty and incomplete, suggesting that this was also a period of at least local nondeposition or erosion. Late Cretaceous time was markedly different. The shoreline of the vast but shallow inland sea that bisected the North American continent from the Arctic Ocean to the Gulf of Mexico during this time shifted back and forth across the area now occupied by the San Juan Basin. The sequence of alternating marine and nonmarine coastal deposits that constitutes the Upper Cretaceous of the region gives silent testimony to the restless nature of this shoreline. By Tertiary time, the sea had retreated from the area and the formation of the basin was accelerating. Structural activity, at least uplift of marginal regions, continued during Paleocene time, as shown by the angular unconformity between the Nacimiento Formation (Paleocene) and overlying San Jose Formation (Eocene) in the area opposite the Nacimiento uplift north of Cuba (fig. 7).

Although the Chuska Sandstone, which caps the Chuska Mountains on the west side of the basin, is stated to be at least Oligocene or possibly late Eocene (Hackman and Olson, 1977), strata of Oligocene, Miocene, and Pliocene age are generally lacking in the basin proper. Such deposits were either never laid down, or have been subsequently removed by erosion. There is much evidence that late Eocene or pre-Oligocene time was marked by extensive erosion in many areas of the Rocky Mountains and adjacent midcontinent (Pettyjohn, 1966; Epis and Chapin, 1975; Scott, 1975). As much as 1,000 ft of the San Jose Formation may have been stripped away in the basin center. If younger Tertiary deposits were laid down in the basin, no trace of them remains. Quaternary deposition included the formation of outwash terraces along the San Juan River and its tributaries (Pleistocene), the growth and migration of sand dunes on higher plateaus (Pleistocene and Recent), and the cutting and filling of alluvial channels throughout the area (Richmond, 1965; Cooley, 1978; Love, 1980).

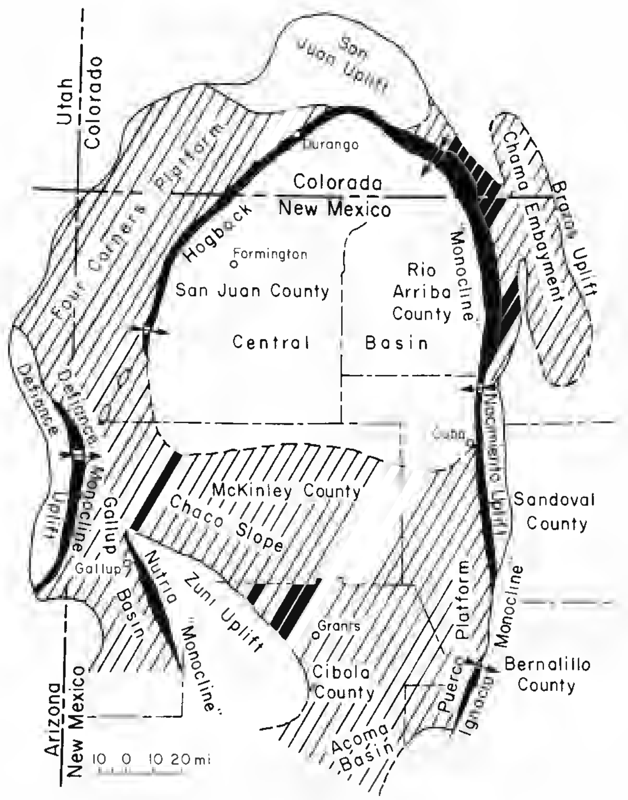


Figure 4—Structural elements recognized in San Juan Basin (modified from Kelley, 1951).

Land use and ownership

Lands at lower elevations are used principally for stock grazing (cattle and sheep), whereas those at higher elevations are used for timber production, wildlife habitat, and various recreational functions (U.S. Bureau of Reclamation, 1976). Irrigated agriculture is practiced in the valleys of the perennial streams and in the Navajo Indian Irrigation Project on the plateau south of the San Juan River, and dry farming is nearly nonexistent. The extraction of uranium, coal, and petroleum coincides mainly with rangelands.

The largest single category of land ownership in the

Figure 5—NUTRIA MONOCLINE, SOUTH OF GALLUP. View to south in NE¼ sec. 29, T. 15 N., R. 17 W. Dipslope on left is formed by Dakota Sandstone; cuesta on right is capped by Gallup Sandstone.

Figure 7—ANGULAR UNCONFORMITY BETWEEN NACIMIENTO FORMATION (PALEOCENE) AND SAN JOSE FORMATION (EOCENE), NORTH OF CUBA. View to north in sec. 11, T. 21 N., R. 1 W.

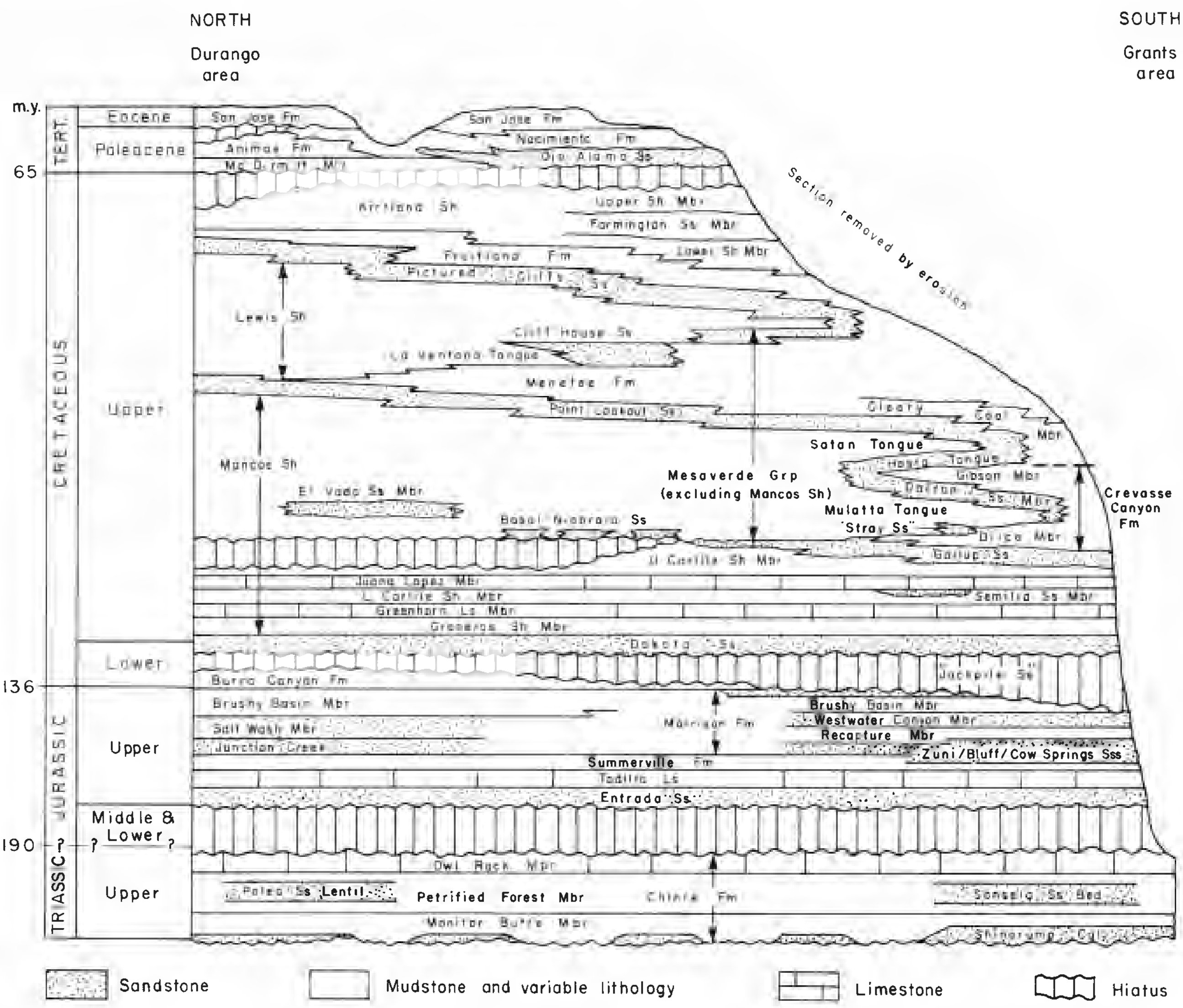


Figure 6—TIME-STRATIGRAPHIC FRAMEWORK AND NOMENCLATURE (TRIASSIC–TERTIARY) OF SAN JUAN BASIN (modified from Molenaar, 1977b).

San Juan Basin is Indian reservation, administered by the U.S. Bureau of Indian Affairs (U.S. Bureau of Reclamation, 1976). The second largest category is federal land, administered by the U.S. Bureau of Land Management. Next in abundance are nearly equal portions of state and private (individual and corporate) lands. Significant areas of U.S. Forest Service land are associated with the Zuni Mountains, Mount Taylor, and the northeast plateau (northwest Rio Arriba County). Several areas are characterized by a checkerboard ownership pattern, involving two or more owners in alternating sections.

Surface-water resources

The Continental Divide crosses the San Juan Basin, separating the Colorado River and Rio Grande drainage basins (fig. 8). The Animas and San Juan Rivers in the Colorado River basin are the largest streams in the study area and flow perennially. Most stream channels, however, are ephemeral; some are intermittent. Several reaches of streams that were formerly ephemeral now (1980) flow continuously because of contributions from energy-related activities and irrigated lands. Diversions from rivers, mostly for irrigation, alter stream-discharge patterns seasonally.

Colorado River drainage basin

The San Juan and Animas Rivers flow into New Mexico from Colorado. The San Juan, joined by the Animas at Farmington, flows westward along an arcuate course, leaving the state near the Four Corners. Since 1963, flow in the San Juan River has been controlled by Navajo Dam, which forms a reservoir with a capacity of 1,708,600 acre-ft (fig. 9). The reservoir was constructed by the U.S. Bureau of Reclamation for irrigation, flood control, recreation, river regulation, and sediment control. Since 1976, water has been diverted from Navajo Reservoir to irrigate Navajo Indian Irrigation Project lands south of the San Juan River. The San Juan–Chama diversion began transporting water from tributaries of the San Juan River upstream from Navajo Dam eastward to the Rio Grande basin in 1971. At capacity, this project will divert 100,000 acre-ft of water per year from the San Juan River.

Flow in the San Juan River at Shiprock averages 2,175 ft^3/s, which is about 200 ft^3/s less than the average flow upstream at Farmington (table 4). Although several ephemeral streams contribute flow to this reach, these contributions are more than offset by diversions for irrigation and power generation, and losses to evapotranspiration. Numerous irrigation ditches lace the San Juan and Animas Valleys.

Discharge records at gaging stations for winter months, when diversions and evapotranspiration rates are negligible, show that the San Juan River may gain as much as 200 ft^3/s between Navajo Dam (Archuleta) and Shiprock from ungaged sources. Much of this gain can be attributed to the return of irrigation water applied to valley-fill deposits during previous growing seasons. Miscellaneous measurements and observations show that contributions from ungaged tributaries are normally less than 5 ft^3/s. Ground water flowing from bedrock sources contributes a presumably small quantity to streamflow.

Tributaries of the San Juan River that contribute large quantities of water during stormflow periods include Cañon Largo, Gallegos Canyon, Chaco River, and the La Plata River (fig. 8).

Cañon Largo drains approximately 1,700 mi^2 of the central part of the San Juan structural basin. A continuous flow of generally less than 2 ft^3/s was measured at the lower end of the canyon during the winter of 1977–78 (U.S. Geological Survey, 1978). This flow volume, from bedrock and alluvium, is probably typical of Cañon Largo in its lower reach.

Gallegos Canyon drains approximately 300 mi^2. A flow of generally less than 1 ft^3/s was measured during January and February 1978 at a new gaging station 4 mi upstream from the canyon mouth (U.S. Geological Survey, 1978). The source of the flow is unknown. Contributions to the San Juan River from Gallegos Canyon are likely to increase as irrigation of adjacent land on the Navajo Indian Irrigation Project increases.

The Chaco River drains more than 4,000 mi^2 of the study area, including many areas containing coal and uranium resources. Since at least 1963, water has flowed perennially in the lower reaches of the Chaco, ranging from 10 to 30 ft^3/s during non-stormflow periods. The flow is mostly effluent from the Four Corners powerplant. It is likely that lower reaches of the Chaco flowed during the winter months even before the powerplant was constructed because of contributions from springs. Flow in several short reaches of the Chaco River upstream from the powerplant is due to springs issuing from the alluvium.

The La Plata River, near its confluence with the San Juan River west of Farmington, flows most of the time at rates of less than 5 ft^3/s. Much of the flow in the La Plata downstream from the New Mexico–Colorado state line is diverted for irrigation.

Shumway Arroyo, draining about 70 mi^2 north of the San Juan River, contributes less than 5 ft^3/s of perennial flow because of power-generation activities at the San Juan powerplant. Shumway was normally dry prior to construction of the power-generation station in 1973.

The Puerco River, draining the extreme southwest part of the study area, is not part of the San Juan River basin but lies in the drainage area of the Little Colorado River. Since 1967, the Puerco has flowed continuously at rates as high as 10 ft^3/s because of effluent from uranium-mine dewatering operations. Municipal effluent from Gallup and discharge from bedrock units also contribute to streamflow between Gallup and the New Mexico–Arizona state line.

Water-quality characteristics of selected streams are summarized in table 4. Increases in specific conductance

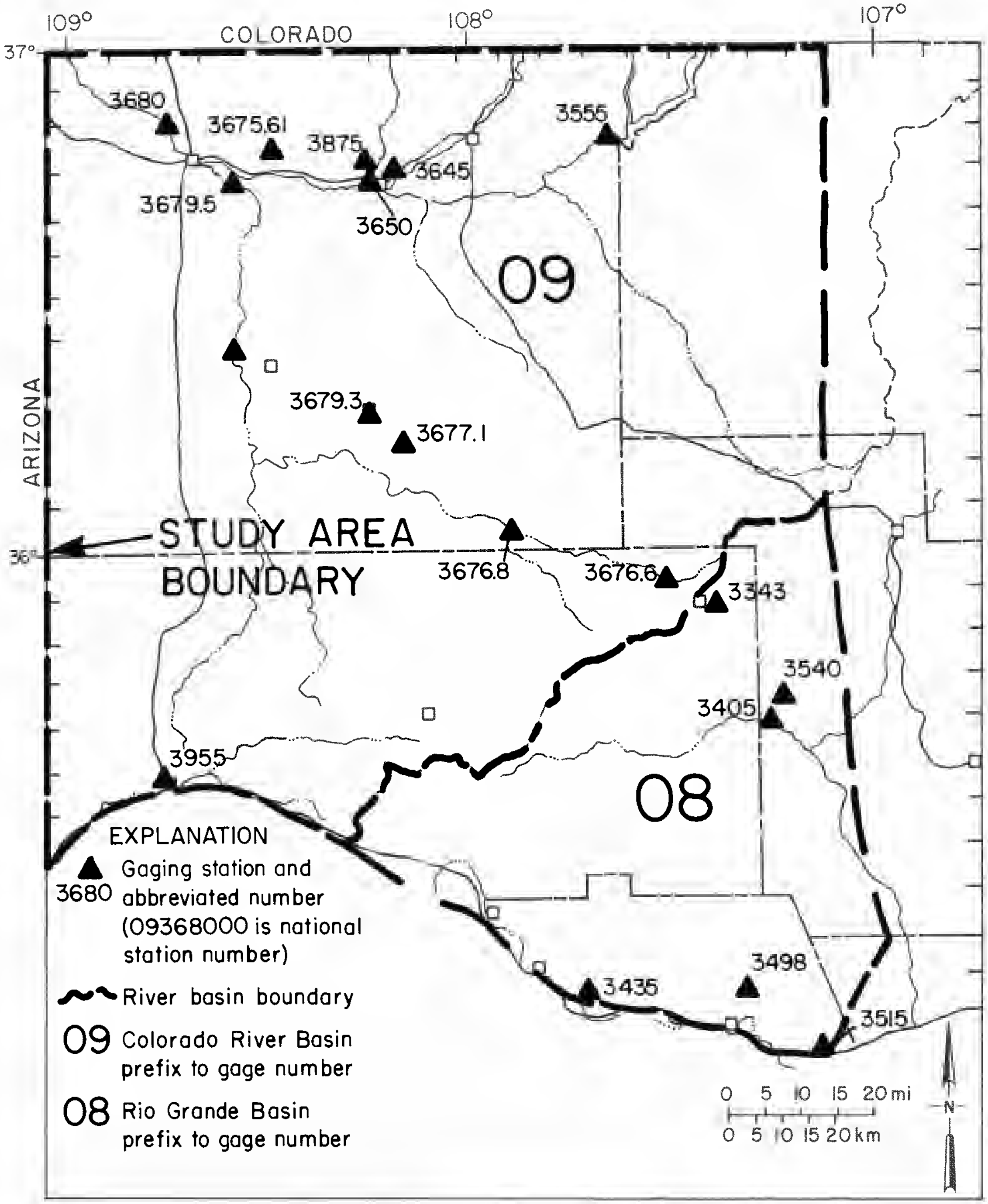


Figure 8—LOCATION OF SURFACE-WATER GAGING STATIONS IN SAN JUAN BASIN; data given in table 4.

along the San Juan River that range from a mean of 311 μmhos at Archuleta to 748 μmhos at Shiprock, can be attributed to irrigation return flow, ground-water discharge from bedrock sources, tributary inflow, and return flow from power-generation activities.

The specific conductance of non-stormflows in lower reaches of tributaries of the San Juan River generally exceeds 2,500 μmhos. The specific conductance of stormflows is highly variable throughout the flow event. Commonly, the highest conductance (as much as 7,000 μmhos) occurs early in the flow when the rising water dissolves salts left by evaporation at the channel floor. Stormflows in tributaries of the San Juan River generally have sediment concentrations exceeding 10,000 mg/L (table 4).

The specific conductance of the Puerco River increases from approximately 700 μmhos near discharging uranium mines to 1,000 μmhos or more at the New Mexico–Arizona state line; the mean specific conductance at Gallup for 1975–77 is 898 μmhos (table 4). Other water-quality characteristics of the Puerco River are discussed in the chapter on water for energy development.

Figure 9—NAVAJO DAM AND RESERVOIR, 18 mi north of Aztec; view to north.

Rio Grande drainage basin

The larger streams in the Rio Grande drainage basin part of the study area include the Rio Puerco and its tributaries, the Rio San Jose and Arroyo Chico, and the Rio Salado (fig. 7). Flow characteristics of some streams are summarized in table 4.

The Rio Puerco, which drains about 6,000 mi^2 of the study area, gains small quantities of flow from springs in headwater areas near and upstream from Cuba. Most of the remaining reach in the study area loses flow except during storms and snowmelt periods.

Arroyo Chico has a sustained low flow in its lower reaches of less than 1 ft^3/s. Craigg (1980, p. 90) found that this flow comes mostly from springs in bedrock units south of Arroyo Chico. Since 1978, some water pumped from the new uranium-mine shaft being constructed at San Mateo has been piped into the upper part of the Arroyo Chico drainage basin and is used for irrigation (J. L. Kunkler, chemist, U.S. Geological Survey, personal communication, 1979).

The Rio San Jose flows perennially in its upper reaches in the Zuni Mountains but is ephemeral in the lava plains area (Malpais) of its lower reaches. Effluent from the Grants wastewater treatment plant causes nearly continuous flow for several miles downstream from that community. San Mateo Creek, a tributary of the Rio San Jose, gains flow from uranium mining and milling operations. This water seldom reaches the Rio San Jose directly because of seepage into alluvium (Brod, 1979). The Rio San Jose gains approximately 6.5 ft^3/s on the average from springs located approximately 8.5 mi downstream from Grants. Most of this water is diverted for irrigation during the growing season, but some reaches the Rio Puerco at other times of the year.

The Rio Salado, draining approximately 100 mi^2 on the eastern side of the study area near San Ysidro, gains flow from saline springs along a fault zone at the south end of the Nacimiento Mountains.

Water quality in streams of the Rio Grande basin is poorly defined. A few samples from the Rio San Jose and Rio Paguate had specific conductances ranging from 1,280 to 2,200 μmhos (table 4). Sediment concentrations in stormflows, especially in the Rio Puerco, are among the highest in the United States, often exceeding 200,000 mg/L (data in U.S. Geological Survey files).

Ground-water resources

Because of the arid setting and limited availability of surface water, the source of most water supplies in the San Juan Basin is ground water that is obtained from wells completed in surficial valley-fill deposits of Quaternary age and sandstones of Tertiary, Cretaceous, Jurassic, and Triassic age. The Glorieta Sandstone and San Andres Limestone of Permian age are extensively developed at the southern edge of the study area along the northern flank of the Zuni Mountains (fig. 10). Most wells provide water for stock or domestic uses, but many also provide municipal and industrial supplies. Numerous springs are also used as sources of domestic and stock water.

The ground water in these aquifers is generally confined. It has been estimated that as much as 2 million acre-ft of water having less than 2,000 mg/L of total dissolved solids could be released from storage in the confined portions of these aquifers, with a resulting water-level decline of 500 ft (Lyford and Stone, 1978).

Overview

A summary of various aspects of ground-water resources of the San Juan Basin is given at the outset as a basis for understanding the detailed aquifer descriptions that follow. Furthermore, because hydrologic properties, regional flow patterns, and water quality do

TABLE 4—SUMMARY OF DISCHARGE AND WATER-QUALITY DATA AT SELECTED SURFACE WATER STATIONS IN THE SAN JUAN BASIN. [1]Data from U.S. Geological Survey (1977, various pages); [2]Data from U.S. Geological Survey's National Water Data Storage and Retrieval system (WATSTORE) for the period through 4-19-79; [3]Flow completely regulated by Navajo Dam since construction in 1962; [4]Average for 7 yrs (1955–62) prior to completion of Navajo Dam; [5]Annual maximum discharge available for 1959–69; [6]Determined from 7 analyses; [7]Maximum gage height on this date; flow not determined.

		Water discharge[1]							Water quality[2]						
				Maximum		Minimum				Specific conductance			Sediment concentration		
Station number	Station name	Period of record	Drainage area (mi^2)	(ft^3/s)	Date	(ft^3/s)	Date	Mean (ft^3/s)	Period of record	Maximum (μmhos)	Minimum (μmhos)	Mean (μmhos)	Maximum (mg/L)	Minimum (mg/L)	Mean (mg/L)
Colorado River Drainage Basin															
09355500	San Juan River near Archuleta[3]	1955–77	3,260	18,900	7-27-57	8	2-28-63	1,304[4]	1955–78	685	119	311	42,800	16	4,831
09364500	Animas River at Farmington	1912–77	1,360	25,000	6-29-27	1	8-11-72	909	1940–78	1,340	205	606	27,900	8	3,003
0936500	San Juan River at Farmington	1912–77	7,240	68,000	6-29-27	14	8-22-39	2,370	1962–78	2,290	165	548	—	—	—
09367500	La Plata River near Farmington	1938–77	583	[7]	9-10-39	0	—	24	—	5,000	518	2,262	35,100	39	3,888
09367561	Shumway Arroyo near Waterflow	1974–77	73.8	1,160	7-26-76	0	—	—	1974–78	16,300	500	6,481	534,000	15	14,653
09367680	Chaco Wash at Chaco Canyon National Monument	1976–77	578	898	7-24-77	0	—	—	1976–78	720	265	470	131,000	395	30,033
09367710	De-Na-Zin Wash near Bisti Trading Post	1975–77	184	1,700	7-20-77	0	—	—	1975–78	1,500	220	709	197,000	0	54,162
09367930	Hunter Wash at Bisti Trading Post	1975–77	45.6	1,570	9-19-76	0	—	—	1975–78	5,010	435	1,074	273,000	0	46,250
09367950	Chaco River near Waterflow	1975–77	4,350	7,300[5]	9-20-69	—	—	—	1976–78	5,000	—	1,878	280,000	2	48,674
09368000	San Juan River at Shiprock	1927–77	12,900	80,000	8-11-29	8	8-25,26-39	2,175	1941–45, 1951–78	2,660	201	748	145,000	32	12,691
09395500	Puerco River at Gallup	—	558	—	—	—	—		1975–77	1,320	495	898	—		—
Rio Grande Drainage Basin															
08334000	Rio Puerco above Arroyo Chico, near Guadalupe	1951–77	420	6,940	7-29-67	0	—	13.0	—	—	—	—	—	—	—
08340500	Arroyo Chico near Guadalupe	1943–77	1,390	15,200	9-12-72	0	—	21.8	—	—	—	—	—	—	—
08343500	Rio San Jose near Grants	1936–77	2,300	1,400	9-30-63	1.9	2-21-73	6.49	—	1,350	1,280	1,315[6]	—	—	—
08349800	Rio Paguate below Jackpile Mine near Laguna	1976–77	107	2,300	8-24-76	0.04[3]	—	—	—	2,200	1,370	1,657[6]	—	—	—
08351500	Rio San Jose at Correo	1943–77	3,660	7,150	8-11-55	0	—	11.7	—	—	—	—	—	—	—
08352500	Rio Puerco at Rio Puerco	1934–76	6,590	28,000	8-21-35	0	—	57.0	—	—	—	—	—	—	—

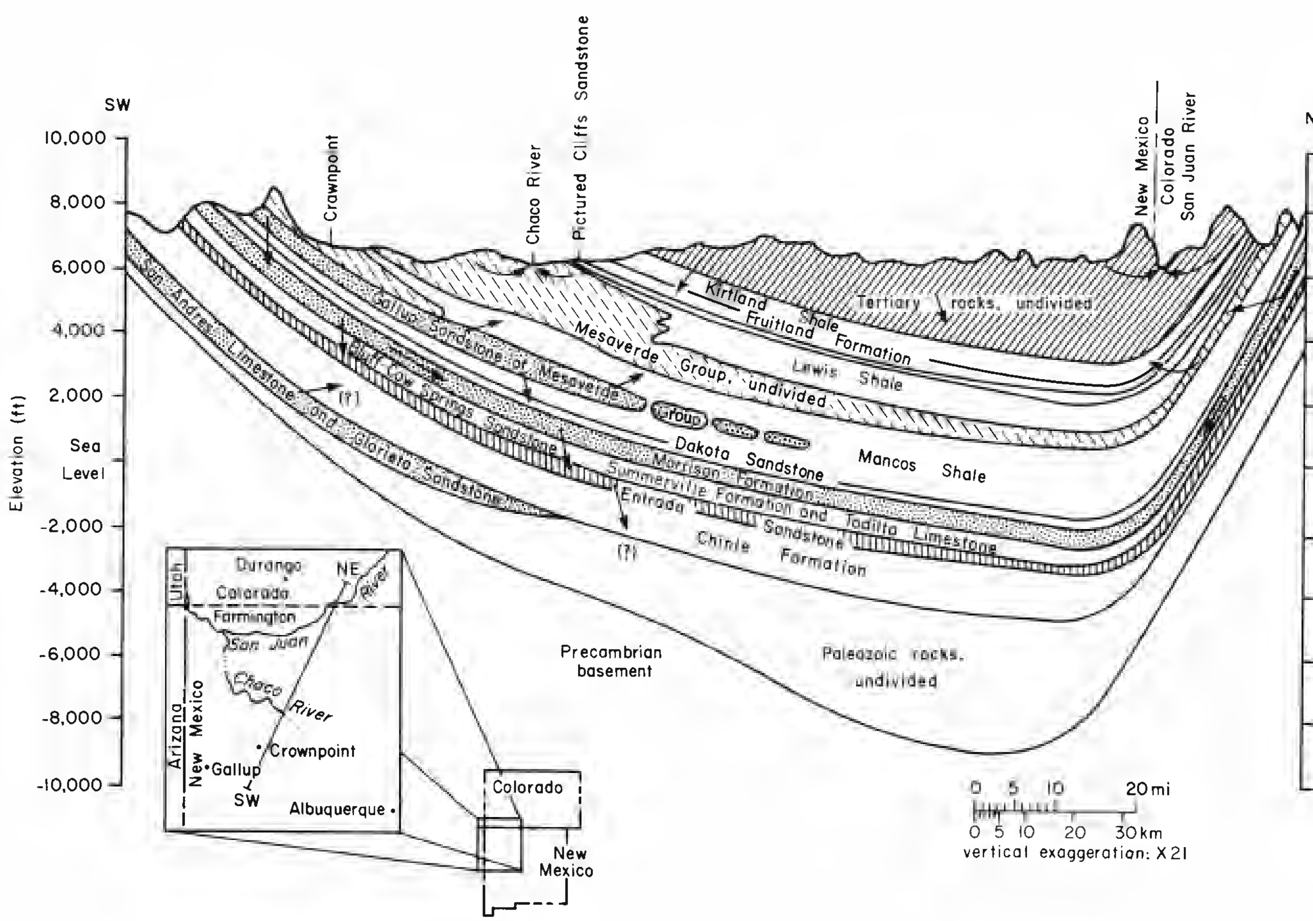


Figure 10—GENERALIZED HYDROGEOLOGIC CROSS SECTION OF SAN JUAN BASIN, showing major aquifers (stippled), confining beds (blank), and directions of ground-water flow (arrows).

not vary significantly from unit to unit, generalizations are made here to avoid repetition below.

Hydrologic properties

Transmissivity of the San Juan Basin aquifers ranges from 450,000 ft^2/d for cavernous limestones of the Glorieta Sandstone–San Andres Limestone aquifer near Bluewater (Gordon, 1961, table 8) to less than 1 ft^2/d for some of the finer grained, well-cemented sandstones, such as the Pictured Cliffs Sandstone, in the central part of the basin (table 5, microfiche pocket). The better yielding sandstone aquifers of Tertiary, Cretaceous, and Jurassic age have transmissivities ranging from 25 to 500 ft^2/d. This report contains maps showing transmissivity zones for three of the aquifers. These maps are generalized and are based on sparse aquifer-test results and aquifer lithology. Because of the inherent variability of the transmissivity data, some of the points do not belong within the zones where they are shown. Because these zones are interpretive, all data are included to permit other interpretations of transmissivity distribution.

Specific storage, a function of the porosity and compressibility of the aquifer, as well as the compressibility of water, probably is similar for all confined aquifers. Lohman (1972, p. 53) stated that a value of 10^{-6}/ft of thickness is a fairly reliable estimate for most purposes. Results of aquifer tests of several days' duration in the Morrison Formation near Crownpoint gave values between 0.3×10^{-6} and 1.0×10^{-6}/ft which, although somewhat lower on the average than Lohman's estimate, are of the same order of magnitude (table 5).

The specific yield of unconfined aquifers, including valley-fill deposits and sandstones in or near outcrop areas, typically ranges from 0.1 to 0.3 (Lohman, 1972, p. 53). The only known test for specific yield in the study area was reported by Mercer and Lappala (1972, p. 53). They cited a value of 0.15 for a core from the Gallup Sandstone in well 16.18.07.3333.

Regional flow

In general, regional ground-water flow is from topographically high outcrop areas toward lower outcrop areas. Much of the recharge to aquifers in the New Mexico part of the basin occurs on the flanks of the Zuni, Chuska, and Cebolleta Mountains. Also contributing to the regional flow systems is recharge in high areas along the northern and northeastern basin margins, including the San Juan Mountains in Colorado. The San Juan River valley in the northwest part of the basin and tributaries of the Rio Grande, such as the Rio Salado, Rio Puerco, and Rio San Jose in the southeast parts of the basin, are the main discharge areas for the basin. Of lesser importance in terms of the volume of outflow is the Puerco River near Gallup. Steady-state analysis gives inflow and outflow rates of less than 20 ft^3/s for the Tertiary aquifers and approximately 40 ft^3/s for the Cretaceous and Jurassic sandstone aquifers (Lyford and Stone, 1978).

Numerous ephemeral-stream channels filled with alluvium are the principal sources of ground-water recharge in some areas and the principal locations of discharge in others. The alluvial cover usually conceals evidence of discharge, and white salt or alkali deposits associated with small-yield springs are often the only surface expression of ground-water discharge in these localities. In places, however, the entire floor of ephemeral-stream channels is covered by such deposits (Brown, 1976, fig. 22). X-ray-diffraction analysis of samples of the alkali from several sites by the New Mexico Bureau of Mines and Mineral Resources has revealed it to be thenardite (Na_2SO_4). Most discharge to alluvial channels is lost by evapotranspiration, but some water also moves as subsurface flow.

Interaquifer movement of water (leakage) is part of the ground-water flow system in the San Juan Basin. Hydraulic-head differences of 200 ft or more, which commonly exist between aquifers in many parts of the basin, provide the driving mechanism for such movement. The geologic section in fig. 10 shows the probable direction of flow through confining beds.

The magnitude of vertical movement between aquifers is difficult to determine using the available data. However, differences in hydraulic head (200 ft or more) and water quality between vertically adjacent aquifers suggest that leakage rates through intervening shale beds are very low in most areas. Perhaps highly fractured areas, such as those along The Hogback near the Four Corners in the northwest and the Rio Puerco fault zone in the southeast, provide relatively high vertical-permeability zones for interaquifer movement of water, but few data are available to verify this possibility. The association of springs with dikes and volcanic necks, reported by Waring and Andrews (1935) and Craigg (1980), indicates that fractured igneous rocks provide avenues for vertical movement. Similar avenues may exist under the Cebolleta Mountains, providing recharge to deep aquifers in that area.

Water quality

Specific conductance is used as a measure of water quality; the dissolved-solids concentration is about 0.7 times the specific conductance in micromhos (μmho). In the study area, specific conductance ranges from less than 500 μmhos, for water in or near outcrops of some of the more transmissive rocks, to more than 100,000 μmhos for water in deeper, less transmissive units (table 6, microfiche pocket).

The specific conductance of water from valley-fill aquifers, although highly variable, generally ranges from less than 1,000 μmhos in headwater areas, where most of the water comes from percolating storm and snowmelt flows, to more than 4,000 μmhos in lower reaches, where water that has a relatively high conductance is contributed by discharge from bedrock sources. Infiltration of irrigation water tends to decrease the specific conductance of the water in the valley fill along the San Juan and Animas Rivers, due to the low specific conductance (generally less than 500 μmhos) of the applied irrigation water.

Proportions of major chemical constituents vary with specific conductance but do not vary appreciably between aquifers (table 6, microfiche pocket). Water that has a specific conductance of 1,000 μmhos or less normally has sodium and sulfate as major constituents, but bicarbonate is also relatively high. Sodium and sulfate are major constituents in water that has a specific conductance between 1,000 and 4,000 μmhos; chloride commonly is a major ion when specific conductance exceeds 4,000 μmhos.

Several maps in this report show generalized zones of specific conductance of water for specific aquifers; the maps are based on measured data and interpretations of the flow system. Some of the data do not fit the zones in which they are plotted because of well-completion methods, erroneous depth data, or other factors. The anomalous data are nonetheless included to allow other interpretations of the specific conductance distribution.

Trace metals and radiochemicals in waters of the study area are summarized in table 7 (microfiche pocket).

Aquifers

In areas where ground water flows across structural and stratigraphic boundaries, the term aquifer loses its meaning. However, the geologic column of the San Juan Basin is characterized by alternating strata of relatively high and low hydraulic conductivities. The major component of ground-water flow is through the higher conductivity units, and use of the term aquifer is not only appropriate but useful.

The following descriptions are restricted to the principal water-yielding strata of the San Juan Basin. The relationships of these aquifers to each other and to confining layers are shown in figs. 6 and 10, sheets 2–4, and table 14 (inside front cover). In the interest of brevity, only those geologic characteristics necessary for stratigraphic identification and petrographic classification of the rock units are presented here. Additional geologic characteristics and their bearing on the behavior of the units as aquifers are discussed in the chapter on hydrogeology. More detailed geologic information is available in the data reports by Stone and Mizell (1978), Stone (1979a, b), and Mizell and Stone (1979).

Valley-fill and terrace deposits (Quaternary)

All drainageways in the basin contain alluvial valley fill. The valleys of the San Juan River and its tributaries also contain extensive terrace deposits.

GEOLOGIC CHARACTERISTICS—Although the alluvial deposits of the San Juan Basin have not been thoroughly studied, several previous workers give characteristics of the deposits in selected areas: Bryan (1925, 1954), Bryan and McCann (1936), Love (1977, 1980), and Hall (1977). These deposits consist of gravel, sand, silt, clay, and various mixtures thereof. Texture and composition vary widely depending on age and source. In the valleys of the San Juan River and its tributaries, the alluvium does not exceed 100 ft in thickness. Rapp (1959) reported a maximum thickness of 80 ft for the fill of the San Juan River valley at Farmington. Brown and Stone (1979) gave a thickness range of 40–100 ft for the fill of the Animas River valley near Aztec. Alluvium in Chaco Canyon (fig. 11) may be as thick as 125 ft (Love, 1977). Greater thicknesses are sometimes erroneously reported by drillers where the fill lies on poorly consolidated bedrock, whose drilling characteristics and cuttings are difficult to distinguish from those of alluvium.

The terrace deposits of the Animas River valley were described by Bandoian (1963); those of the San Juan and La Plata River valleys were studied by Pastuszak (1968). The terrace deposits consist of boulder gravel resting on benches cut into the Tertiary bedrock units of the area (fig. 12). The boulders are very well rounded and consist of various igneous and metamorphic rock types, crossbedded quartzite being especially conspicuous. The maximum diameter observed is 12 inches. These deposits can be traced upstream to late Pleistocene glacial moraines in the mountains of Colorado and are properly termed outwash terraces (Atwood and Mather, 1932; Richmond, 1965). The thickness of the deposits generally does not exceed 30 ft. The valley fill and terrace deposits form a disconformable contact with all underlying units.

HYDROLOGIC PROPERTIES—The transmissivity of valley fill varies widely, depending on the lithology and thickness of the fill materials. Highest transmissivities can be expected in the San Juan, Animas, and La Plata River valleys where coarse sand and gravel predominate. For example, in the Animas River valley near Farmington one aquifer test indicated a transmissivity of more than 40,000 ft^2/d (table 5). Relatively high transmissivities of more than 17,000 ft^2/d (table 5) were also reported for the Rio San Jose valley between Grants and Laguna (Dinwiddie and Motts, 1964, p. 36), but transmissivities in the Puerco River valley near Gallup (Shomaker, 1971, p. 87–90) and other ephemeral-stream channels are generally less than 1,000 ft^2/d.

Much of the water in the valley fill of the San Juan, Animas, and La Plata River valleys currently comes from drainage of irrigated lands; these valleys also receive water from underlying and adjacent bedrock units. Although small in quantity compared with irrigation drainage, these contributions can appreciably affect water quality because of their relatively high dissolved-solids concentrations. Much of the water in the valley fill ultimately reaches the rivers and contributes to their dissolved-solids concentrations.

In the ephemeral-stream channels, most recharge to the valley fill results from infiltration of stormflow, but small quantities are also contributed from bedrock sources, especially in lower reaches. In their upper reaches, these channels may be major sources of water for recharge to underlying bedrock aquifers.

WATER QUALITY AND USE—The quality of water in the alluvium is highly variable (tables 6 and 7) and often unpredictable, but some generalizations can be made. For example, as shown in fig. 13 (sheet 5, pocket), the average specific conductance of water from wells in the Animas River valley (approximately 1,500 μmhos) is somewhat lower than that of water from wells in the San Juan and La Plata River valleys (approximately 2,500 μmhos). The upper reaches of ephemeral channels, such as the Chaco River, normally contain water that has a specific conductance of less than 1,500 μmhos; higher values of 4,000 μmhos or more are commonly found in the lower reaches. The specific conductance of water from alluvium in the Puerco River valley east of Gallup generally does not exceed 1,500 μmhos (Shomaker, 1971, table 5). East of the Continental Divide, the specific conductance of water from alluvium and interbedded basalts along the Rio San Jose normally ranges from 600 to 2,500 μmhos, although values of 6,000 μmhos or more have been reported (Gordon, 1961, table 10; Dinwiddie and Motts, 1964, table 4).

Numerous shallow wells produce water from valley fill for stock and domestic uses along many streams in the San Juan Basin. In many areas, valley fill provides the only source of potable water for rural inhabitants. Shallow wells also produce water for irrigation from valley fill and interbedded basalt in the Rio San Jose valley.

Figure 11—ALLUVIUM EXPOSED ALONG CHACO WASH, CHACO CANYON NATIONAL MONUMENT. View to south in NE¼ sec. 28, T. 21 N., R. 10 W.

Figure 12—TERRACE GRAVEL LYING ON SAN JOSE FORMATION IN BLUFFS ON EAST SIDE OF ANIMAS RIVER, 3 MI NORTH-NORTHEAST OF CEDAR HILL. View to north in sec. 22, T. 32 N., R. 10 W.

Chuska Sandstone (Eocene/Oligocene?)

The Chuska Sandstone is the youngest bedrock unit outside the central basin. It is restricted to, and generally forms the caprock of, the Chuska Mountains (sheet 1).

GEOLOGIC CHARACTERISTICS—This interval of sandstone, shale, and conglomerate was originally named by Gregory (1916) for exposures on Chuska Peak, McKinley County, New Mexico. The age of the Chuska has been problematical but, based on its relationship to volcanics that have been dated, it must be at least as old as Oligocene and possibly even late Eocene (Hackman and Olson, 1977). The bulk of this unit is medium-grained, submature arkose (fig. 14; tables 8 and 9). Thickness ranges from 700 to 1,800 ft. The contact between the Chuska and all underlying rocks is everywhere an angular unconformity.

HYDROLOGIC PROPERTIES—Hydraulic conductivity and transmissivity data are not available for the Chuska Sandstone. Much of the recharge to the Chuska Sandstone, by infiltration of rainfall and melting snow and seepage from numerous shallow lakes (Wright, 1964), is discharged by springs at the base of the sandstone on the west and east sides of the Chuska Mountains. However, some of the water infiltrates downward into underlying sandstones of Permian through Cretaceous age.

WATER QUALITY AND USE—Water from the Chuska Sandstone has a specific conductance of less than 500 μmhos (Harshbarger and Repenning, 1954, p. 15). Many springs issuing from the Chuska provide water for domestic, stock, and irrigation use.

Figure 14—CHUSKA SANDSTONE EXPOSED AT WASHINGTON PASS. View to north, approximately 12 mi west of Sheep Springs.

San Jose Formation (Eocene)

The San Jose Formation is the youngest Tertiary bedrock unit in the San Juan Basin proper. It occurs at the surface over a vast portion of the central basin (sheet 1).

GEOLOGIC CHARACTERISTICS—This sequence of interbedded sandstones and mudstones was named by Simpson (1948) for exposures along the San Jose Valley in northwest Sandoval County, New Mexico. Baltz (1967) subdivided the formation into four members: Cuba Mesa, Regina, Llaves, and Tapicitos (in ascending order). He mapped these members in the southern half of the Jicarilla Apache Indian Reservation. Baltz (1967, p. 45) recognized, but did not map, an additional unnamed member north of his report area. Based on the present study, this appears to be the thick sandstone unit extending north of the latitude of Stone Lake. Lack of access to the Jicarilla Reservation for detailed mapping precludes further interpretation of the extent and character of this and other members in the north. Although the Cuba Mesa and Llaves Members are predominantly sandstone, and the Regina and Tapicitos Members are predominantly mudstone, the stratigraphy is complicated by extensive intertonguing of adjacent members.

The sandstones of the Cuba Mesa and Llaves Members are generally coarse-grained, often pebbly, submature arkose (tables 8 and 9). Baltz and West (1967) reported that the thickness of the Cuba Mesa Member is 150–800 ft and that of the Llaves Member is 50–1,300 ft.

The mudstones of the Regina and Tapicitos Members commonly are silty or sandy and contain beds and lenses of claystone, siltstone, and poorly consolidated sandstone. The abundance of swelling clay is attested to by the familiar popcorn weathering habit of these members. Baltz and West (1967) reported that the thickness of the Regina Member is 100–1,700 ft and that of the Tapicitos Member is 120–500 ft.

Total thickness of the San Jose Formation ranges from less than 200 ft in the west and south to nearly 2,700 ft in the basin center between Cuba and Gobernador.

The character of the contact between the San Jose Formation and underlying Nacimiento Formation varies across the basin. Opposite the Nacimiento uplift, the contact is an angular unconformity (fig. 7). In the basin center, the contact is slightly disconformable to conformable (fig. 15).

HYDROLOGIC PROPERTIES—The aquifers in the San Jose Formation are largely untested. Brimhall (1973, p. 206) reported a specific capacity of 0.23 gpm/ft for the Cuba Mesa Member of the San Jose (well 29.8.9.343). Brown (1976, p. 164) obtained a vertical hydraulic conductivity of 1.7 ft/d from a core of outcrop sample of San Jose sandstone. For two wells penetrating only 100 ft of the formation (24.05.23.4223 and 25.05.03.233), aquifer tests gave transmissivities of 40 and 120 ft^2/d (table 5). These values would support the conclusion by

Figure 15—CONTACT BETWEEN NACIMIENTO FORMATION (**Tn**) AND OVERLYING SAN JOSE FORMATION (**Tsj**), 2.5 mi north-northeast of Cedar Hill. View to east in sec. 22, T. 32 N., R. 10 W.

Baltz and West (1967, p. 65) that a well open to all sandstones in the formation might yield 1,440 gpm.

WATER QUALITY AND USE—The specific conductance of water from wells and springs ranges from 320 to 5,000 μmhos, averaging about 2,000 μmhos (fig. 16). Although supporting data are not available, specific conductance may increase with depth in most localities (a characteristic common of other aquifers in this area). The San Jose Formation yields water to numerous wells and springs used for stock and domestic supplies.

Nacimiento/Animas Formations (Paleocene)

The Nacimiento Formation lies at the surface in a broad belt at the western and southern edges of the central basin and dips beneath the San Jose Formation in the basin center (fig. 17, sheet 5, pocket). To the north

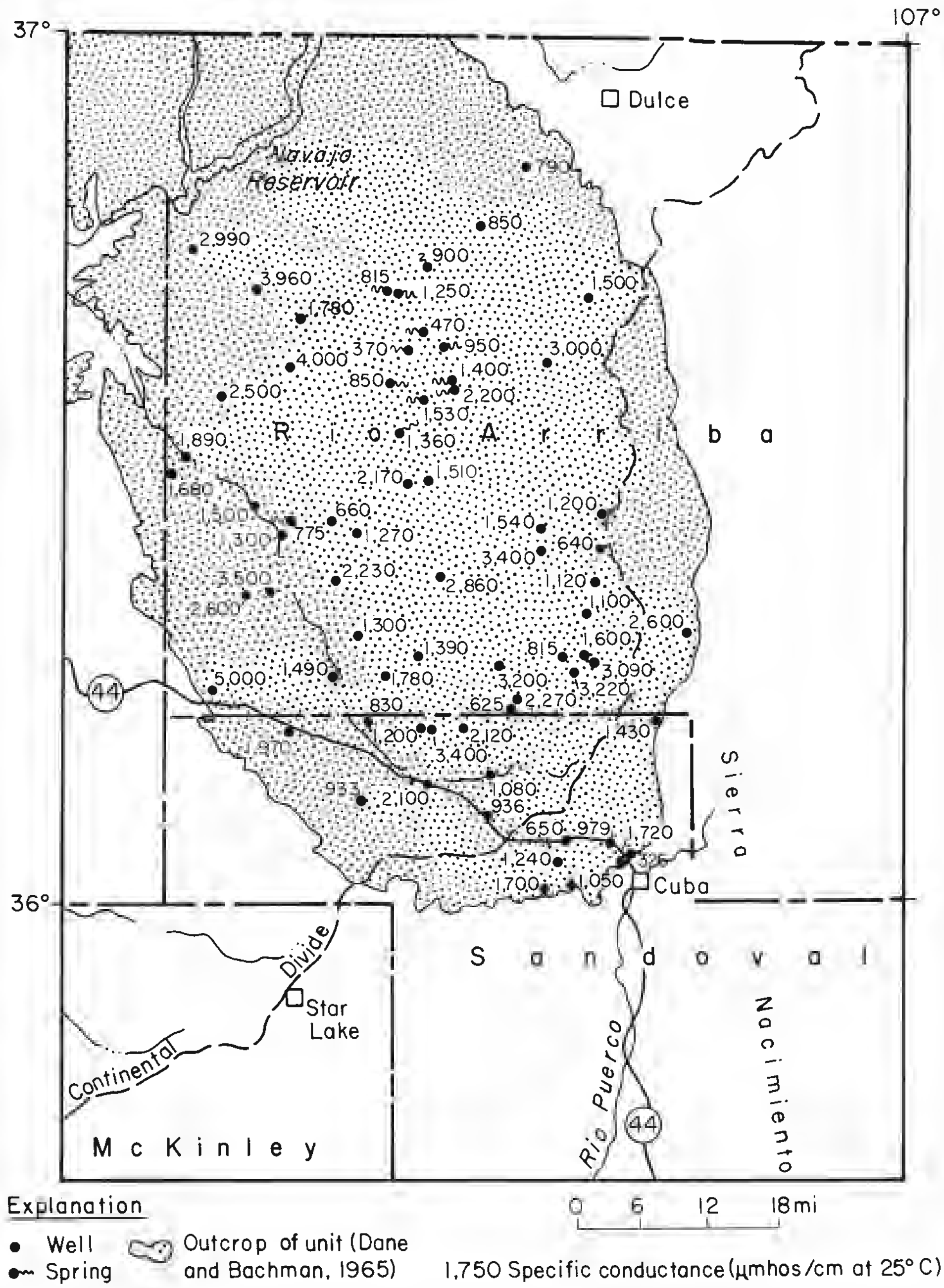


Figure 16—SPECIFIC CONDUCTANCE FROM SELECTED WELLS AND SPRINGS IN SAN JOSE FORMATION.

TABLE 8—Results of textural (mechanical) analyses of major aquifers, San Juan Basin aquifers.

Anal. no.	Unit	A/S	Sample no.	Location (¼, sec,T,R)	Size fractions (ϕ)—% by weight: C <1	M 1–2	F 2–3	VF 3–4	S/C >4	Total	Mode: ϕ	Mode: Verb.	Median: ϕ	Median: Verb.	Mean: ϕ	Mean: Verb.	Sorting: S_{ig}	Sorting: S_g	Sorting: Verb	S/M Ratio
1	Tc	LF	SJR-69	NE,6,35N,30E	4.98	62.80	26.90	4.96	0.34	100.00	2.00	M	1.70	M	1.77	M	0.56		MW	293
2	Tsj	DB	AR-B	SW,24,31N,10W	59.09	26.65	7.28	2.07	4.90	99.99	1.00	C	0.88	M	1.07	M	0.97		M	19.4
3	Tsj	DB	2B-12	NW,28,32N,11W	69.19	11.8	4.83	2.11	7.05	99.98	1.00	C	0.61	C	0.77	C		1.05	P	13.1
4	Tn	DB	8-1	SW,28,30N,13W	22.46	62.06	6.04	2.15	7.28	99.99	2.00	M	1.43	M	1.43	M		0.55	M	12.7
5	Tn	DB	2B-1	SE,28,32N,11W	40.36	35.89	8.72	2.03	13.00	100.00	1.00	C	1.27	M	1.60	M		1.10	P	6.7
6	Toa	SA	SJR-11	SW,28,29N,12W	8.94	40.50	24.75	5.73	20.08	100.00	1–2	M	2.02	F	2.51	F	1.36	1.44	P	4.0
7	Toa	LF	SJR-14	SW,28,29N,12W	Agg.	13.58	40.59	39.29	6.54	100.00*	3.00	F	2.90	F	2.90	F	1.60		VP	14.3
8	Toa	SA	SA-1	SE,33,26N,1E	9.76	40.55	18.54	5.91	25.24	100.00	1–2	M	1.99	M	2.56	F	1.41	1.52	P	3.0
9	Kk (f)	LF	SJ2-4-1	SW,21,29N,13W	Agg.	Agg.	36.12	56.14	7.73	99.99*	3–4	VF	3.20	VF	NA	NA	NA		NA	11.9
10	Kk (f)	LF	SJ2-4-2c	SW,21,29N,12W	9.00	60.70	23.50	4.60	2.30	100.00	1–2	M	1.70	M	1.80	M	0.70		MW	42.5
11	Kpc	LF	SJ1W-3-2	SW,32,30N,15W	Agg.	Agg.	Agg.	60.20	9.90	100.01*	3–4	VF	3.87	VF	3.97	VF	NA		NA	1.5
12	Kpc	LF	SJ1W-3-3	SW,32,30N,15W	Agg.	Agg.	Agg.	57.44	42.56	100.00*	>4	VF	3.93	VF	3.98	VF	NA		NA	1.4
13	Kch	LF	SJR-68	SE,13,22N,13W	0.00	0.49	72.09	15.78	11.60	99.96	2–3	F	2.85	F	2.96	F		0.43	MW	7.6
14	Kmf	SA	BMS3-1	SW,20,19N,1W	?	7.80	66.10	9.28	16.82	100.00	2–3	F	2.50	F	2.83	F	1.45	1.0	P	5.0
15	Kmf	SA	BMS3-2	SW,20,19N,1W	?	9.05	65.89	5.98	19.08	100.00	2–3	F	2.25	V	3.08	VF	1.70	1.5	P	4.2
16	Kpl	LF	SJR-40	SE,5,29N,16W	0.00	5.86	83.73	8.88	5.17	100.00	2–3	F	2.60	F	2.57	F	0.39		W	19.1
17	Kcda	BB	BB-4	NW,14,14N,8W	0.18	1.95	63.24	23.97	10.68	100.02	2–3	F	2.50	F	2.67	F	1.03	0.25	P	8.4
18	Kmm	BB	BB-5	NW,20,13N,8W	0.18	2.18	48.05	34.55	15.04	100.00	2–3	F	2.50	F	2.83	F	1.16	0.50	M	5.7
19	Kg	LF	SJ3-5-3	NW,21,30N,19W	2.00	79.10	13.30	2.70	2.90	100.00	1–2	M	1.70	M	1.77	M	0.70		MW	33.5
20	Kg	LF	SJ3-6-1	NW,17,27N,19W	0.30	20.40	64.60	9.80	4.90	100.00	2–3	F	2.40	F	2.60	F	0.91		M	19.4
21	Kg	LF	SJ3-6-3	NW,17,27N,19W	0.20	8.00	71.20	13.80	6.80	100.00	2–3	F	2.60	F	2.69	F		0.54	M	13.7
22	Kg	LF	SJ3-6-7b	NW,17,27N,19W	0.53	27.60	62.80	4.60	4.50	100.00	2–3	F	2.30	F	2.33	F	0.99		M	21.2
23	Kd	LF	SJ3-2-3	NO,26,30N,20W	0.02	19.40	70.70	4.70	5.20	100.02	2–3	F	2.40	F	2.41	F	0.79		M	18.2
24	Kd	LF	SJ3-3-10	SE,34,28N,20W	1.30	76.00	14.50	2.90	5.30	100.00	1–2	M	1.70	M	1.83	M	0.92		M	17.9
25	Kd	BB	BB-6	SE,14,13N,10W	0.05	6.15	49.03	30.74	14.04	100.01	2–3	F	2.50	F	2.67	F	0.91	0.75	M	6.1
26	Jmb	LF	SJ3-3-4a	SE,34,28N,20W	0.70	13.60	71.30	8.50	6.00	100.00	2–3	F	2.50	F	2.51	F		0.47	MW	15.7
27	Jmw	BB	BB-7	SE,14,13N,10W	91.60	2.75	3.10	1.59	0.98	100.02	<1	VC-G	<1.00	VC-G	1.00	VC-G	1.26	1.00	P	101.1
28	Jmw	BB	BB-8	SE,14,13N,10W	38.30	44.54	12.07	2.75	2.32	99.98	1–2	M	1.00	C	1.17	M	0.83	0.75	M	42.1
29	Jms	LF	SJ3-1-10b	SW,14,30N,21W	1.10	15.70	52.70	27.00	3.40	99.90	2–3	F	2.50	F	2.66	F	1.11		P	28.4
30	Jb	BB	BB-9	SE,14,13N,10W	0.24	31.69	50.41	10.00	7.68	100.02	2–3	M	2.00	M	2.17	F	1.36	0.75	P-M	12.0
31	Js	LF	SJ3-1-7	SW,14,30N,21W	0.00	0.60	18.50	72.30	8.50	99.90	3–4	VF	3.40	VF	3.38	VF		0.48	MW	10.8
32	Js	LF	SJ3-1-8	SW,14,30N,21W	0.70	1.40	43.50	41.40	13.00	100.00	2–3	F	3.10	VF	3.18	VF		0.67	M	6.7
33	Jeu	LF	SJ3-1-3	SW,14,30N,21W	0.00	4.80	47.00	38.90	9.30	100.00	2–3	F	3.00	F	3.05	F		0.68	M	9.8
34	Jeu	BB	BB-10	SW,23,13N,10W	0.16	11.01	62.49	16.35	9.19	99.20	2–3	F	2.50	F	2.50	F	1.24	0.50	P-M	9.8
35	Jem	LF	SJ3-1-2	SW,14,30N,21W	0.00	0.03	14.40	73.10	12.40	99.93	3–4	VF	3.50	VF	3.50	VF		0.45	MW	7.1
36	Jem	BB	BB-11	SW,23,13N,10W	0.00	0.72	3.67	52.04	43.56	99.99	3–4	VF	3.50	VF	>4.00	Slt	1.88	2.25	P-EP	1.3
37	Trw	BB	BB-12	SW,23,13N,10W	0.34	72.35	17.94	2.64	6.73	100.00	1–2	M	1.50	M	1.67	M	1.19	0.25	M	13.9

Anal. no. = analysis number
Units:
Tc = Chuska Sandstone
Tsj = San Jose Formation
Tn = Nacimiento Formation
Toa = Ojo Alamo Sandstone
Kk (f) = Farmington Sandstone Member of Kirtland Shale
Kpc = Pictured Cliffs Sandstone
Kch = Cliff House Sandstone
Kmf = Menefee Formation
Kpl = Point Lookout Sandstone
Kcda = Dalton Sandstone Member of Crevasse Canyon Formation
Kmm = Mulatto Tongue of Mancos Shale
Kg = Gallup Sandstone
Kd = Dakota Sandstone
Jmb = Brushy Basin Member of Morrison Formation
Jmw = Westwater Canyon Member of Morrison Formation
Jms = Salt Wash Member of Morrison Formation
Jb = Bluff Sandstone
Js = Summerville Formation
Jeu = Upper member of Entrada Sandstone
Jem = Middle member of Entrada Sandstone
Trw = Wingate Sandstone
A/S = analyst/source (SA = Anderholm, 1979; BB = Brod, 1979; DB = Brown, 1979; LF = Fleischhauer *in* Stone, 1979)
ϕ = phi
Slt = silt
VC = very coarse sand; VC-G = very coarse-granular
C = coarse sand
M = medium sand
F = fine sand
VF = very fine sand
S/C = silt and clay
Verb. = verbal description of mode
Agg. = aggregate
S_{ig} = inclusive graphic standard deviation of Folk (1974, p. 46)
S_g = graphic standard deviation of Folk (1974, p. 45); S_g is used where specific size of the 95th percentile is uncertain.
Verbal sorting:
EP = extremely poor
P = poor
M = moderate
MW = moderately well
NA = not applicable
S/M = sand/mud ratio
* = samples contained appreciable amounts of aggregate; not plotted.
Additional data in Anderholm (1979) and Craigg (1980)

TABLE 9—RESULTS OF MINERALOGICAL (THIN-SECTION) ANALYSES OF MAJOR SAN JUAN BASIN AQUIFERS

Anal. no.	Unit	A/S	Sample no.	Location (¼,sec,T,R)	Whole Rock (%) Frmwk	Cem	Mtx	Por	Framework (%) Q	F	RF	Size range	Texture Mo	Srt	Rdns	Sph	Elong	TM	Class.
1	Tc	SC	SJR-54	NE,6,35N,30E	70	25	3	2	76	23	1	Cslt-C	M	M	A-WR	P-E	VEL-VE	Sub	SA
2	Tsj	SC	SJR-48	NE,23,25N,4W	83	4	4	9	66	32	2	VF-c	M	W	A-WR	P-E	VEL-VE	Sub	A
3	Tsj	DB	AR-B	SW,24,31N,10W	71	(10)		19	57	37	6	C-VC	VC	P-M	SA-R	F-G		Sub	A
4	Tsj	DB	6-7	SE,22,31N,10W	78	(6)		16	61	32	7	C-VC	VC	M-W	SA-R	G		Sub	A
5	Tn	SC	SJR-46	NW,12,20N,2W	84	2	6	8	61	31	8	Cslt-C	F	W	A-WR	P-E	VEL-VE	I	A
6	Tn	SC	SJR-50	NE,27,31N,11W	84	14	2	0	48	42	10	M-GrV	C	VP	SA-WR	P-E	VEL-VE	Sub	A
7	Tn	DB	6-3	NW,27,31N,10W	70	(18)		12	46	39	15	VC	VC	M	SA-Sr	F-G			A
8	Tn	DB	6-4	NW,27,31N,10W	38.5	(60)		1.5	91	6	3		C	M	SR	F		I	A
9	Tn	DB	6-5	SE,22,31N,10W	76	(9)		15	55	32	13	C	C	M-W	SR-R	G		Sub	A
10	Toa	SC	SJR-11	SW,28,29N,12W	89	3	5	3	54	29	17	Cslt-C	M+C	P	SA-WR	P-E	VEL-VE	I	LA
11	Toa	SC	SJR-14	SW,28,29N,12W	81	4	9	6	51	34	15	Cslt-C	F	VP	A-SR	P-G	VEL-E	I	LA
12	Ta	SC	SJ-1W-4B-1b	SW,24,30N,14W	85	10	3	2	73	18	9	Cslt-C	F/M	W	A-WR	P-E	VEL-VE	Sub	LA
13	Ta	SC	SJ-1W-4B-2d	SW,24,30N,14W	74	10	14	2	68	18	14	Cslt-VC	M	M	A-WR	P-E	VEL-VE	I	LA
Average framework (%) for Tertiary sandstone aquifers analyzed									62	29	9								
14	Kk (f)	SC	SJ-2-4-1	SW,21,29N,13W	82	6	9	3	80	17	3	VF-M	F	M	A-SR	P-G	VE-VEL	I	SA
15	Kk (f)	SC	SJ-2-4-2c	SW,21,29N,13W	77	6	7	10	64	28	8	VF-VC	M	P	A-R	P-G	VE-VEL	I	A
16	Kf	SC	SJR-59	(Navajo mine)	73	3	23	1	81	12	7	Cslt-F	VF	W	A-SR	P-E	VE-VEL	I	SA
17	Kf	SC	SJR-64	(San Juan mine)	63	31	4	2	67	26	7	Cslt-M	F	W	A-SR	P-E	VE-VEL	Sub-M	A/LA
18	Kpc	SC	SJ-1W-3-2	SW,32,30N,15W	69	7	19	5	74	25	1	Cslt-F	VF	VW	A-R	P-E	VE-VEL	I	A/SA
19	Kpc	SC	SJ-1W-3-6	SW,32,30N,15W	58	42	—	—	79	20	1	Cslt-F	VF	W	A-R	P-E	VE-VEL	Sup	SA
20	Kch	SC	SJR-68	SE,13,22N,13W	82	3	10	5	80	19	1	Cslt-M	M	W	SA-WR	P-G	VE-VEL	I	SA
21	Klv	SC	SJR-23	NW,16,19N,1W	83	6	3	8	83	13	4	Cslt-M	F	SA-R		P-E	VE-VEL	Sub	SA
22	Klv	SC	SJR-42	SE,19,19N,1W	76	21	2	1	84	13	3	Cslt-M	F	VW	A-R	P-G	VE-VEL	Sub	SA
23	Kmf	SC	SJR-4	NE,11,23N,1W	68	11	21	—	61	26	13	Cslt-F	VF	W	A-SA	P-G	VE-VEL	I	LA
24	Kmf	SC	SJR-5	SE,5,29N,16W	78	5	8	9	59	26	15	VF-C	M	M	SA-WR	P-E	VE-VEL	I	LA
25	Kmf	SC	SJ-1W-2B-34	SW,4,29N,16W	60	38	2	—	62	23	15	Cslt-M	F	M	A-WR	P-E	VE-VEL	Sub	LA
26	Kpl	SC	SJR-6	SE,5,29N,16W	76	15	4	5	70	16	14	VF-C	M	M	SA-R	F-G	SE	Sub	A
27	Kpl	SC	SJR-7	SE,5,29N,16W	78	12	4	6	67	20	13	VF-C	M	M	A-W	P-E	I	Sub	A
28	Kpl	SC	SJR-8	SE,5,29N,16W	62	38	—	—	60	26	14	VF-C	M	M	A-R	F-E	I-SE	Sub	A
29	Kpl	SC	SJR-9	SE,5,29N,16W	73	11	7	9	69	21	10	VF-C	M	MW	A-R	P-G	I	I	A
30	Kpl	SC	SJ-1W-1-2	NW,7,31N,16W	80	14	3	3	59	35	6	Slt-F	F	MW	A-SR	P-G	I	Sub	A
31	Kpl	BB	2B-16(1)	NW,15,13N,8W	61	5	32	2	57	29	12*	VF-M	F	W	SA	G-E	VE	I	LA
32	Kcda	BB	2B-7(2)	NW,14,14N,8W	67	16	13	4	64	31	5	Slt-C	F	W	SA	G-E	E	I	LA
33	Kmm	BB	2B-3(3)	NW,20,13N,8W	63	—	26	11	62	30	8	Slt-M	F	VW	SA	G	E	I	LA
34	Kg	SC	SJR-31	NW,9,30N,19W	80	8	3	9	74	14	12	Cslt-F	VF	VW	SA-R	F-E	VE-VEL	Sub	LA
35	Kg	SC	SJR-34	NE,26,28N,20W	86	8	3	4	70	28	2	F-C	M	W	SA-WR	P-E	VE-VEL	M	LA
36	Kg	SC	SJR-41	NW,21,30N,19W	87	4	2	7	73	23	4	F-C	C	W	SA-WR	P-E	VE-VEL	Sub	LA
37	Kg	BB	1B-3(4)	SW,16,14N,9W	84	3	7	6	56	41	2*	Slt-C	M	W	A-SA	G	E	M	LA
38	Kd	SC	SJR-2	SE,36,21N,1W	89	6	3	2	78	19	3	VF-M	F	VW	SA-WR	P-E	VE-VEL	Sub	SA
39	Kd	BB	1A-16(5)	SE,14,13N,10W	84	4	6	6	57	42	1	VF-M	F	W	A-SA	G-E	E-EL	M	A
Average framework (%) for Cretaceous sandstone aquifers analyzed									69	24	7								

TABLE 9 (continued)

Anal. no.	Unit	A/S	Sample no.	Location (¼,sec,T,R)	Whole Rock (%) Frmwk	Cem	Mtx	Por	Framework (%) Q	F	RF	Size range	Texture Mo	Srt	Rdns	Sph	Elong	TM	Class.
40	Jmj	SC	SJR-16	SW,27,15N,1W	85	0	3	12	86	13	1	VF-C	M	W	SR-WR	F-E	EL-VE	Sub	A
41	Jmb	SC	SJ3-3-4a	SE,34,28N,20W	83	9	3	5	73	21	6	Cslt-C	M	W	SR-WR	P-E	VEL-VE	M	A
42	Jmb	SC	SJ3-3-4b	SE,34,28N,20W	71	29	0	0	81	11	8	VF-C	M	VW	SR-WR	F-E	E-VE	Sup	SA
43	Jmb	SC	SJ3-3-8b	SE,34,28N,20W	83	4	4	9	75	17	8	VF-C	C	W	SR-WR	F-E	EL-VE	M	SA
44	Jmw	SC	SJR-18	SW,36,17N,1W	72	21	4	3	67	27	6	Cslt-C	M	W	SA-WR	P-E	VEL-VE	Sub	A
45	Jmw	SC	SJR-19	SW,36,17N,1W	84	5	5	6	69	29	2	Cslt-M	M	MW	SA-SR	F-E	EL-VE	I	A
46	Jmw	SC	SJR-20	SW,36,17N,1W	85	4	3	8	69	21	10	VF-C	M	W	SA-WR	P-E	EL-VE	Sub	LA
47	Jmw	SC	SJR-30	(Kermac Sec. 30 mine)	75	9	6	10	61	26	13	Cslt-VC	M&C	VP	A-WR	P-E	VEL-VE	I	LA
48	Jmw	BB	1A-12(6)	SE,14,13N,10W	76	6	8	10	45	47	8	F-C	M	M	SR	G	E-EL	I	A
49	Jms	SC	SJ3-1-10b	SW,14,30N,21W	80	11	2	7	82	13	5	VF-F	F	W	A-WR	P-E	VEL-VE	M	SA
50	Jb	BB	1A-8	SE,14,13N,10W	80	7	6	7	60	40	0	F-M	M	W	SA	G	E	M	A
51	Js	SC	SJ3-1-7	SW,14,30N,21W	76	17	2	5	80	19	1	VF-F	F	VW	SA-SR	F-E	VEL-VE	M	SA
52	Js	SC	SJ3-1-8	SW,14,30N,21W	78	14	2	6	81	18	1	Cslt-M	F	VW	SA-SR	F-E	VEL-VE	M	SA
53	Je	SC	SJ3-1-2	SW,14,30N,21W	83	11	1	5	78	18	4	Cslt-F	VF	VW	SA-WR	P-E	VEL-VE	M	SA
54	Je	SC	SJ3-1-3	SW,14,30N,21W	82	6	2	10	80	18	2	Cslt-M	VF+M	W	SA-WR	P-E	VEL-VE	M	SA
55	Je	BB	1A-4(7)	SW,23,13N,10W	70	19	0	11	66	30	4	VF-M	F	VW	SR	G-E	E	Sup	LA
56	TRw	BB	1A-1	SW,23,13N,10W	80	0	3	17	73	25	2	VF-M	M	W	SR	G-E	E-EL	M	A
Average framework (%) for Jurassic and Triassic sandstone aquifers analyzed									72	23	5								

Anal. no. = analysis number
Unit abbreviations same as in table 1 (microfiche pocket)
A/S = analyst/source (BB = Brod, 1979; DB = Brown, 1976; SC = Craigg, 1980)
Frmwk = framework
Cem = cement } parentheses denote
Mtx = matrix } composite values
Por = porosity
Q = quartz pole
F = feldspar pole
RF = rock fragment pole (Folk, 1974)
* = does not total 100%
Slt = silt
Cslt = coarse silt
VF = very fine sand
F = fine sand
M = medium sand
C = coarse sand
VC = very coarse sand
Grv = gravel
Mo = modal grain size
Srt = estimated sorting (Folk, 1974)
VP = very poor
P = poor
M = moderate
MW = moderately well
W = well
VW = very well
Rdns = roundness (Krumbein and Sloss, 1956, figs. 4–9)
A = angular
SA = subangular
SR = subrounded
R = rounded
WR = well rounded
Sph = sphericity (Krumbein and Sloss, 1956, figs. 4–9)
P = poor
F = fair
G = good
E = excellent
Elong = elongation (Folk, 1965)
VEL = very elongate
EL = elongate
SEL = subelongate
I = intermediate
SE = subequant
E = equant
VE = very equant
TM = textural maturity (Folk, 1974)
I = immature
Sub = submature
M = mature
Sup = supermature
Class. = classification (Folk, 1974)
A = arkose
LA = lithic arkose
SA = subarkose
Additional data in Anderholm (1979) and Craigg (1980)

and northeast, the Nacimiento grades into the Animas Formation. The Animas Formation is exposed only in a narrow belt around the northeast part of the study area and along the La Plata River valley near the Colorado border.

Because these units occupy essentially the same stratigraphic interval, they aré treated together. This aquifer lies at a depth of 2,660 ft in the basin center (fig. 18, sheet 5, pocket).

GEOLOGIC CHARACTERISTICS—The Nacimiento Formation was named by Keyes (1906) for exposures near the town of Cuba (formerly Nacimiento). Although no attempt at subdivision of this unit has been successful, one gets an impression from exposures at the southern end of Cuba Mesa that the lower part of the Nacimiento is characterized by interbedded black, carbonaceous mudstones and white, coarse-grained sandstones (fig. 19), whereas the upper part of the formation is dominated by more somber beds of mudstone and sandstone. Although there is an area along NM-44 north of Cuba where the Nacimiento is black and white as at the base of Cuba Mesa, poor exposures of the lower part of the formation in the intervening area prohibit lateral tracing and make this correlation uncertain.

Because of its slope-forming habit (fig. 20), the Nacimiento is often assumed to be mainly a mudstone unit; however, close inspection reveals that sandstone makes up many of the slope-forming beds. These sandstones are medium to very coarse grained, immature to submature arkose (tables 7 and 8). The mudstones display the popcorn weathering characteristic of swelling clays. Thickness of the Nacimiento ranges from 418 to 2,232 ft (fig. 21, sheet 5, pocket).

The Animas Formation was named by Cross (Emmons and others, 1896) and Gardner (1917) for exposures along the Animas River below Durango, Colorado. Reeside (1924) divided this sequence into the McDermott Formation (below) and the Animas Formation (above). Barnes and others (1954) redefined the Animas as consisting of two members: the McDermott (Late Cretaceous) at the base and an unnamed upper member (Paleocene) at the top. The McDermott is restricted to the northwest part of the basin and in this study area is exposed only in the La Plata River valley near the Colorado border. In that area, it lies below the Ojo Alamo Sandstone and is ultimately cut out by erosion at the base of this unit. Although the upper member of the Animas does not extend into New Mexico in this northwest area, it appears to constitute the entire Animas section exposed near Dulce in the northeast part of the basin. At the type area, the McDermott Member is 127 ft thick and the upper member is 106 ft thick (Barnes and others, 1954).

The Nacimiento conformably overlies the Ojo Alamo Sandstone. Locally the two units can be shown to intertongue (sheet 3). The McDermott Member of the Animas Formation is generally disconformable on the Kirtland Shale.

HYDROLOGIC PROPERTIES—The potentiometric surface of ground water in the Ojo Alamo is shown in within the Nacimiento Formation. Brimhall (1973, p. 201–202) described one of these sandstone bodies in the western part of Rio Arriba County near Cañon Largo where several flowing wells occur. Brown (1976, p. 44) reported that from 16 to 100 gpm are produced by wells constructed by El Paso Natural Gas Company. Although no aquifer tests are available for the Nacimiento Formation, transmissivities of as much as 100 ft^2/d may be expected in some of the coarser and more continuous sandstone bodies, based on tests of similar aquifers.

WATER QUALITY AND USE—Water in some of the more extensive sandstones has a specific conductance of less than 1,500 μmhos; however, specific conductance exceeds 2,000 μmhos in the finer grained Nacimiento strata (fig. 22, sheet 5, pocket). The specific conductance of water in the Nacimiento along the San Juan River commonly exceeds 4,000 μmhos. The Nacimiento provides water for domestic and stock use on ranches in its outcrop area.

Ojo Alamo Sandstone (Paleocene)

The Ojo Alamo Sandstone is the lowest Tertiary rock unit in the San Juan Basin. From its narrow outcrop belt, the Ojo Alamo dips toward the basin center to a maximum depth of 3,645 ft (figs. 23 and 24, sheet 5, pocket).

GEOLOGIC CHARACTERISTICS—This sequence of

Figure 19—LOWER PART OF NACIMIENTO FORMATION AT SOUTH END OF MESA DE CUBA. View to north in sec. 11, T. 20 N., R. 2 W.

Figure 20—NACIMIENTO FORMATION EXPOSED IN KUTZ CANYON as seen looking east from Angel Peak overlook, east of NM-44, 11 mi southeast of Bloomfield.

sandstone, conglomeratic sandstone, and shale was named by Brown (1910) for exposures at Ojo Alamo (Cottonwood Spring) in southeast San Juan County, New Mexico. Baltz and others (1966) redefined the unit to clarify its boundaries and relationship with the underlying Kirtland Shale. The sandstone is a medium to very coarse grained, often pebbly, immature, lithic arkose (tables 8 and 9). Pebbles occur as floating clasts, thin stringers, and in beds up to 10 ft thick (fig. 25). Although the Ojo Alamo is conglomeratic in the type area and to the northwest, it lacks pebbles in the southeast and east (fig. 26). The thickness of the Ojo Alamo ranges from 72 to 313 ft (fig. 27, sheet 5, pocket). The Ojo Alamo disconformably overlies the Kirtland Shale.

HYDROLOGIC PROPERTIES—The potentiometric surface of ground water in the Ojo Alamo is shown in fig. 28 (sheet 5, pocket). Several aquifer tests conducted between Farmington and Cuba gave transmissivities between 50 and 250 ft^2/d (Brimhall, 1973, p. 206; Anderholm, 1979, p. 29; fig. 29, sheet 5, pocket, and table 5). Evidently, the transmissivity decreases northward as shown by results of tests at the Gasbuggy site (Mercer, 1969, p. 17–28) where transmissivities of less than 0.5 ft^2/d were calculated for two test holes (table 5).

WATER QUALITY AND USE—Specific conductance of water from the Ojo Alamo Sandstone increases from less than 1,000 μmhos near outcrops to more than 9,000 μmhos at the Gasbuggy site (fig. 30, sheet 5, pocket). The Ojo Alamo Sandstone aquifer is a widely used source of domestic and stock water in a northwest-trending strip bordered on the south by the sandstone outcrop and on the north by NM-44.

Fruitland Formation–Kirtland Shale (Late Cretaceous)

The Fruitland Formation contains the principal coal reserves of the San Juan Basin, and the overlying Kirtland Shale has been a significant petroleum reservoir. The two units are treated together here because they are often lumped together in mapping and have similar hydrologic properties. Although depth of the composite unit was not mapped, a maximum depth to the top of this interval of nearly 3,000 ft may be approximated by adding the thickness and depth of the overlying Ojo Alamo Sandstone.

GEOLOGIC CHARACTERISTICS—The Fruitland Formation was named by Bauer (1916) for exposures near the village of Fruitland in San Juan County, New Mexico. The formation consists of interbedded, sandy shale, carbonaceous shale, clayey sandstone, coal, and sandstone (fig. 31). The sandstone is a very fine to medium-grained, immature subarkose or submature to mature arkose to lithic arkose (tables 8 and 9). The thickness of the Fruitland is generally 200–300 ft; at the New Mexico–Colorado state line the Fruitland is 530 ft thick.

The Kirtland Shale was also named by Bauer (1916). The type area is the vicinity of the Kirtland Post Office, San Juan County, New Mexico. Bauer recognized three members: a lower shale member, a middle sandstone member (which he named the Farmington Sandstone Member), and an upper shale member (fig. 32). The lower member is 271–1,031 ft thick, the Farmington Sandstone Member is 20–480 ft thick, and the upper member is 12–475 ft thick. Sandstone is not restricted to the middle member of the Kirtland and the upper member is very sandy as well. In fact, Fassett and Hinds (1971) adopted a twofold subdivision of the Kirtland because of the difficulty in differentiating the middle and upper members. These sandstones are apparent on electric logs throughout the central basin (sheets 2–4) and in outcrops on the east side of the basin.

The combined thickness of the Fruitland–Kirtland interval ranges from less than 100 ft, along the east side of the basin, to more than 2,000 ft where the outcrop crosses the state line north of Farmington (Fassett and Hinds, 1971). The occurrence of maximum thickness corresponds to that of the maximum for the middle and upper Kirtland.

The Fruitland conformably overlies the Pictured Cliffs Sandstone. In many places an intertonguing relationship between the two units can be demonstrated (sheets 2–4).

HYDROLOGIC PROPERTIES—Several tests conducted as a part of U.S. Geological Survey coal studies on lands administered by the U.S. Bureau of Land Management

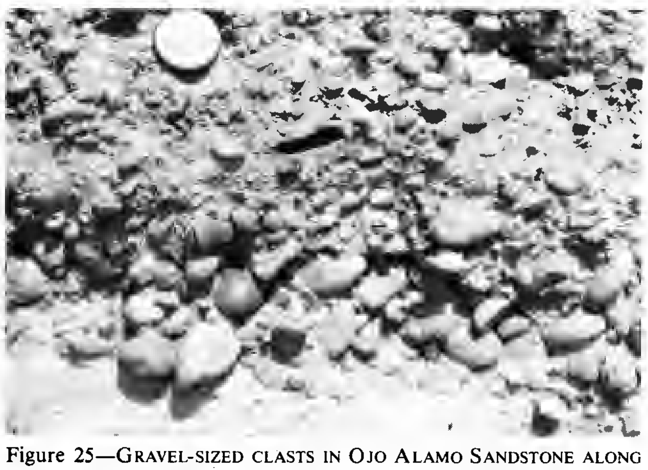


Figure 25—GRAVEL-SIZED CLASTS IN OJO ALAMO SANDSTONE ALONG NM-371, SOUTHWEST OF FARMINGTON (NE¼ NW¼ sec. 29, T. 29 N., R. 13 W.

Figure 26—OJO ALAMO SANDSTONE ALONG EAST EDGE OF MESA PORTALES. View to north in SW¼ SE¼ sec. 26, T. 20 N., R. 2 W.

Figure 31—Coal, mudstone, and sandstone in Fruitland Formation exposed in Navajo mine, approximately 12 mi southwest of Fruitland.

Figure 32—Mudstone and sandstone in Kirtland Shale exposed in bluffs along south side of San Juan River at Farmington. View to south in SW ¼ sec. 21, T. 29 N., R. 13 W.

indicated a wide range of transmissivities (from 0.6 to 130 ft^2/d) for coal beds and associated sediments in the Fruitland Formation (table 5). In general, transmissivities between 1 and 10 ft^2/d can be expected.

WATER QUALITY AND USE—Specific conductance of water from the Fruitland Formation–Kirtland Shale generally exceeds 5,000 μmhos, although lower values occur in some areas (fig. 33, sheet 5, pocket). Although the unit yields only small quantities (generally <10 gpm) of water to a few stock wells, the Fruitland Formation–Kirtland Shale is important because it is the principal aquifer disturbed by mining of coal in the Fruitland Formation.

Pictured Cliffs Sandstone (Late Cretaceous)

The Pictured Cliffs Sandstone is the highest marine sandstone in the San Juan Basin (Molenaar, 1977b) and the unit underlying the Fruitland coals. From a narrow outcrop belt it descends to a maximum depth of 4,130 ft in the basin center (figs. 34 and 35, sheet 5, pocket).

GEOLOGIC CHARACTERISTICS—This unit was named by Holmes (1877) for exposures in cliffs bearing petroglyphs on the north side of the San Juan River, west of Farmington, San Juan County, New Mexico (fig. 36). Reeside (1924) redefined the unit to include the sandstone-mudstone interval lying between the Lewis Shale (below) and the main cliff-forming sandstones (above).

There has been some disagreement concerning the occurrence of the Pictured Cliffs along the eastern edge of the basin (Dane and Bachman, 1965; Baltz and West, 1967; Fassett and Hinds, 1971; Woodward and others, 1972). One reason for this may be the difference in weathering habit of the unit in this part of the basin. As the name implies, the Pictured Cliffs is a cliff-forming unit in most places. However, southwest of Cuba and in places between Cuba and Dulce it is a slope-forming unit. For example, near Johnson Trading Post (SW¼, SW¼, sec. 30 T. 19 N., R. 3 W.) the Pictured Cliffs forms slopes similar to those of the underlying Lewis Shale, but *Ophiomorpha*-bearing sandstone beds are readily recognized upon examination of the outcrops. In places north of Cuba, digging to very shallow depths on slopes apparently formed in the Lewis Shale or the Kirtland/Fruitland undivided often yields soft sand containing *Ophiomorpha*.

Another reason for the disagreement seems to be the different lithologic definitions of the Pictured Cliffs used by the various workers. In places the Pictured Cliffs is represented by only a thin interval of interbedded sandstone and shale. According to Reeside

(1924), such material, occurring at the transition zone between the Lewis Shale and the main body of the Pictured Cliffs Sandstone is properly included in the Pictured Cliffs. Although they cited Reeside's (1924) revision of the unit to include such material, Fassett and Hinds (1971, fig. 6) chose not to recognize such material at Cuba as Pictured Cliffs. More recently, Anderholm (1979, section SA-2, Appendix A) has reported approximately 25 ft of Pictured Cliffs Sandstone in an adjacent outcrop.

The sandstone is a very fine to fine-grained, immature to supermature subarkose or plots on the arkose-subarkose boundary. Thickness ranges from 25 to 281 ft (fig. 37, sheet 5, pocket). The Pictured Cliffs conformably overlies the Lewis Shale. The contact is marked by a zone of alternating sandstone and mudstone beds in the lower part of the Pictured Cliffs.

HYDROLOGIC PROPERTIES—Several aquifer tests in areas of anticipated coal development gave transmissivities ranging from 0.001 to 3 ft^2/d. Based on permeability data given by Reneau and Harris (1957, p. 40), a hydraulic conductivity of about 0.007 ft/d seems reasonable for gas-producing horizons (table 5, microfiche pocket). For a thickness of 100 ft, this value gives an average transmissivity of 0.7 ft^2/d, which is consistent with values obtained by aquifer testing.

WATER QUALITY AND USE—The Pictured Cliffs Sandstone is a natural-gas reservoir in the San Juan Basin. Specific conductance of water from the Pictured Cliffs Sandstone normally exceeds 2,000 μmhos in or near outcrop areas and exceeds 30,000 μmhos in deeper, gas-producing areas (fig. 38, sheet 5, pocket). Although a few stock wells produce water from the Pictured Cliffs Sandstone near outcrop areas, the formation cannot be considered a major aquifer and is important only because it is the water-bearing horizon immediately underlying the coals in the Fruitland Formation.

Cliff House Sandstone (Late Cretaceous)

The Cliff House Sandstone is the uppermost unit in the Mesaverde Group. West of Farmington, it forms the top or eastern flank of The Hogback monocline, thus marking the edge of the central basin. The Cliff House descends to a depth of 6,150 ft in the basin center (figs. 39 and 40, sheet 6, pocket).

GEOLOGIC CHARACTERISTICS—This coastal marine sandstone was named by Collier (1919) for the numerous cliff dwellings associated with the unit in Mesa Verde National Park in southwest Colorado. Several tongues occur in the Cliff House (sheet 2), but only one, the La Ventana, has been formally named (Beaumont and others, 1956). Other tongues have been referred to by the informal names Chacra and Tsaya (Fassett, 1977), but regional correlations and priority are uncertain. The Cliff House is a very fine to fine-grained, immature to submature subarkose (tables 8 and 9). Thickness of this unit ranges from 20 to 245 ft over most of its extent but exceeds 800 ft just north of Chaco Canyon National Monument (fig. 41; fig. 42, sheet 6, pocket). The Cliff House unconformably overlies or intertongues with the Menefee Formation. Commonly, a thin interval of Lewis Shale intervenes between the Menefee and Cliff House. The upper contact of the Cliff House is characterized by intertonguing with the Lewis Shale.

HYDROLOGIC PROPERTIES—The potentiometric surface of ground water in the Cliff House is shown in fig. 43 (sheet 6, pocket). Transmissivity data are limited for the Cliff House Sandstone. A test well in a thicker part of the unit, in T. 21 N., R. 5 W., gave a specific capacity of 0.3 gpm/ft, indicating a possible transmissivity of more than 60 ft^2/d (J. W. Shomaker, consulting geologist, personal communication, 1978). A recovery test in T. 20 N., R. 8 W., which gave a transmissivity of about 2 ft^2/d, probably better reflects average characteristics of the Cliff House in areas where the sandstone is less than 200 ft thick. Permeability data reported by Reneau and Harris (1957, p. 41) suggest lower values; an average hydraulic conductivity of 10^{-3} ft/d for oil- and gas-producing horizons (or only 1 ft^2/d for a 1,000-ft thickness) is indicated.

WATER QUALITY AND USE—The specific conductance is lowest in recharge or outcrop areas and increases in the direction of ground-water flow (fig. 44, sheet 6, pocket). Even in recharge areas, however, the specific conductance commonly exceeds 2,000 μmhos. Although no data are given here, water produced from this unit

Figure 36—PICTURED CLIFFS SANDSTONE IN THE TYPE AREA. View to east in SW¼ sec. 32, T. 30 N., R. 15 W.

Figure 41—CLIFF HOUSE SANDSTONE EXPOSED IN CHACO CANYON NATIONAL MONUMENT. View to north in SE¼ sec. 12, T. 21 N., R. 11 W.; Chetro Ketl ruins in foreground (*see cover*).

with oil or gas in deeper parts of the basin probably has a specific conductance exceeding 30,000 μmhos.

Several wells produce water from the Cliff House Sandstone for stock and domestic use near outcrops in the central part of the study area. The potential exists for relatively high yields (more than 50 gpm) from thicker parts of the sandstone.

Menefee Formation (Late Cretaceous)

The Menefee Formation, middle unit of the classical tripartite Mesaverde Group, crops out in the center of The Hogback monocline west of Farmington (fig. 45) and in a vast area on the Chaco slope (sheet 1). Although the depth was not mapped for the Menefee, a maximum value of 6,240 ft may be calculated for the basin center by adding the thickness (90 ft) and the depth (6,150 ft) of the overlying Cliff House Sandstone in that area.

GEOLOGIC CHARACTERISTICS—The Menefee Formation was named by Collier (1919) for exposures on Menefee Mountain in Mesa Verde National Park. Two members have been recognized locally in the Menefee based on the presence or absence of coal: the basal Cleary Member (coal bearing) and the overlying Allison Member (barren). In the Torreon area, Tabet and Frost (1979) and Craigg (1980) recognized a third informal subdivision above the Allison: the upper member. The Menefee consists of interbedded claystone, carbonaceous siltstone and shale, coal, and sandstone (fig. 45). The sandstone is a fine-grained, immature to submature, lithic arkose (tables 8 and 9). The thickness of the Menefee Formation ranges from 400 to 1,000 ft. The Menefee conformably or disconformably overlies the Point Lookout Sandstone.

HYDROLOGIC PROPERTIES—Transmissivity of the Menefee as calculated in aquifer tests depends largely on the total thickness of the sandstone bodies that are penetrated; most wells do not penetrate the full thickness. Values reported in table 5 are generally less than 50 ft^2/d, although one test at Mexican Springs gave a value of about 100 ft^2/d. In oil and gas horizons, the hydraulic conductivity averages 0.01 ft/d (from permeability data of Reneau and Harris, 1957, p. 41). If this value were representative of all sandstones of the Menefee, transmissivities would not exceed 10 ft^2/d. Craigg (1980, p. 39) calculated transmissivities of 1×10^{-4} ft^2/d and 20 ft^2/d in coal beds of the Menefee south of Torreon.

WATER QUALITY AND USE—The specific conductance of water from the Menefee south of the Chaco River (fig. 46, sheet 6, pocket) is generally less than 1,000 μmhos in several wells on the flanks of the Chuska and Cebolleta Mountains but more than 1,500 μmhos in most other localities. Fluoride concentrations exceed recommended limits for drinking water in many areas south and west of the Chaco River. Water-quality data are not available for most of the area north and east of the Chaco River. The Menefee Formation, because of its widespread distribution at the surface and the aggregate thickness of its sandstone members, is a common source of water for stock and domestic uses. Most wells produce less than 10 gpm. Sandstones in the Menefee also yield oil in some localities, such as at Red Mountain where commercial quantities are produced from wells less than 1,000 ft deep (Kuhn, 1958, p. 145).

Point Lookout Sandstone (Late Cretaceous)

The Point Lookout Sandstone, lowest unit in the classical Mesaverde Group, dips toward the basin center to a maximum depth of 6,400 ft (figs. 47 and 48, sheet 6, pocket).

GEOLOGIC CHARACTERISTICS—This coastal marine sandstone was named by Collier (1919) for exposures on the prominent topographic feature of that name in Mesa Verde National Park, southwest Colorado. The Point Lookout is well exposed in The Hogback monocline west of Farmington (fig. 49). Along the southern margin of the basin, the unit is split in two by the Satan Tongue of the Mancos Shale (fig. 6). The lower part is known as the Hosta Tongue and the upper part is referred to either as the main body of the Point Lookout or simply as the Point Lookout Sandstone. The sandstone is a very fine to medium-grained, immature to submature, lithic arkose to arkose (tables 8 and 9). Thickness of the Point Lookout ranges from 40 to 415 ft

Figure 45—MENEFEE FORMATION IN THE HOGBACK, 19 MI WEST OF FARMINGTON. View to north in SE¼ sec. 5, T. 29 N., R. 16 W.

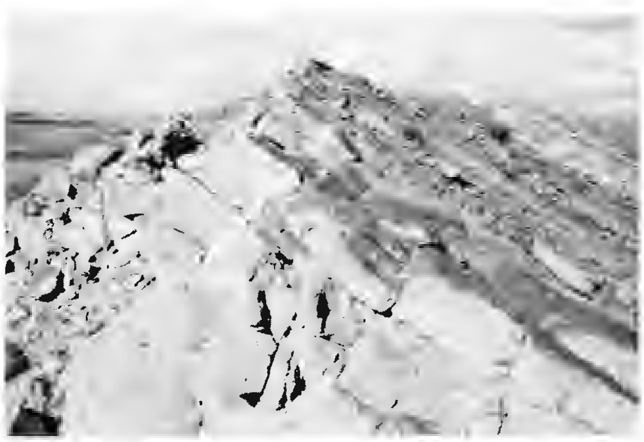


Figure 49—POINT LOOKOUT SANDSTONE EXPOSED IN THE HOGBACK, 19 MI WEST OF FARMINGTON. View to north in SE¼ sec. 5, T. 29 N., R. 16 W.

(fig. 50, sheet 6, pocket). The Point Lookout lies conformably on the Mancos Shale. The contact is marked by a change from shale to an interval of interbedded mudstone and sandstone in the lower part of the Point Lookout.

HYDROLOGIC PROPERTIES—The potentiometric surface of ground water in the Point Lookout is shown in fig. 51 (sheet 6, pocket). Aquifer-test data are sparse. A test by Dames and Moore (1977) northeast of Crownpoint (19.11.31.131) gave a transmissivity of approximately 240 ft^2/d for the main body of the Point Lookout Sandstone and a transmissivity of approximately 70 ft^2/d for the Hosta Sandstone Tongue (table 5). In contrast, Craigg (1980, p. 52) reported that several tests of the Point Lookout Sandstone south of Torreon gave transmissivities of less than 1 ft^2/d. An average hydraulic conductivity of 0.01 ft/d (from permeability data of Reneau and Harris, 1957, p.41) would give a transmissivity of approximately 2 ft^2/d for a 200-ft-thick section. Craigg (1980, p. 52) reported hydraulic conductivities ranging from 0.002 to 0.02 ft/d in the horizontal direction and from 0.002 to 0.01 ft/d in the vertical direction for tests on three cores taken from test holes south of Torreon.

WATER QUALITY AND USE—The specific conductance of water from the Point Lookout Sandstone, like that from the Menefee, generally exceeds 1,500 μmhos, although water with a conductance of less than 1,000 μmhos is produced from a few wells and springs on the flanks of the Chuska and Cebolleta Mountains (fig. 52, sheet 6, pocket). In deeper parts of the basin, waters produced with oil and gas have specific conductances of at least 59,000 μmhos. The Point Lookout Sandstone is not widely used as a source of water; a few stock and domestic wells tap this unit on the southern and western side of the basin.

Crevasse Canyon Formation (Late Cretaceous)

The Mesaverde Group was revised by Beaumont and others (1956) to include this sequence of coal-bearing strata lying immediately beneath the Hosta Tongue of the Point Lookout Sandstone in the southwest part of the basin (fig. 53). The depth to the top of this unit was not mapped but, based on its occurrence only near the basin margin, a maximum value of approximately 3,200 ft seems reasonable.

GEOLOGIC CHARACTERISTICS—The Crevasse Canyon Formation was named by Allen and Balk (1954) for exposures near the mouth of a canyon of that name in San Juan County, New Mexico. The formation consists of four members, originally regarded by Sears (1925) as members of the Mesaverde before its elevation to group status: the Dilco Coal Member at the base (coal bearing), the Dalton Sandstone Member, the Bartlett Member (barren) and the Gibson Coal Member at the top (coal bearing). The Dalton and Bartlett Members are locally equivalent, each lying above the Dilco and below the Gibson Members. Locally, the Dilco is separated from the overlying Dalton Sandstone Member by the Mulatto Tongue of the Mancos Shale (fig. 6). Additional details of these relationships were given by Kirk and Zech (1977). The major aquifer in the Crevasse

Figure 53—CREVASSE CANYON FORMATION IN CLIFF BEHIND KERR-MCGEE SECTION 25 MINE SHAFT. View to north in T. 17 N., R. 16 W., approximately 13 mi northeast of Church Rock. Head frame (at left) rests on Dalton Sandstone Member; bulk of cliff above is Gibson Coal Member. Point Lookout Sandstone caps higher parts of mesa.

Canyon Formation is the Dalton Sandstone Member, a very fine to medium-grained, immature, lithic arkose (tables 8 and 9). Thickness of the Dalton at the type area is 180 ft; this member pinches out toward the west. Total thickness of the Crevasse Canyon Formation ranges from 420 to 700 ft. The Crevasse Canyon lies conformably to disconformably on the Gallup Sandstone. The unit overlying the Crevasse Canyon varies across the area. In some places the Crevasse Canyon is disconformably overlain by the Hosta Tongue of the Point Lookout Sandstone; elsewhere, deposition was more or less continuous into the Menefee Formation.

HYDROLOGIC PROPERTIES—Transmissivity of sandstones within the Crevasse Canyon probably is less than 50 ft^2/d. Dames and Moore (1977, plate 4–16) reported a possible range for transmissivity of between 10 and 30 ft^2/d northeast of Crownpoint.

WATER QUALITY AND USE—Many of the wells that produce water from sandstone in the Crevasse Canyon Formation have also been completed in the overlying Point Lookout Sandstone or underlying Gallup Sandstone. For this reason, it is difficult to characterize water quality. The specific conductance of water in the Crevasse Canyon, like that of other Cretaceous sandstones, generally does not exceed 2,000 μmhos in or near outcrop areas but increases in the direction of ground-water flow. Scattered wells and springs in the Crevasse Canyon Formation produce water for stock and domestic use.

Gallup Sandstone (Late Cretaceous)

The Gallup Sandstone is the lowest unit in the Mesaverde Group as revised by Beaumont and others (1956). Although the unit has a greater areal extent than the Dalton Member of the Crevasse Canyon Formation, the Gallup Sandstone has a smaller extent than most of the other Cretaceous marine sandstones in the basin because of truncation along a pre-Niobrara erosion surface (fig. 54, sheet 7, pocket). Maximum observed depth to the Gallup is 4,298 ft (fig. 55, sheet 7, pocket).

GEOLOGIC CHARACTERISTICS—This interval of marine and nonmarine sandstones was named by Sears (1925) for exposures at the town of Gallup, McKinley County, New Mexico. Molenaar (1973, 1974) recognized several sandstone bodies within the Gallup and correlated them throughout the basin. He named the uppermost of these the Torrivio Member, but merely assigned letters to the others (fig. 56). These sandstones intertongue with the Mancos Shale and pinch out toward the northeast (fig. 57). The Gallup is generally a fine- to medium-grained, submature to mature, lithic arkose (tables 8 and 9). Thickness of the Gallup ranges from 93 to 700 ft (fig. 58, sheet 7, pocket). The Gallup lies conformably on the Mancos Shale. The contact is commonly marked by a zone of alternating sandstone and mudstone beds in the lower Gallup.

HYDROLOGIC PROPERTIES—The potentiometric sur-

Figure 56—LOWER PART OF MAIN BODY OF GALLUP SANDSTONE, APPROXIMATELY 2 MI NORTH OF PINEDALE. View to east in SE¼ NW¼ sec. 8, T. 16 N., R. 15 W.

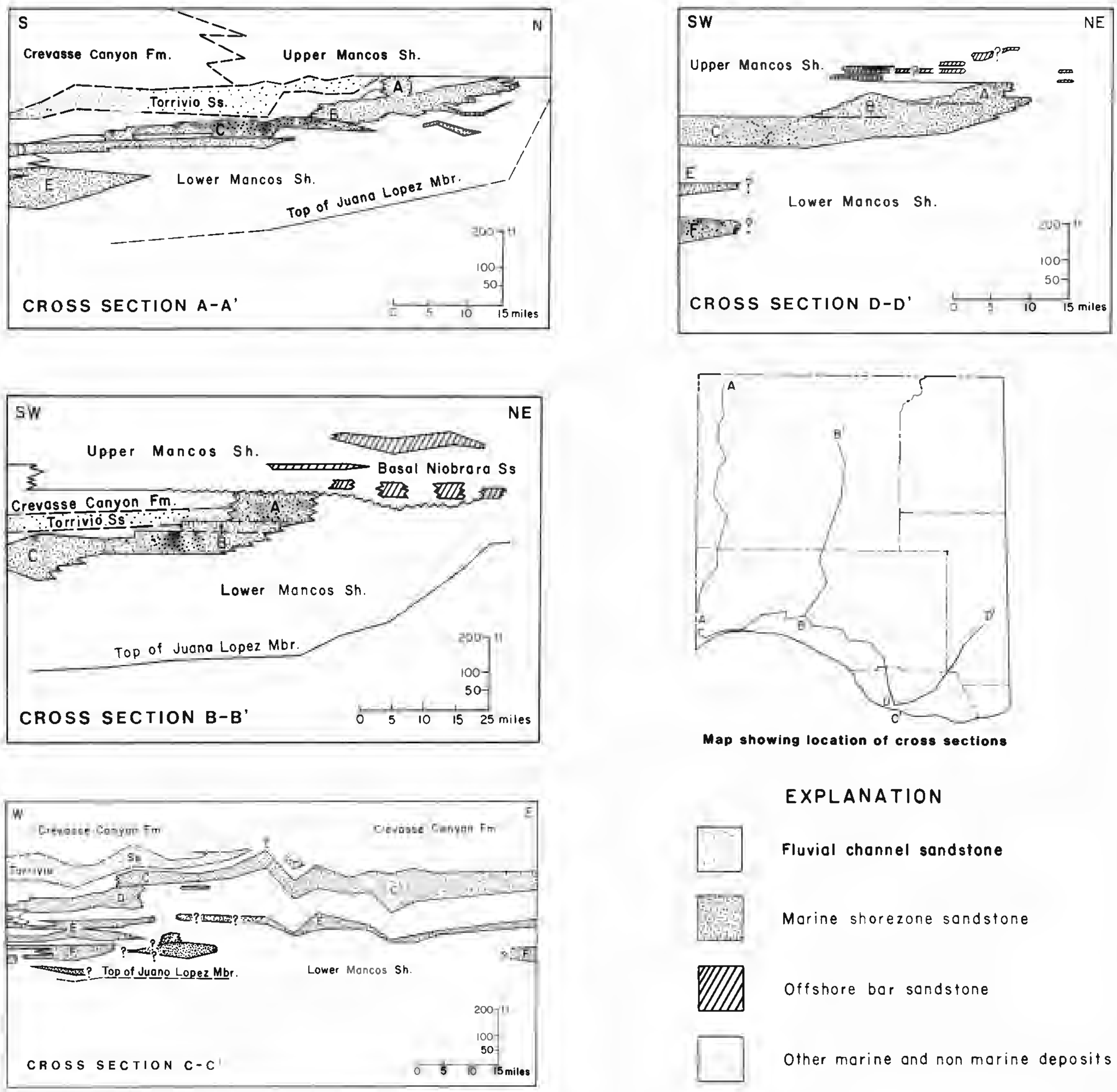


Figure 57—REGIONAL SANDSTONE BODIES RECOGNIZED IN GALLUP SANDSTONE.

face of ground water in the Gallup is shown in fig. 59 (sheet 7, pocket). Recent declines in water levels have been measured near Gallup and Crownpoint (fig. 60). Large declines near Gallup are the result of pumping for municipal supply. Prior to pumping in the early 1900's, wells completed in the Gallup Sandstone flowed at Gallup (Waring and Andrews, 1935, p. 93). Declines west of Crownpoint may be largely the result of pumpage of water for use in uranium-exploratory drilling. Waring and Andrews (1935, p. 104) described several flowing wells that are probably completed in the Gallup Sandstone north of Crownpoint. One of these (in sec. 30, T. 20 N., R. 10 W.) is 2,550 ft deep and reportedly flowed at 150 gpm. Another well at Whiterock (sec. 31, T. 22 N., R. 13 W.) is 2,695 ft deep and flowed at 100 gpm. The effects of these flowing wells on water levels in the area are unknown.

The highest transmissivities occur in the southwest part of the basin near Gallup (fig. 61, sheet 7, pocket). Mercer and Lappala (1972) reported a transmissivity of 250 ft^2/d for well 16.18.07.3333 in the Yah-Ta-Hey well field north of Gallup (table 5). The well also produces water from the Dalton Sandstone Member of the Crevasse Canyon Formation. McLean (1980) analyzed results of 75 days of continuous pumping from one well in the Yah-Ta-Hey field. From water-level data in the pumped well and two observation wells, he computed a transmissivity of 300 ft^2/d and a storage coefficient of 10^{-4}. Northeastward, transmissivity decreases to about 100 ft^2/d or less as shown by results of a test on a well at Chaco Canyon National Monument (21.10.21.3444), that gave a value of 115 ft^2/d (J. W. Shomaker, personal communication, 1972), and another test, northeast of Crownpoint (19.11.31.131), that gave a value of 59 ft^2/d (Dames and Moore, 1977). Oil-producing sandstones near the northeast edge of the main body of the Gallup Sandstone have hydraulic conductivities that average 0.1 ft/d (based on permeability data of Reneau and Harris, 1957, p. 42). For a 100-ft thickness, this value would give a transmissivity of about 10 ft^2/d. A test on a well in the Gallup Sandstone on the east side of the basin (16.04.35.2321) gave a transmissivity of about 350 ft^2/d (table 5). This well, however, is near a fault where fracturing could be responsible for the relatively high value (Craigg, 1980, p. 98).

WATER QUALITY AND USE—The specific conductance of water from the Gallup Sandstone is less than 2,000 μmhos near recharge areas on the southern and western margins of the basin, increasing to more than 4,000 μmhos toward the deeper part of the basin (fig. 62, sheet 7, pocket). The city of Gallup is the principal user of water from the Gallup Sandstone. In addition, numerous wells and springs in this unit produce water for stock and domestic use throughout the southern and western sides of the basin. Recently the Gallup Sandstone has been a common source of water for uranium-exploration drilling in the Crownpoint area.

Dakota Sandstone (Late Cretaceous)

The Dakota Sandstone, the basal Cretaceous unit in the basin, lies at depths of 1,000–3,000 ft on the marginal platforms but extends to depths in excess of 8,500 ft in the basin center (figs. 63 and 64, sheet 7, pocket).

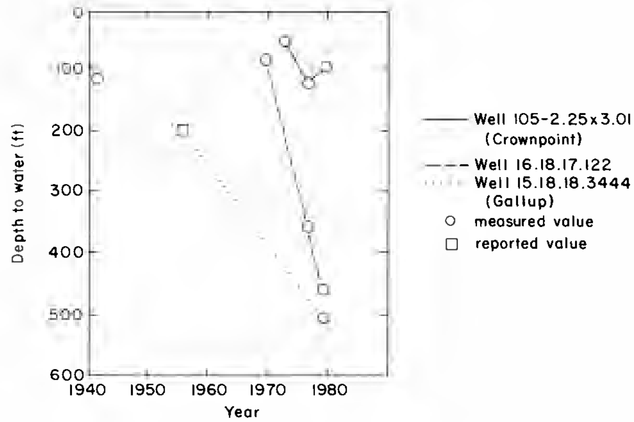


Figure 60—WATER-LEVEL DECLINES IN GALLUP SANDSTONE.

GEOLOGIC CHARACTERISTICS—This sequence of sandstone, mudstone, and coal (fig. 65) was named by Meek and Hayden (1862) for exposures in the Missouri River bluffs, Dakota County, Nebraska. Based on studies of the Dakota in the San Juan Basin by Owen (1963, 1966, and 1973) and Landis and others (1973), four subdivisions are recognized: the Twowells, Paguate, and Cubero Sandstone Tongues and the Oak Canyon Member (in descending order). Like those of the Gallup, these members also intertongue with the Mancos Shale.

The Dakota is generally a fine- to medium-grained, submature subarkose to mature arkose (tables 8 and 9). Thickness is generally 200–300 ft; maximum observed thickness is 350 ft (fig. 66, sheet 7, pocket). The Dakota lies disconformably on the Morrison Formation in most of the area. Locally, however, it lies disconformably on the Burro Canyon Formation (Early Cretaceous); available data do not permit separate treatment of this unit. The Dakota is conformably overlain by the Mancos Shale.

HYDROLOGIC PROPERTIES—Prior to major uranium-mine dewatering in the Ambrosia Lake area, water levels in the Dakota Sandstone may have been more than 200 ft higher than water levels in the underlying Morrison Formation (Cooper and John, 1968, table 1). Similarly, in 1978 water levels in the Dakota Sandstone at a proposed mine site 6 mi west of Crownpoint were

Figure 65—DAKOTA SANDSTONE EXPOSED IN TRIBUTARY CHANNEL WEST OF RED WASH. View to south, approximately 6 mi southeast of Biklabito.

nearly 200 ft higher than in the Morrison Formation (Mobil Oil Corporation, 1978, table 2). Although water levels in the Morrison have declined in recent years as a result of uranium-mine dewatering and pumping for Crownpoint's water supply, hydraulic-head differences probably existed prior to development. Because recharge areas for the Dakota and Morrison are at similar altitudes, the head differences probably reflect better lateral flow in the Morrison Formation toward discharge points because of higher transmissivities, better continuity of the sandstones, or both. The fact that hydraulic-head differences persist is an indication that a relatively low vertical permeability exists in the confining layer between the two units.

Very few aquifer tests have been performed on the Dakota Sandstone alone because most wells also produce from other sandstones above or below the Dakota. Dames and Moore (1977) reported transmissivities of 44 and 85 ft^2/d for two tests (19.11.31.131) northeast of Crownpoint (table 5). Results of specific-capacity tests indicate that transmissivity values are generally less than 50 ft^2/d (table 5).

Berg (1979, p. 899) gave reservoir characteristics for the Dakota Sandstone in the Lone Pine oil and gas field near Hospah. Here, fluvial sandstones within the Dakota have the highest hydraulic conductivity, ranging from approximately 0.7 to 1.5 ft/d. A net sandstone thickness of about 70 ft given for the Lone Pine field would give transmissivities of 49 to 105 ft^2/d.

Much lower values of transmissivity can be expected in oil- and gas-producing horizons in deeper parts of the basin. The hydraulic conductivity averages approximately 0.03 ft/d in oil-producing horizons (based on permeability data of Reneau and Harris, 1957, p. 43) and 4×10^{-4} ft/d in gas reservoirs (Deischl, 1973, p. 168).

WATER QUALITY AND USE—Specific conductance increases from less than 2,000 μmhos near recharge areas to more than 10,000 μmhos in deeper parts of the basin (fig. 67, sheet 7, pocket). In those areas where data are available, the specific conductance of water from the Dakota is generally higher than that of water from the underlying Morrison Formation. Scattered stock and domestic wells produce water from the Dakota Sandstone. Many of the wells that produce from the Dakota, however, are also completed in overlying or underlying rocks or both.

Morrison Formation (Late Jurassic)

The Morrison Formation is the uppermost Jurassic unit present in the basin and is a major source of both uranium and water in the Grants uranium region. This unit lies at depths of 1,500–3,000 ft on the marginal platforms but dips to depths of nearly 9,000 ft in the basin center (figs. 68 and 69, sheet 7, pocket).

GEOLOGIC CHARACTERISTICS—This sequence of nonmarine sandstone, mudstone, and minor limestone was defined by Eldridge (Emmons and others, 1896) for exposures at the town of Morrison, Jefferson County, Colorado. The Morrison consists of four members (in ascending order): the Salt Wash Sandstone Member, the Recapture Shale Member, the Westwater Canyon Sandstone Member, and the Brushy Basin Shale Member.

The Salt Wash Sandstone Member, named by Lupton (1914) for exposures 30 mi southeast of the town of Green River, Grand County, Utah, is restricted to the extreme northwest part of the San Juan Basin. The Salt Wash consists of sandstone and mudstone with lenses of conglomerate. The sandstone is a fine-grained, mature subarkose (tables 8 and 9). This member is approximately 200 ft thick near the Four Corners, but thins southward, pinching out completely just north of Toadlena. In the subsurface, east and southeast of the Four Corners, the Salt Wash intertongues with and grades laterally into the upper part of the Bluff Sandstone (Sears and others, 1974).

The Recapture Shale Member was named by Gregory (1938) for exposures near the town of Bluff, San Juan County, Utah, and redefined by Stokes (1944). This member is present more or less throughout the San Juan Basin and consists mainly of interbedded, red shale and white sandstone. Thickness is approximately 125–150 ft in the north, 125–300 ft in the east and southeast (Sears and others, 1974). Like the Salt Wash, the Recapture also thins southward and southeastward, pinching out south of Gallup and southeast of Grants (Granger, 1968).

The Westwater Canyon Sandstone Member was named by Gregory (1938) and redefined by Harshbarger and others (1957) for exposures south of Blanding, Utah. This sequence of sandstone, conglomeratic sandstone, and mudstone is both the major ore horizon and principal aquifer in the Grants uranium region (fig. 70). The Westwater Canyon consists mainly of fine- to medium-grained, immature to submature, arkose to lithic arkose (tables 8 and 9). The member thins southward and eastward and has an average thickness of 250 ft (Sears and others, 1974; Kelly, 1977).

The Brushy Basin Shale Member, also named by Gregory (1938) for exposures near Blanding, Utah, is an interval of mudstone, sandstone, conglomeratic sandstone, and limestone. The sandstone is generally fine, mature to supermature arkose to subarkose (tables 8 and 9). The major ore-bearing sandstone in the Brushy Basin has been named the Jackpile ore-bearing bed for exposures in the Jackpile mine near Laguna, New Mexico (Freeman and Hilpert, 1956). Flesch (1974) described what he believed to be a correlative sandstone near San Ysidro to the north. Sandstones from the

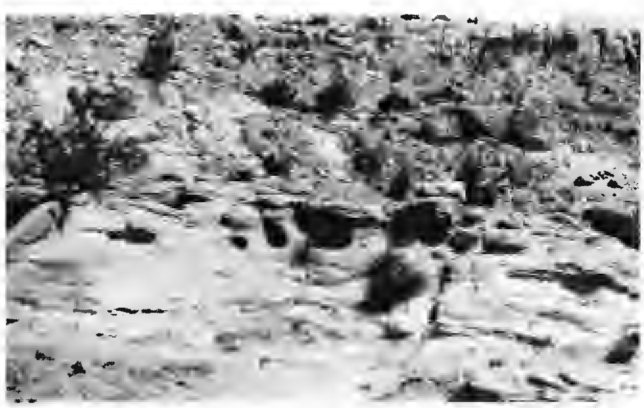


Figure 70—WESTWATER CANYON MEMBER OF MORRISON FORMATION EXPOSED ON NORTHWEST SIDE OF NM-53, APPROXIMATELY 1.5 MI SOUTHWEST OF INTERSECTION WITH NM-509. View to northwest in SW¼ sec. 21, T. 13 N., R. 9 W.

Brushy Basin are fine- to medium-grained, submature to supermature arkose to subarkose. Average thickness of the Brushy Basin Shale Member is 185 ft; this member is not present in the southwest part of the basin (Sears and others, 1974).

The Morrison Formation generally intertongues with the underlying Cow Springs Sandstone or Bluff Sandstone. Total thickness of the Morrison ranges from 330 to 915 ft (fig. 71, sheet 7, pocket).

HYDROLOGIC PROPERTIES—The potentiometric surface of ground water in the Westwater Canyon Sandstone Member is shown in fig. 72 (sheet 7, pocket). In 1978, a combined discharge of about 16,000 gpm was produced from uranium mines in the Morrison Formation (J. G. Dudley, geohydrologist, New Mexico Environmental Improvement Division, personal communication, 1979). These and other withdrawals have caused water-level declines as shown in fig. 73.

Transmissivity of the Morrison Formation does not exceed 500 ft^2/d (table 5, fig. 74). The highest values occur in the southern part of the basin northeast of Gallup and southeast of Ambrosia Lake. Values of transmissivity have been previously reported by Kelly (1977) and Jobin (1962). Because the grain size and percentage of sand in the Westwater Canyon Member decreases toward the northeast (Ridgely and others, 1978, p. 37; Sears and others, 1974, plate XXIII), transmissivity can be expected to decrease in that direction. Transmissivity data shown in fig. 74 (sheet 7, pocket), although not conclusive, tend to confirm this trend.

WATER QUALITY AND USE—Some of the lowest specific conductances for ground water in the San Juan

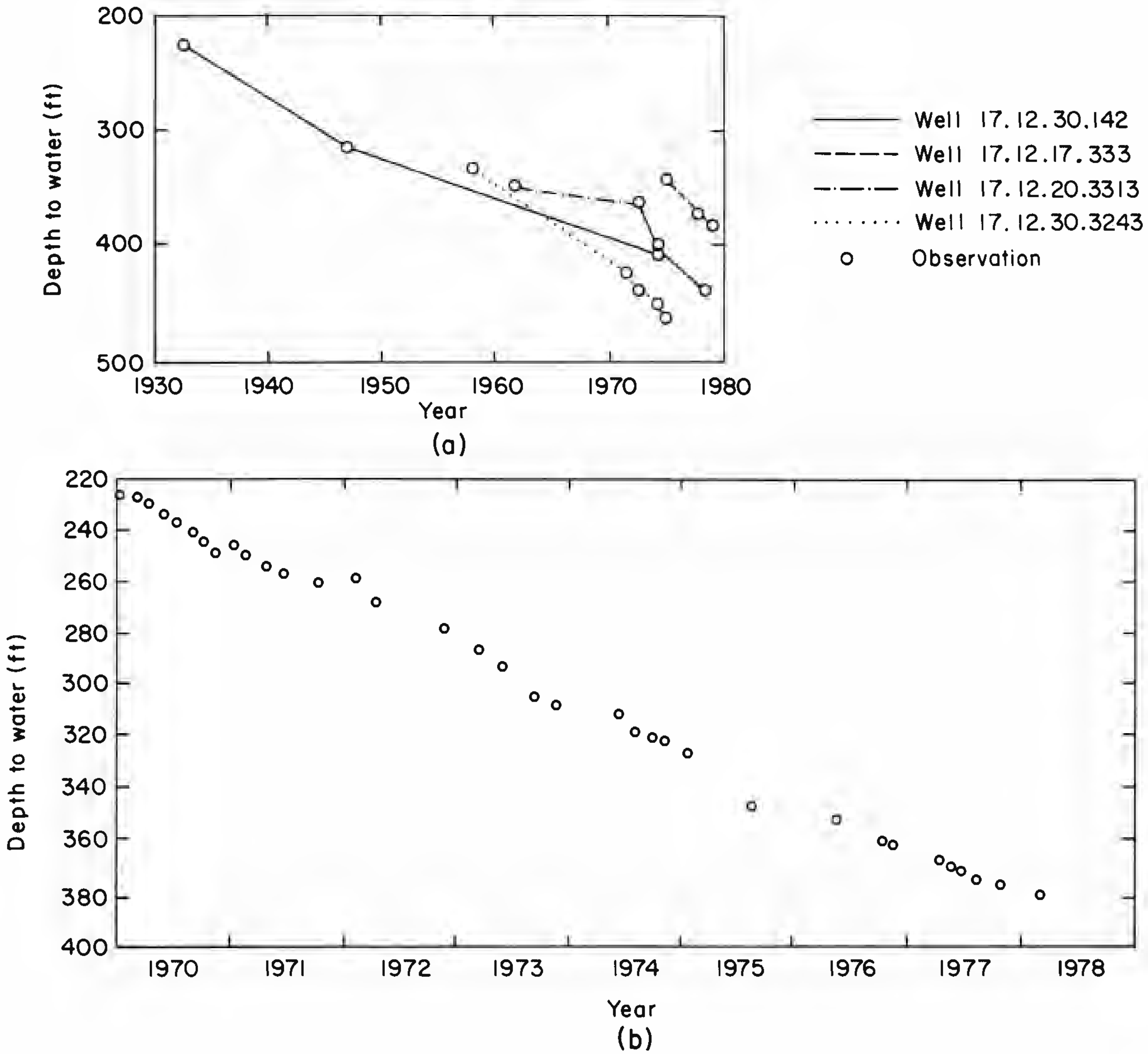


Figure 73—WATER-LEVEL DECLINES IN DAKOTA SANDSTONE AND MORRISON FORMATION.
a) Morrison Formation near Crownpoint
b) Dakota and Morrison at abandoned mine shaft (16.16.17.2141); water level in 1968 before dewatering of Church Rock mines reported at 114 ft below land surface (Hiss, 1977, p. 53).

Basin are associated with the Morrison Formation. Values of less than 1,000 μmhos occur in the Crownpoint–Church Rock area and near the Chuska Mountains between Tohatchi and Shiprock (fig. 75, sheet 7, pocket).

The specific conductance of Morrison water may exceed 10,000 μmhos in the northeast part of the study area and near outflow points. A sharp transition is apparent in the northwest part of the basin where water flowing toward the San Juan River from the northeast merges with flow from the Chuska Mountains. A relatively high conductance might be expected near the Rio Puerco as a result of flow from the northwest and possibly from vertical leakage from deeper units.

The Morrison Formation is the source of the public water supply for the village of Crownpoint. The city of Gallup also has numerous wells that are completed in both the Gallup Sandstone and the Morrison Formation (West, 1957, table 4). Several wells south of Crownpoint also produce water from the Morrison for domestic use. Numerous flowing wells, some of which are converted uranium-test holes, produce water for stock and domestic use along the western edge of the basin between Crownpoint and Shiprock.

Cow Springs–Bluff Sandstone (Late Jurassic)

These two formations are treated together because they are closely related stratigraphically and probably behave as a single unit hydraulically.

GEOLOGIC CHARACTERISTICS—The name "Cow Springs Sandstone" is generally credited to Harshbarger and others (1951). The type area is the north face of Black Mesa near Cow Springs Trading Post, Coconino County, Arizona. This unit intertongues with the Summerville Formation and the lower part of the Morrison Formation. Although not analyzed separately in this study, the Cow Springs is generally a fine-grained, arkosic sandstone (fig. 76). It is 240 ft thick at Lupton, Arizona, just across the state line, southwest of Gallup (Harshbarger and others, 1951).

The Bluff Sandstone was named by Baker and others (1936) for exposures along the San Juan River at the town of Bluff, San Juan County, Utah. Harshbarger and others (1957, p. 3) believed the Bluff to be "a tongue of the Cow Springs but because of its homogeneous and mappable character and its areal extent, it [was] considered a separate formation and assigned to the San Rafael Group." The Bluff is a medium-grained, mature arkose (tables 8 and 9). Thickness reportedly ranges from a few feet to approximately 300 ft (Harshbarger and others, 1957). In our study, thickness was not determined separately for the Bluff unit. Observed thickness of the Cow Springs–Bluff Sandstone and Summerville Formation combined (fig. 77, sheet 6, pocket) ranges from 60 to 200 ft.

The Cow Springs and Bluff generally display an intertonguing relationship with both the underlying Summerville Formation and the overlying Recapture Shale Member of the Morrison Formation.

HYDROLOGIC PROPERTIES—The water in the Cow Springs–Bluff has an origin and flow pattern similar to the water in the overlying Morrison Formation, but significant hydraulic-head differences exist between the two units in some areas. For example, Mercer and Cooper (1970, p. 78) reported that in the Munoz 1 test hole north of Gallup (16.18.17.122) the water level in the Cow Springs Sandstone was nearly 200 ft higher than the water level in the overlying Morrison Formation.

Figure 76—COW SPRINGS SANDSTONE, NORTHWEST OF CHURCH ROCK MINE ROAD, 1.5 MI NORTH OF CHURCH ROCK. View to northwest in SE¼ sec. 1, T. 15 N., R. 17 W.

Although the Cow Springs–Bluff is a fairly thick and continuous sequence consisting predominantly of sandstone, the transmissivity is relatively low. Jobin (1962, p. 55) reported transmissivities of about 50 ft^2/d for this aquifer in most of the San Juan Basin, increasing to as much as 300 ft^2/d near the Four Corners. These values appear high when compared with a value of 3 ft^2/d (Cooley and others, 1969, p. 46) for one aquifer test at an unspecified location and a yield of less than 2 gpm reported by Mercer and Cooper (1970, p. 471) in the Munoz 1 test hole.

WATER QUALITY AND USE—The specific conductance of water from the Cow Springs–Bluff probably is less than 2,000 μmhos in or near outcrops on the southern and western margins of the basin. No data are available for greater depths except in the Gallup area where Mercer and Cooper (1970, p. 78) reported a value of 4,300 μmhos. No wells are known to derive their water exclusively from this aquifer and those wells tapping this unit are also completed in the underlying Entrada or overlying Morrison.

Entrada Sandstone (Late Jurassic)

The Entrada Sandstone forms the distinctive red cliffs at Red Rock State Park east of Gallup and along the southern basin margin north of I-40. Depth to the top of the Entrada ranges from generally less than 4,000 ft on the marginal platforms to 9,310 ft in the basin center (figs. 78 and 79, sheet 6, pocket).

GEOLOGIC CHARACTERISTICS—This unit was named by Gilluly and Reeside (1926) for exposures in the northern part of the San Rafael Swell, in southeast Utah. Nomenclature of the Entrada in New Mexico has had a problematical history. Strata now included in the Entrada at Fort Wingate, on the southern margin of the basin, were originally named the Wingate Sandstone by

Dutton (1885). After intermediate revisions by various workers, Baker and others (1947) finally replaced the Wingate there with the Entrada; the Wingate is no longer recognized in the San Juan Basin (Green and Pierson, 1977; O'Sullivan, 1977). In the San Juan Basin, the Entrada consists of three members: a lower sandstone member (named the Iyanbito Member by Green, 1974), a middle siltstone member, and an upper sandstone member (Harshbarger and others, 1957). The Iyanbito Member is present only in the southern part of the basin. The middle and upper members are generally present throughout the basin. The upper member is generally a fine-grained, mature to supermature, subarkose to lithic arkose (tables 8 and 9). Thickness of the upper member is approximately 167 ft along the Church Rock mine road (fig. 80), 135 ft north of Prewitt, and 133 ft at Haystack Mountain; at San Ysidro the combined thickness of upper and middle Entrada is 115 ft (Stone, 1979a). The thickness of the Entrada based on subsurface data is mapped in fig. 81 (sheet 6, pocket). The Entrada conformably to unconformably overlies the Chinle Formation.

HYDROLOGIC PROPERTIES—Transmissivity, as indicated by a few specific-capacity tests, is less than 50 ft^2/d along the southern edge of the basin but more than 100 ft^2/d near the basin center (J. W. Shomaker, consulting geologist, personal communication, 1974). Values of hydraulic conductivity ranging from 0.5 to 5 ft/d in oil wells (Fassett and others, 1977, p. 24), would substantiate transmissivities of 100 ft^2/d or more. Jobin (1962, p. 42) reported a similar range of from 130 to 350 ft^2/d for the Entrada in the study area.

WATER QUALITY AND USE—In many places in or near recharge areas, water in the Entrada has a specific conductance less than 1,500 μmhos (fig. 82, sheet 6, pocket). Specific conductance increases to more than 10,000 μmhos in deeper parts of the basin.

In an elongate area between Bisti and San Ysidro, the Entrada produces oil from several fields (Fassett and others, 1977, p. 23). Large quantities of saline water that has a specific conductance of between 10,000 and 20,000 μmhos are produced with the oil. Test wells in this area produce water similar in quality to that of water produced from oil wells.

A well at Sanostee produced fresh water from the Entrada, but the water was unusable because of associated oil and gas (Halpenny and Harshbarger, 1950, p. 19). Domestic and stock wells in the area between Smith Lake and Mariano Lake produce much of their water from the Entrada Sandstone. Generally, however, water from the Entrada is not suitable for drinking, especially in deeper parts of the basin.

Figure 80—ENTRADA SANDSTONE NORTHWEST OF CHURCH ROCK MINE ROAD, 0.5 MI NORTH OF CHURCH ROCK. View to north in NE¼ SE¼ sec. 11, T. 15 N., R. 17 W.

Deeper deposits (pre-Jurassic)

Although there has been extensive drilling for petroleum in the San Juan Basin, most of these wells bottom in the Cretaceous section, and thus little is known of the deeper deposits of the area. The pre-Jurassic rocks are generally too deep to play a significant part in the energy-resource development or to be used extensively for water supply. The following general statements are included merely for completeness.

CHINLE FORMATION (TRIASSIC)—The Chinle Formation crops out in a considerable area at the southern margin of the basin, forming a broad valley between the northern flank of the Zuni Mountains and the red cliffs of the Entrada Sandstone. The Chinle Formation was first described by Gregory (1917). Subdivisions proposed by Stewart (1957) for southeast Utah are generally applied in New Mexico, but not all members are present (fig. 83). Other members have been recognized on the east side of the basin by Wood and Northrop (1946). The Chinle consists of mudstone, sandstone (often pebbly), and limestone. Total thickness of the formation is reportedly 700–1,500 ft (Molenaar, 1977a). The Chinle disconformably overlies the San Andres Limestone.

Aquifer tests of the Sonsela Sandstone Bed of the Petrified Forest Member of the Chinle northeast of Prewitt (well 13.10.18.212) gave a transmissivity of >100 ft^2/d. Specific conductances of water from the Sonsela and the shallower Correo Sandstone Bed of the Petrified Forest Member at this well exceed 10,000 μmhos. Generally, water quality deteriorates rapidly with depth, making the water unacceptable for stock or domestic use, except in or very near outcrop areas.

GLORIETA SANDSTONE–SAN ANDRES LIMESTONE (PERMIAN)—These formations are grouped because they intertongue and behave as a single unit hydraulically. The Glorieta Sandstone and overlying San Andres Limestone form the northern flank of the Zuni uplift. The Glorieta Sandstone, named by Keyes (1915) for exposures on Glorieta Mesa, San Miguel County, New Mexico, consists of fine- to medium-grained, quartzose sandstone. Baars and Stevenson (1977, fig. 4) gave a thickness map for the Glorieta that shows that it thins northward and northeastward, pinching out at approximately the latitude of Lybrook and Nageezi. The San Andres Limestone was named by Lee (Lee and Girty, 1909) for exposures in Rhodes Canyon, San Andres Mountains, Socorro County, New Mexico. The San Andres Limestone consists of thin-bedded dolostone, massive, micritic limestone (often fossiliferous), and fine-grained clastic rocks (Baars and Stevenson, 1977). The San Andres also thins northward and pinches out in the southern part of the San Juan Basin (Baars, 1962). The Glorieta Sandstone conformably overlies the Yeso Formation.

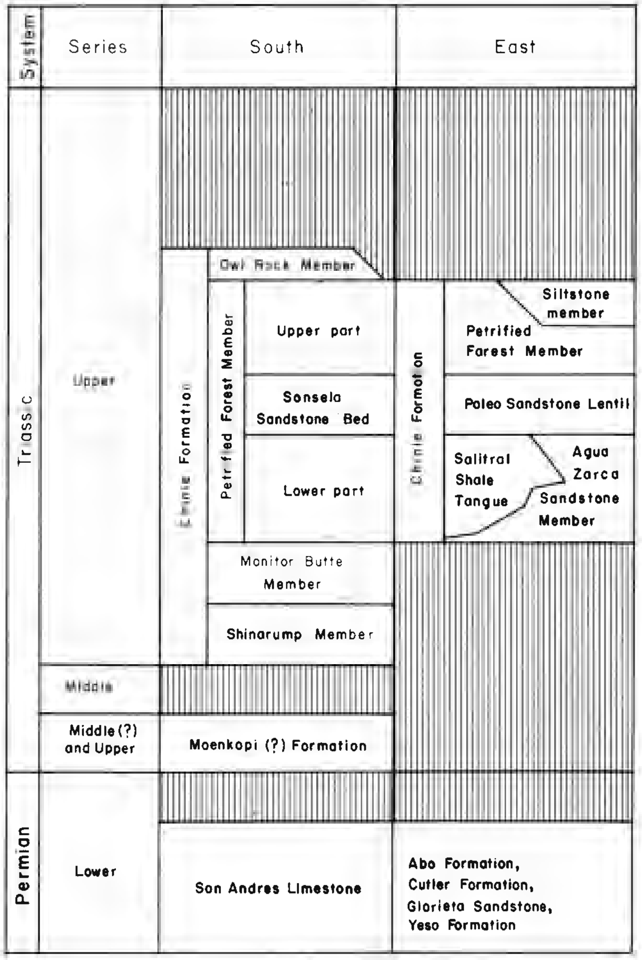


Figure 83—STRATIGRAPHIC NOMENCLATURE AND CORRELATION OF TRIASSIC AND ADJACENT DEPOSITS IN SAN JUAN BASIN (modified from O'Sullivan, 1977).

In the Grants–Bluewater area, dissolution of carbonate rocks has caused relatively high transmissivities. Gordon (1961, table 8) reported values ranging from 60,000 to 450,000 ft²/d. Near Fort Wingate, the transmissivity is considerably lower, ranging from 5 to 3,700 ft²/d (Shomaker, 1971, p. 36). A transmissivity of 90 ft²/d for a well at Smith Lake may be typical for areas away from outcrops and not subjected to dissolution of carbonates. The Glorieta–San Andres yielded less than 1 gpm to a test hole drilled by Sohio north of Laguna (L. Jacobson, geologist, Sohio, personal communication, 1975), indicating a very low transmissivity for this aquifer in the southeast part of the study area.

The specific conductance of water from this aquifer ranges from 500 to 3,300 µmhos in the Grants–Bluewater area (Gordon, 1961, table 10) and from 800 to 3,500 µmhos near Fort Wingate (Shomaker, 1971, p. 46). The Smith Lake well yielded water with a specific conductance of 960 µmhos. Iron and manganese concentrations in this well are relatively high, making the water unsuitable as a domestic supply unless it is treated (Robert Mayers, engineer, U.S. Public Health Service, personal communication, 1976). The Glorieta–San Andres aquifer is the principal source of water along I-40 between Grants and Gallup. The city of Grants derives its water from this aquifer.

YESO FORMATION (PERMIAN)—Lee (Lee and Girty, 1909) named the Yeso Formation for exposures of sandstone, red beds, and gypsum on Mesa del Yeso, Socorro County, New Mexico. According to Baars and Stevenson (1977), the marine evaporites of the Yeso thicken south from a line roughly connecting Gallup and Albuquerque but are missing north of this line. The Yeso of the San Juan Basin is, therefore, almost exclusively an interval of red beds. The Yeso conformably overlies the De Chelly Sandstone.

The Yeso Formation is largely untested. A test of a well near Grants, which was drilled to determine the feasibility of injecting wastes from a uranium-processing mill, gave a transmissivity of 850 ft²/d for the Yeso Formation (West, 1972, p. 16). Water from the well had dissolved-solids concentrations of between 3,000 and 4,000 mg/L (West, 1972, p. 13).

DE CHELLY SANDSTONE (PERMIAN)—The De Chelly Sandstone was named by Gregory (1915) for exposures in the Canyon de Chelly, Apache County, Arizona. The boundaries and correlation of this unit have been the subject of a lengthy debate. Recent drilling in the San Juan Basin has generally confirmed what Baars (1962) had advocated nearly 20 years ago: that the sandstone known as the Meseta Blanca Member of the Yeso Formation in the Albuquerque region and the De Chelly Sandstone of the Four Corners region are one and the same (Baars and Stevenson, 1977). The De Chelly consists of highly crossbedded, clean, eolian sandstone. Its thickness ranges from 800 ft in the southwest corner of San Juan County to less than 100 ft northeast of a line roughly connecting La Plata and Cuba (Baars and Stevenson, 1977, fig. 2). The De Chelly conformably overlies the lower Cutler and Abo Formations.

Cooley and others (1969, p. 47) reported transmissivities for this aquifer ranging from 40 to 100 ft²/d. Water from the De Chelly, in places, has dissolved-solids concentrations of less than 500 mg/L (Harshbarger and Repenning, 1954, p. 15). Springs yielding as much as 80 gpm near Toadlena (Harshbarger and Repenning, 1954, p. 12) supply stock and domestic water to local users.

LOWER CUTLER/ABO FORMATION (PERMIAN)—A sequence of arkosic red beds overlies the Pennsylvanian strata throughout the San Juan Basin. In the northern part of the basin, these red beds are termed the lower Cutler Formation, and in the south they are termed the Abo Formation. The Abo was named by Lee (Lee and Girty, 1909) for exposures in Abo Canyon at the south end of the Manzano Mountains, Valencia and Torrance Counties, New Mexico. The Cutler was named by Cross and Howe (Cross and others, 1905) for exposures along Cutler Creek, near Ouray, Ouray County, Colorado. Thickness of the lower Cutler/Abo Formation ranges from 1,800 ft, where differentiated in the northeast part of the basin, to 200 ft, southeast of Gallup (Baars and Stevenson, 1977, fig. 1). The lower Cutler/Abo disconformably overlies various Pennsylvanian strata.

The lower Cutler/Abo Formation is largely untested as a source of water. West (1972, p. 13) reported a hydraulic conductivity of approximately 4×10^{-2} ft/d and a dissolved-solids concentration of 9,000 mg/L for water from the Abo near Grants. Water from the Abo near Fort Wingate has a dissolved-solids concentration of about 4,600 mg/L (Shomaker, 1971, table 5). Anderholm (1979) reported on two springs issuing from sandstones in the Abo in the Cuba quadrangle; one of these, developed by the U.S. Forest Service, is a major source of drinking water for residents of Cuba.

PENNSYLVANIAN STRATA—The stratigraphy of the Pennsylvanian deposits in the San Juan Basin is complex and the nomenclature applied to them differs from area to area (fig. 84). These deposits consist mainly of marine carbonate rocks and associated, very fine to medium, clastic terrigenous rocks. Although they crop out in most of the uplifts surrounding the basin, little is known of them in the basin subsurface, except where local structure has prompted petroleum exploration (such as at Tocito dome, northwest San Juan County). Thickness generally ranges from 2,500 ft in the northwest to <1,000 in the southeast and <500 in the east (Jentgen, 1977, fig. 2). The Pennsylvanian strata disconformably overlie deeper units.

West (1972, p. 13) reported an average hydraulic conductivity for Pennsylvanian rocks near Grants of approximately 6×10^{-4} ft/d. In the central part of the basin, these rocks are relatively tight and have not readily yielded water to drill stem tests (David Versteeg, geologist, Amoco Production Co., personal communication, 1979).

Water produced with oil from the Pennsylvanian units in several fields near the Four Corners is highly mineralized; total-dissolved-solids concentrations range from 35,000 to 150,000 mg/L (David Versteeg, personal communication, 1979). On or near outcrop areas in Colorado, dissolved-solids concentrations are commonly less than 500 mg/L (Brogden and Giles, 1976). An oil well north of San Ysidro, known as Warm Spring, formerly flowed warm water from the Magdalena Group. A specific conductance of 15,700 μmhos obtained for this water (Trainer, 1978, p. 79), may reflect general water quality in Pennsylvanian units in the basin.

OLDER PALEOZOIC ROCKS—Cambrian, Devonian, and Mississippian deposits are present in the extreme north and northwest parts of the San Juan Basin (Stevenson and Baars, 1977; Armstrong and Mamet, 1977). These strata are the least well known in the area, but because of their great depth, they are of little interest as potential aquifers.

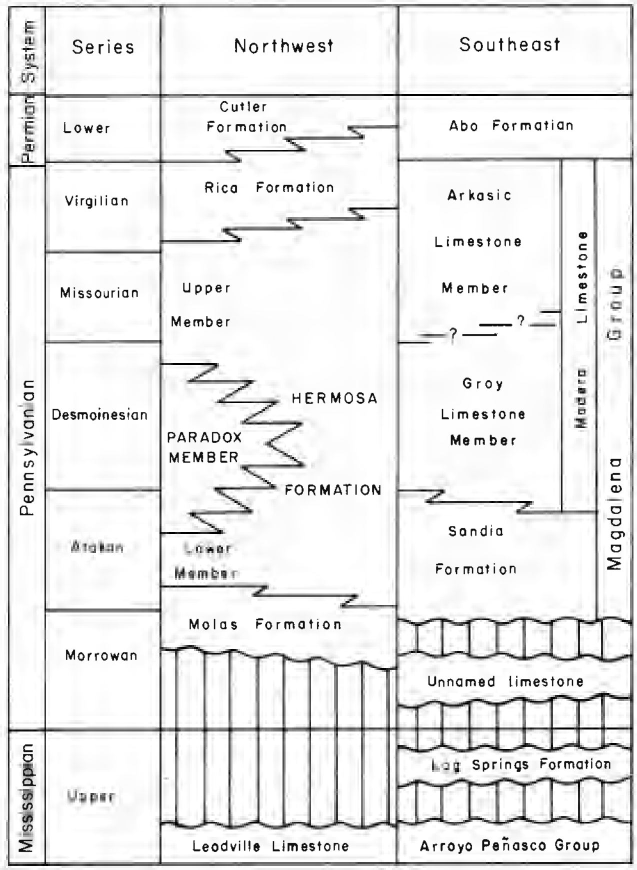


Figure 84—STRATIGRAPHIC NOMENCLATURE AND CORRELATION OF PENNSYLVANIAN AND ADJACENT DEPOSITS IN SAN JUAN BASIN (after Jentgen, 1977).

Hydrogeology

Hydrogeology may be defined as the science that uses geologic principles to interpret hydrologic phenomena (May, 1976); as such, the term "hydrogeology" is not synonomous with ground-water hydrology. Assessing the hydrogeology of an area or aquifer involves delineating the geologic controls of the occurrence, movement, and quality of its ground water.

Basic principles

A major control on the characteristics of a ground-water-flow system is topography; it determines the location of recharge and discharge areas, the direction of ground-water flow, and the hydraulic gradient. Topography is the result of structural and geomorphic processes acting on the local stratigraphic column. Structure provides the elevation and general configuration of the recharge area: cuesta, fault block, or plateau, for example. Geomorphic processes acting through time determine the extent to which these structural features have been modified by erosion or deposition. The local stratigraphic sequence is of utmost importance; the topographic expression of a block of crystalline rock is markedly different from that of a sequence of alternating marine sandstones and shales.

In the case of sandstone aquifers, like those that prevail in the San Juan Basin, minor controls may also be exerted by the texture, geometry, and orientation of the aquifers, or permeability zones within them. Texture includes both grain size and sorting. These parameters affect the size and degree of interconnection of pores, which in turn influence hydraulic conductivity. Geometry includes the dimensions of the aquifer (thickness, width, and length) and their interrelationships. Geometry primarily depends on the depositional origin of the aquifer. Channel sandstone bodies are elongate or shoestring in geometry (thickness and width may be similar, but length is much greater than either of these two dimensions). Regressive, coastal-marine-sandstone bodies are prismatic in geometry (width is greater than thickness, but length is much greater than width). Thickness of such sandstones may diminish seaward. Zones of relatively higher hydraulic conductivity may serve as conduits for greater flow. The orientation of such zones with respect to hydraulic gradient may exert a supplementary influence on flow direction.

In summary, the geologic framework ultimately controls the occurrence, movement, and quality of ground water. Occurrence is controlled by the presence of porous and permeable media. Where ground water is associated with distinct aquifers, occurrence is controlled by the distribution of the aquifers. Location of recharge areas and effectiveness of the recharge process are determined by the structural and geomorphic setting. Direction of flow is dictated by hydraulic gradient, which is variously influenced by structure, geomorphology, and orientation of permeability zones in the aquifer; the latter is related to the depositional origin of the aquifer. Flow volume is a product of hydraulic conductivity and hydraulic gradient. Conductivity depends on texture and degree of fracturing; gradient is determined by structure and geomorphology. Ground-water quality is controlled by abundance and character of soluble materials in the aquifer, geologic conditions suitable for mixing of fresh and saline waters from adjacent aquifers, and residence time.

Post-Triassic deposits

This discussion is restricted to the post-Triassic sandstone aquifers because little is known of the geology and hydrology of the older (deeper) deposits. Inasmuch as rock units of similar age in the study area have similar physical characteristics, aquifers are grouped according to age for summarizing geologic controls of their hydrologic behavior.

Tertiary sandstones

The Tertiary sandstone aquifers were deposited in alluvial or fluvial environments. The Ojo Alamo Sandstone as well as the Cuba Mesa and Llaves Members of the San Jose Formation accumulated in broad, wet, alluvial aprons. The Nacimiento and Animas Formations also resulted from stream deposition, but apparently under more humid conditions, as evidenced by the presence of lignite and carbonaceous plant debris in these units.

CONTROLS OF OCCURRENCE—The ground water is associated with alluvial- and fluvial-sandstone aquifers. Thus, the occurrence of ground water is mainly controlled by the distribution of sandstone in the Ojo Alamo Sandstone, Nacimiento Formation, Animas Formation, and San Jose Formation. The distribution of such sandstone is the result of original depositional extent plus any post-depositional modifications, namely erosion and structural deformation.

CONTROLS OF MOVEMENT—Ground-water movement consists of recharge, flow, and discharge. Recharge of the Tertiary sandstone aquifers is facilitated by their exposure on the flank of the Nacimiento uplift and, at the surface, on the broad plateau that characterizes the central basin. Both of these features receive more precipitation than surrounding areas because of their higher elevation. Flow direction and discharge areas are controlled mainly by the regional topography and geomorphology. At the local and intermediate scales, ground water moves from upland recharge areas toward discharge areas along the floors of the major canyons that deeply incise the Tertiary section in the central basin. These canyons also play a role at the regional level in that they convey this water from the Tertiary aquifers to the San Juan River as subflow through their channel fills. At depths substantially beneath the canyon floors, geomorphology has little effect on ground-water movement. This would be the case for the Nacimiento Formation. The orientations of channel-sandstone bodies in this unit are not well known, but locally orientation may control the direction of ground-water flow in such settings. Based on paleocurrent analyses, Powell (1973) concluded that the source of the Ojo Alamo Sandstone was to the northwest. Distribution and size of gravel in this unit supports such an interpretation. Flow directions in this unit may be influenced locally by the orientation of channels radiating from such a source area.

Flow volume is a product of hydraulic conductivity, hydraulic gradient, and flow area, as described by Darcy's Law. Conductivity of the Tertiary sandstones is determined mainly by their texture (grain size and sorting) and cementation. Gradient is determined by the topography, that is, the difference in elevation of the recharge and discharge areas. Structural effects on ground-water movement appear to be minor for these Tertiary deposits. The swarm of dikes intruding the section near Dulce may provide local barriers to flow (fig. 85).

CONTROLS OF WATER QUALITY—Although some mineral material is undoubtedly dissolved by ground water flowing through the Tertiary sandstone aquifers, most of the dissolved solids are probably derived at the interfaces with adjacent confining shale beds. The more complex the sandstone-shale intertonguing, the more

Figure 85—One of several dikes intruded into San Jose Formation in northeast part of basin, north of NM-17. View to northeast in SW¼ NE¼ sec. 25, T. 30 N., R. 3 W.

opportunity for this uptake of solids. Mixing of fresh ground water with saline waters from other aquifers may occur in areas of intense fracturing or where head differentials permit interaquifer flow, but these are probably minor sources of salinity for the Tertiary deposits.

Cretaceous sandstones

The Cretaceous sandstone aquifers were deposited in various coastal environments. The Menefee Formation, Fruitland Formation, and Kirtland Shale accumulated in fluvial systems that terminated at the shoreline of the Late Cretaceous seaway. The Dakota Sandstone, Gallup Sandstone, Dalton Sandstone Member of the Crevasse Canyon Formation, Point Lookout Sandstone, Cliff House Sandstone, and Pictured Cliffs Sandstone represent sedimentation in various marine shoreline environments. Specifically, these sandstones were deposited along strandplain beaches or at wave-dominated delta fronts. The fluvial and marine deposits intertongue complexly as a result of the alternating transgressive/regressive pulses that characterized the Late Cretaceous shoreline.

CONTROLS OF OCCURRENCE—Ground-water resources in the Cretaceous deposits are associated with fluvial and marine sandstone aquifers. Therefore, the main control on occurrence is the distribution of the rock units making up or containing these aquifers.

CONTROLS OF MOVEMENT—Recharge of the Cretaceous sandstone aquifers is controlled by the distribution and characteristics of outcrop areas. Outcrop belts are narrow, and only a small number of the recharge areas lie in areas of high precipitation. Although most recharge occurs through infiltration in these outcrop areas, some leakage from adjacent units may occur locally. Flow direction and discharge area are mainly controlled by topography; however, flow direction may be influenced locally by structure, as well as by the geometry and orientation of permeability zones within the sandstone units. Detailed study of one of the marine sandstones (the Gallup Sandstone) has shown that deposition resulted in the accumulation of linear to lobate bodies of fairly homogeneous, fine-grained sand (Stone, 1981). The linear bodies more or less parallel both the reported trend of the ancient shoreline along which they accumulated, approximately N. 55° W. (Beaumont, 1971, p. 15), and a line of similar trend marking the northeast extent of the Gallup due to pre-Niobrara erosion (fig. 86). The orientation of transmissivity zones and, locally, flow direction, correspond to the orientation of these linear sandstone bodies (figs. 59 and 86). Similar controls may apply to the other Cretaceous marine sandstones, because of their similar origin and geologic characteristics. Hydraulic conductivity of the marine sandstone aquifers is generally low because of their fine-grained texture. Hydraulic gradient is mainly controlled by topography, but structural and stratigraphic conditions may locally exert an additional influence. Although one would expect ground-water flow in the nonmarine Cretaceous units to be controlled by the orientation of the fluvial, channel-sandstone bodies, data have not been sufficient for detailed study of such control.

CONTROLS OF WATER QUALITY—At first glance, the total-dissolved-solids concentrations in the Cretaceous deposits appear to increase with distance from recharge area or outcrop (figs. 44, 52, and 62) and be merely a function of residence time (the longer the water is in the aquifer, the more material it dissolves). Upon closer examination, however, the distribution of dissolved solids is found to parallel that of other aquifer properties. In the case of the Gallup Sandstone, water-quality zones nearly coincide with transmissivity zones (figs. 61 and 62); water in zones of higher transmissivity is fresher and water in zones of lower transmissivity is more saline. The orientation of these transmissivity zones is in turn controlled by the seaward thinning of the sandstone bodies in the Gallup (Stone, 1981).

In addition to residence time, an additional control is provided by the geologic framework. All of the Cretaceous sandstones intertongue to some extent with the overlying or underlying marine shales; this is especially true at their bases (fig. 87). Water traveling along the sandstone-shale interfaces picks up dissolved solids from the shale. The more complex the intertonguing, the greater the surface area over which such contact takes place. No cases of mixing with saline waters from adjacent aquifers are known.

Jurassic sandstones

The Jurassic sandstone aquifers were deposited in one of two major depositional environments. The Entrada, Cow Springs, and Bluff Sandstones are the result of predominantly eolian deposition under arid conditions. The Morrison Formation marks the onset of more humid conditions prior to the invasion of the area by the Late Cretaceous sea; specifically, deposition in wet alluvial-fan systems prevailed at this time.

CONTROLS OF OCCURRENCE—Ground water in the Jurassic deposits is associated with eolian and alluvial sandstone aquifers. Thus, the occurrence of ground water is mainly controlled by the distribution of the Entrada Sandstone, the Cow Springs–Bluff Sandstone, and the Westwater Canyon Sandstone Member of the Morrison Formation. Their distribution is the net result of original depositional extent, erosion, and structural deformation.

CONTROLS OF MOVEMENT—Recharge of the Jurassic sandstone aquifers is facilitated by their exposure at the surface, mainly in cuestas adjacent to major uplifts. Intense fracturing, especially near faults, enhances recharge locally. Flow direction and discharge area are largely factors of topography, but locally may be controlled by the geometry and orientation of permeability zones within the aquifers. The eolian sandstones are fairly homogeneous and isotropic and probably do not provide any preferred flow paths. The alluvial sandstones are less homogeneous, because of textural variations and the presence of mudstone stringers between alluvial-channel deposits; these sandstones also are less isotropic as a result of these stringers and the depositional fabric produced in this setting. Maps of texture, thickness, and sand percentage suggest a southwesterly or westerly source for the Westwater Canyon Sandstone Member of the Morrison Formation (figs. 88, 89, and 90). Galloway (1980) suggested the Mogollon upland as the probable source area. Permeability zones in this aquifer correspond to the channel deposits that are narrow, elongate, and radiate outward from this source. Ground-water movement was apparently similar in the earlier post-depositional hydrologic system that gave rise to the uranium mineralization of the Westwater Canyon (Galloway, 1980). The northeast extent of the coarse sandstone facies roughly coincides with the 150 ft^2/d transmissivity boundary (figs. 74 and 88).

Flow volume depends on hydraulic conductivity and hydraulic gradient. Conductivity is controlled both by texture and fracturing of these sandstone aquifers. Gradient is controlled mainly by the difference in elevation of the recharge and discharge areas. The structural configuration of the aquifer may exert an additional control on gradient locally.

CONTROLS OF WATER QUALITY—Elevated ground-

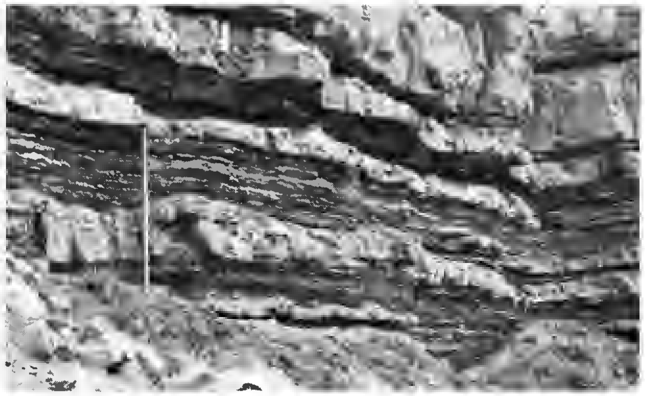


Figure 87—INTERTONGUING SANDSTONE AND MUDSTONE AT BASE OF LAVENTANA TONGUE OF CLIFF HOUSE SANDSTONE, EAST OF NM-44 NORTH OF LAVENTANA. View to north in SW¼ SW¼ sec. 17, T. 19 N., R. 1 W.

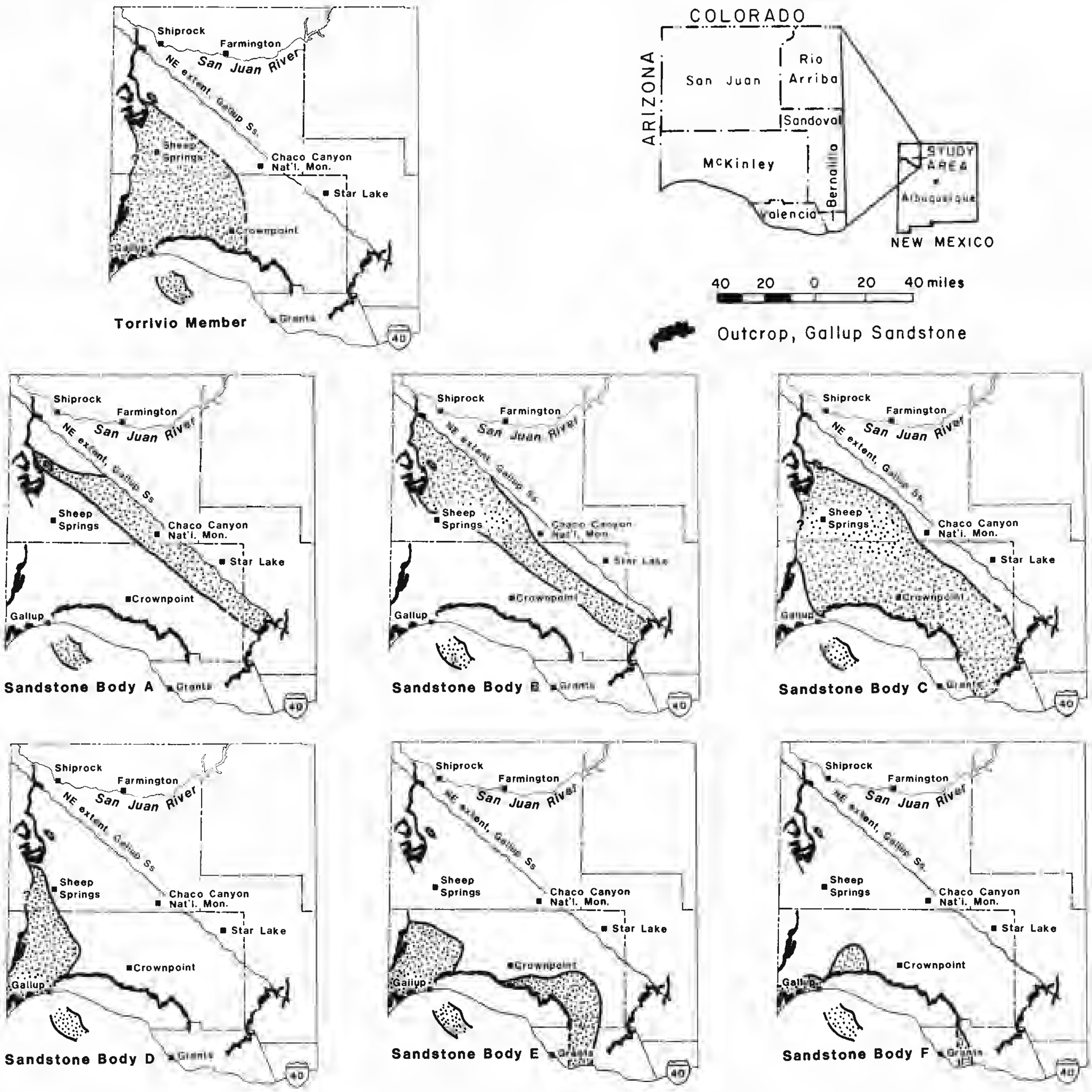


Figure 86—EXTENT OF SANDSTONE BODIES IN GALLUP SANDSTONE.

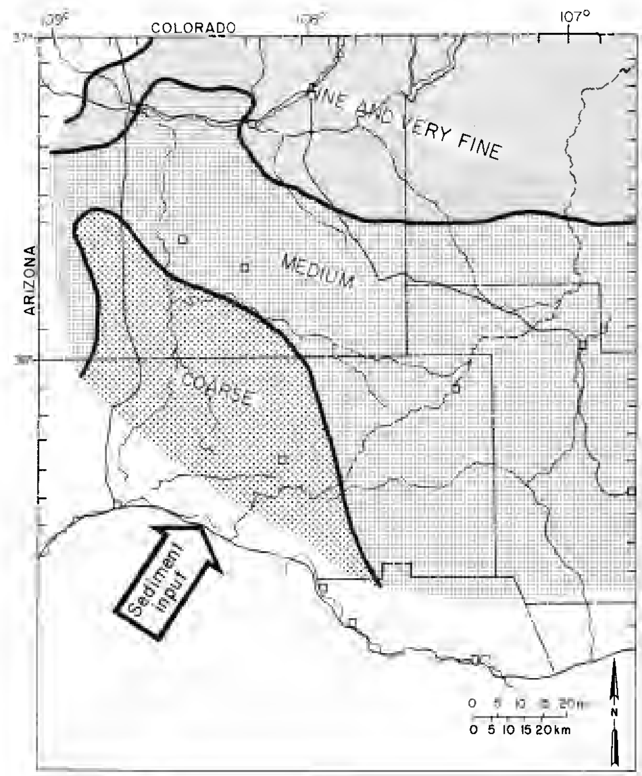


Figure 88—DISTRIBUTION OF SAND SIZE IN WESTWATER CANYON MEMBER OF MORRISON FORMATION (modified from Sears and others, 1974; Kelly, 1977).

water salinities in the Entrada Sandstone are attributable to solution of gypsum from the overlying Todilto Limestone. High dissolved-solids contents of water in the Cow Springs-Bluff aquifer are mainly due to the low hydraulic conductivity of these fine-grained sandstones, but solution of the underlying Todilto may be a factor locally. Conversely, the freshness of the water in the sandstones of the Morrison Formation is a result of the higher hydraulic conductivities associated with their coarser textures.

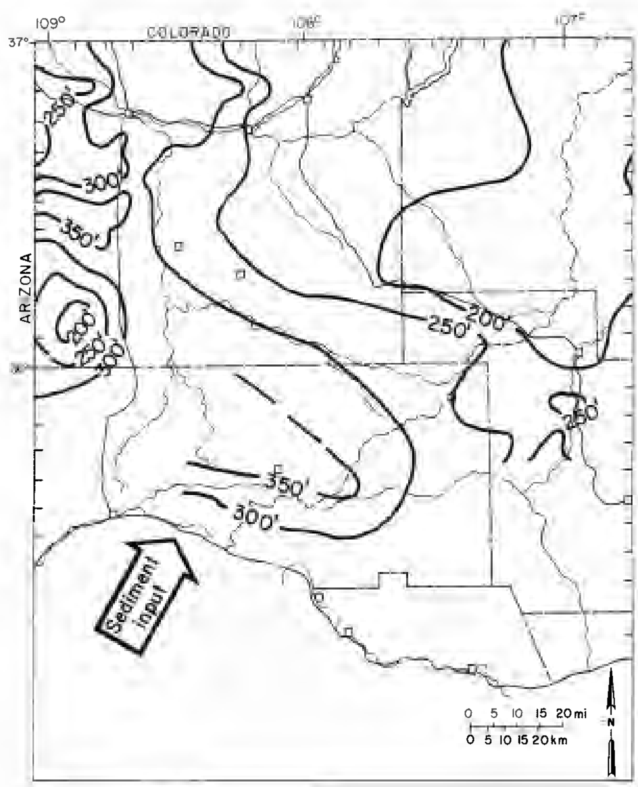


Figure 89—THICKNESS OF WESTWATER CANYON MEMBER OF MORRISON FORMATION (modified from Sears and others, 1974; Kelly, 1977).

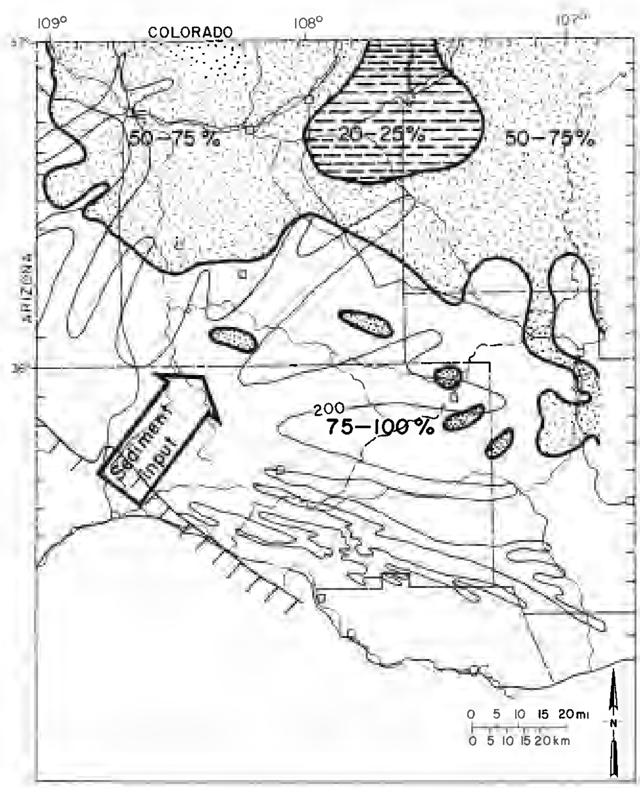


Figure 90—DISTRIBUTION OF SANDSTONE IN WESTWATER CANYON MEMBER OF MORRISON FORMATION (percent sandstone by thickness (after Sears and others, 1974; 200 ft sandstone isolith after Galloway, 1980).

Water for energy development

The San Juan Basin is known for its vast reserves of uranium and coal, as well as its numerous oil and gas pools (fig. 91). Although the petroleum is largely depleted or under production by now, the extraction of the uranium and coal is far from complete. Water plays a different but key role in the development of each of these energy resources (Stone, 1979c).

The calendar for the development of uranium and coal is not clear. Uranium production has been sharply reduced recently. Several companies have ceased exploration drilling and have laid off miners. Anaconda's Jackpile–Paguate mine near Laguna, the world's largest open-pit uranium mine, closed at the end of February 1981. These actions are largely in response to lowered prices, increased costs, and reduced demand for yellowcake as a result of the general moratorium on nuclear-powerplant construction. Coal development was delayed until federal approval of New Mexico's coal surface-mining regulations was obtained in February 1982. Some mines cannot be developed until railroad spurs are constructed, but the railroad has had trouble obtaining permission to cross Navajo Tribal lands. One new coal-fired, electric-power-generating plant near Thoreau may utilize Wyoming coal because local supplies are not assured.

The intensity of energy-resource development (and even the estimate of coal or uranium reserves) fluctuates with market as well as economic conditions. Thus, any production and reserves data given below will be out of date soon after publication. Yearly summaries of New Mexico's energy-resource-development activity have been prepared by the state Bureau of Geology (Mining and Minerals Division, Energy and Minerals Department, Santa Fe) since 1976 (covering 1975). Before November 1981, these summaries were published as Circulars of the New Mexico Bureau of Mines and Mineral Resources. As of November 1981, they are designated Annual Reports of the Bureau of Geology. Monthly developments in the mining industry are reported by New Mexico Pay Dirt (P.O. Drawer 48, Bisbee, Arizona 85603). These publications are major sources of detailed production information and should be consulted for more current or historical development data.

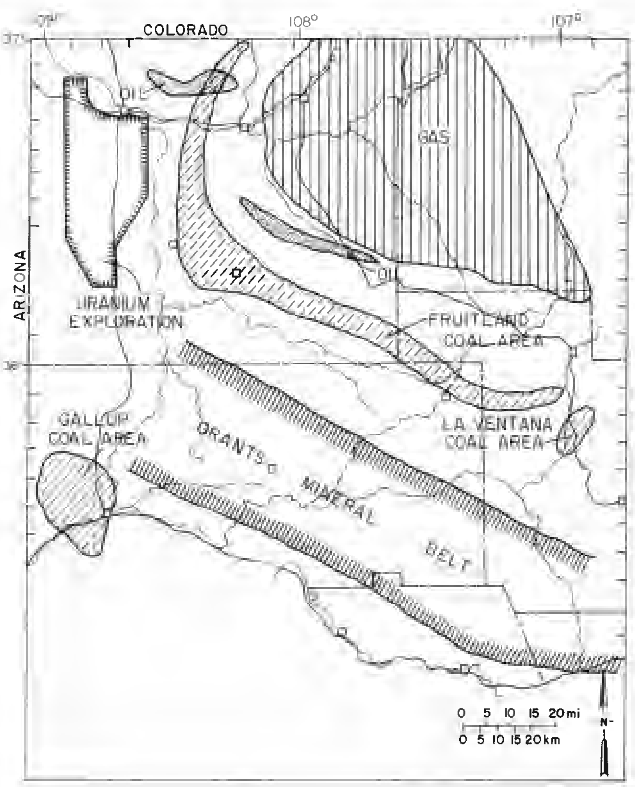


Figure 91—MAJOR AREAS OF PRESENT AND PROPOSED ENERGY-RESOURCE DEVELOPMENT (modified from Lyford, 1979, fig. 2).

Uranium

Minable deposits of uranium occur throughout the Jurassic section and the lowermost part of the Cretaceous section. Major production has been from the Todilto Limestone, the Morrison Formation, and the Dakota Sandstone. Reserves in the $50/lb cost category were estimated at 325,000 tons of uranium oxide (U_3O_8) or yellowcake as of January 1, 1981 (Hatchell, 1981).

A large quantity of freshwater is currently being pumped to keep the mines dewatered. The quantity will increase as more and deeper mines are constructed. Dewatering will, in turn, cause large declines in water levels in wells completed in the Morrison Formation (Lyford and others, 1980). Water pumped from mines often contains elevated levels of radiochemicals and toxic metals (Kaufmann and others, 1976). Water discharged with mill tailings also contains high levels of many chemicals that have been added or mobilized during the extraction process.

Present

Although both underground- and surface-mining methods have been employed in uranium extraction in the San Juan Basin (fig. 92), most mines currently use underground methods (New Mexico State Inspector of Mines, 1980). Work on applying in-situ leaching methods to uranium extraction has already begun at Crownpoint. In 1980, 45 mines and 5 mills produced 7,407 tons of yellowcake in New Mexico, mostly from the Morrison Formation in the San Juan Basin (Hatchell, 1981). This constitutes 35% of the concentrate produced in the United States for that year. Active and proposed mines as of 1978 are shown in fig. 93. By 1980, activity at many of these mines had been reduced to production from stockpiles or recovery from mine water (Hatchell, 1981, table 6). However, most of these mines will again be responsible for major production when market and economic conditions permit.

Discharges of water from uranium mines in the San Juan Basin during 1956–1977 are shown in fig. 94. The quantities of water discharged and used for milling and other purposes are given in table 10.

Much of the water needed for uranium mining and milling operations is provided by dewatering of mines.

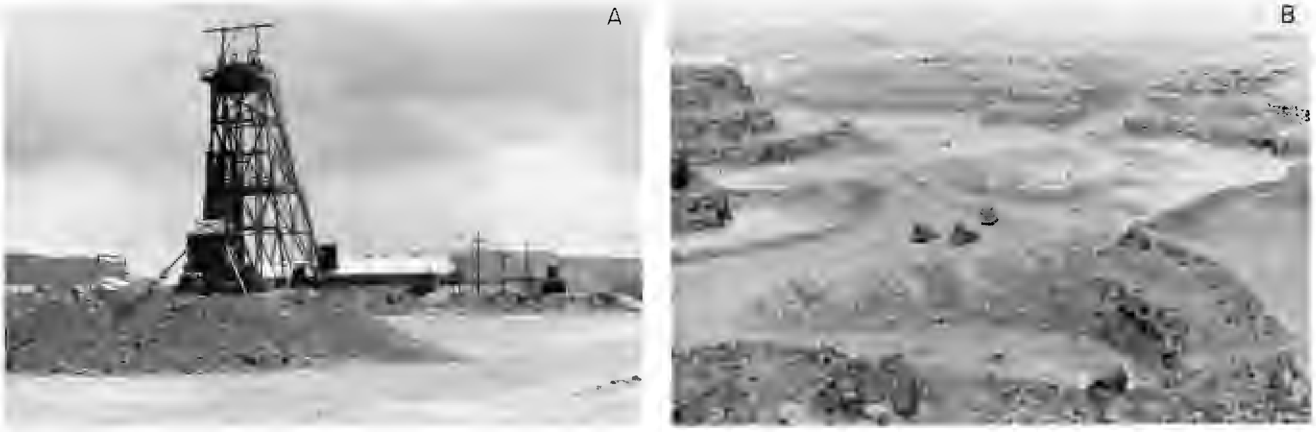


Figure 92—Typical uranium mines in Grants mineral belt: a) Kerr-McGee Section 30-West underground mine, Ambrosia Lake district; b) Anaconda Paguate pit at Jackpile–Paguate open-pit mine, Laguna district.

In addition, water is produced for milling from wells completed in the Glorieta Sandstone–San Andres Limestone near Grants and from wells tapping the Morrison Formation north of Laguna. Perkins (1979, p. 117) stated that the average water requirement for milling is about 1.25 tons of water (300 gal) per ton of ore processed.

Water used in the milling process and discharged with the mill tailings either evaporates or infiltrates to recharge shallow aquifers. Kaufman and others (1976, p. 304) stated that about 30% of the tailings water in the Ambrosia Lake area infiltrates, causing high levels of radium and selenium in shallow ground water near the tailings piles.

Since the U.S. Environmental Protection Agency (Kaufmann and others, 1976) detected possible contamination of ground water as a result of uranium-mining activities, other agencies such as New Mexico Environmental Improvement Division and U.S. Geological Survey also have sampled water from mines and mill workings. Some of these analyses have been presented by Perkins (1979, p. 105) and Kunkler (1979, table V-7). Several water samples were collected as a part of this study from the Puerco River and an unnamed tributary that drains the Church Rock mines. Results of chemical analyses of these samples, given in table 11 (microfiche pocket) and plotted in fig. 95, show the concentration of selected chemical and radiochemical constituents along the river channel, downstream from the mines. The noteworthy parameters are: specific conductance, which increased with distance, particularly below Gallup where municipal waste-water effluent contributes to the flow; activity of radium-226, which was removed from solution a short distance from the origin; the toxic metal selenium, which remained above the U.S. Environmental Protection Agency (1977) mandatory drinking-water standard of 10 μg/L (micrograms/liter) throughout most of the sampled reach; and uranium, which apparently remains in solution. Activity levels of suspended gross beta, although quite variable, also were high throughout the reach. Additional water-quality data for discharges from uranium mines and mills during 1977–1979 may be found in a recent report by the Environmental Improvement Division (Perkins and Goad, 1980).

Although most impacts of uranium development on ground-water quality are associated with mine discharge or tailings-pond effluent, mine dewatering also can result in undesirable mixing of ground waters and degradation of water quality. Kelly and others (1980) reported that mine dewatering has sufficiently lowered heads in the Westwater Canyon Sandstone Member of the Morrison Formation at Ambrosia Lake to cause saline water from the Dakota Sandstone to flow into this fresh-water aquifer.

Collapse has probably also caused some deterioration of water quality in the Morrison Formation near Ambrosia Lake by providing a connection to the overlying Dakota Sandstone; here the Dakota contains higher concentrations of dissolved solids than the Morrison (Cooper and John, 1968, table 3).

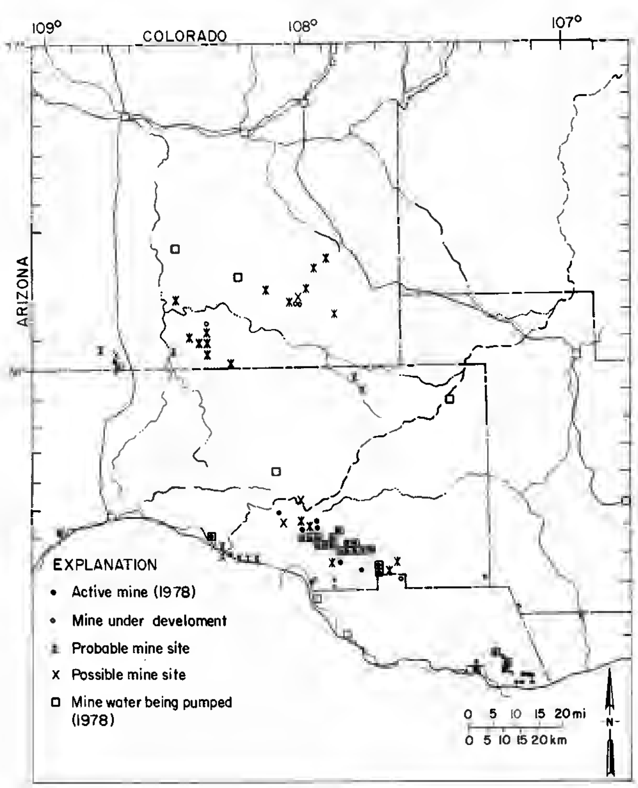


Figure 93—Location of active and proposed uranium mines in Grants mineral belt (Perkins, 1979).

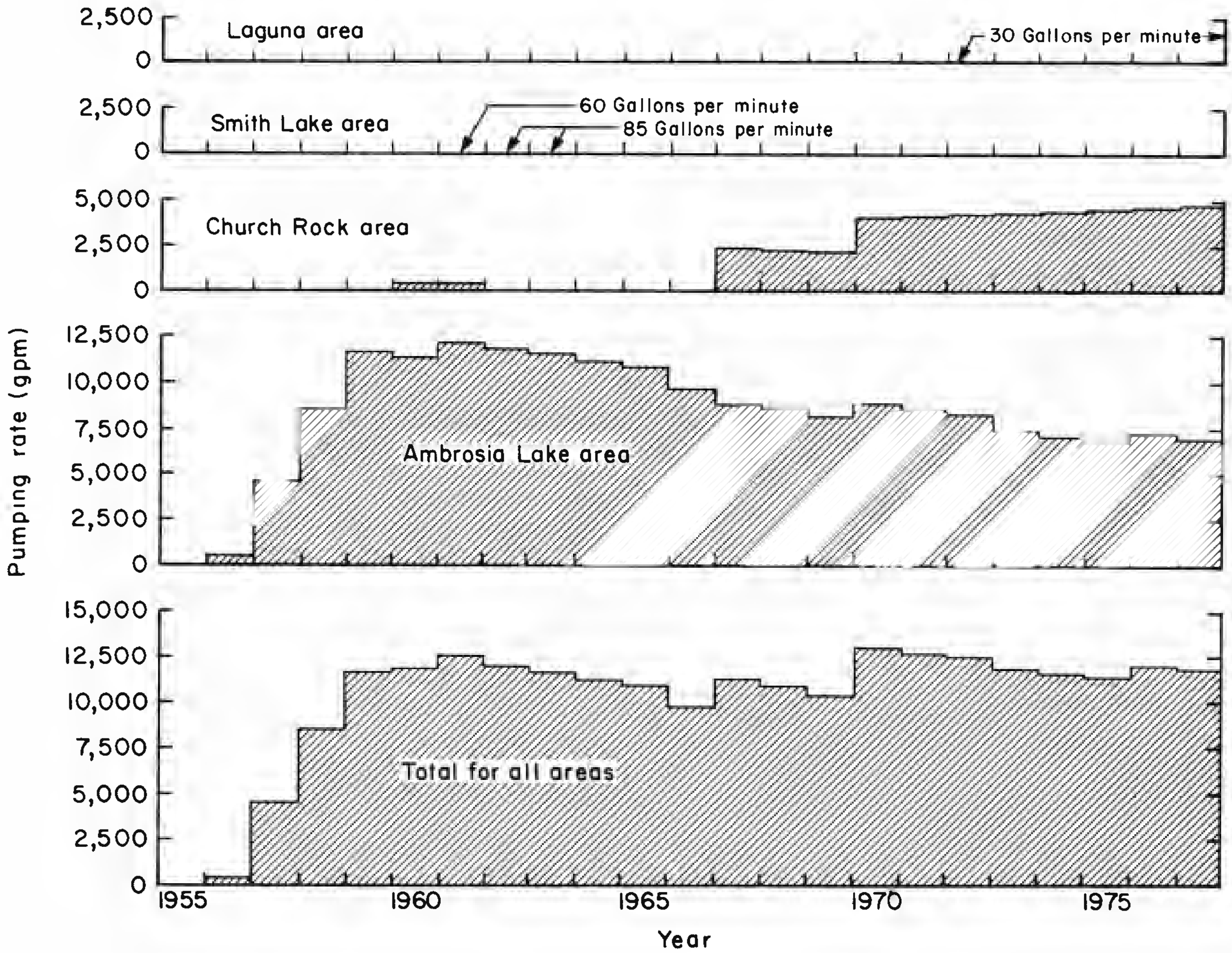


Figure 94—WATER PRODUCTION BY URANIUM MINES, 1955–1977 (modified from Guyton and Associates, 1978, plate 19).

Future

New mines are either under construction or have been proposed for the Crownpoint area and the area between San Mateo and the Rio Puerco (fig. 93). Most of these mines will be completed at depths of 2,000 ft or more and will produce large quantities of water, causing water-level declines in wells penetrating the Morrison Formation. Lyford and others (1980) estimated that a cumulative pumpage of more than 0.5 million acre-feet of water may result from existing and planned mines by the year 2000. They also predicted that a total of 72 mines, many of which are in hypothetical locations, might pump nearly 1.5 million acre-ft of water by the year 2000. Water-level declines in the Morrison Formation would exceed 3,000 ft near some of the deeper mines.

Although some of the water pumped from the mines will be used in the milling process, much of the water will be used for other purposes or discharged to arroyos or underground. The quality of water discharged will be monitored by the U.S. Environmental Protection Agency and the New Mexico Environmental Improvement Division for adherence to National Pollutant Discharge Elimination System and New Mexico State Water Quality Control Commission discharge regulations.

The results of mining activities may affect water quality in aquifers even after operations have ceased. Of concern is the persistence of radiochemicals and toxic substances and the interaquifer mixing of water caused by collapse of mines. Recently, the mining companies have been backfilling abandoned workings with the sand fraction of tailings (Perkins, 1979, p. 104). This practice should reduce the possibility of caving and the consequent mixing of waters, but concurrently it may introduce undesirable substances that have been concentrated or added by the milling process.

The radium-226 concentrations in mine water are normally higher than background concentrations (Kaufmann and others, 1976, p. 296). Continental Oil Company personnel, after conducting a literature search on the mobility of radium in ground-water systems, concluded that dispersion, ion exchange, and radioactive decay will prevent extensive migration of excessive radium concentrations that might persist in the immediate area of a mine (W. M. Jensen, Continental Oil Company, personal communication, 1978). These geochemical processes may also limit migration of other toxic substances, but studies of this relationship are not known to have been conducted in the Grants uranium region.

Analyses of water samples collected by United Nu-

TABLE 10—QUANTITIES OF WATER PUMPED FROM URANIUM MINES AND DISCHARGED TO STREAMS, 1978 (data from J. G. Dudley, New Mexico Environmental Improvement Division, personal communication, 1979); *data supplied to New Mexico Environmental Improvement Division by mining companies, 11–78.

Location of mine	Quantity pumped (gal/min)	Quantity discharged to streams (gal/min)	Other
		Ambrosia Lake area	
14.10.22 14.09.33 14.09.30 14.09.24 14.09.17 14.09.30 14.09.19	2,500*	300–500	2,200 gal/min is used in mill process. Some is recirculated for stope leaching.
14.09.35	1,600*	0	Water diverted for irrigation of rangeland.
14.09.36	1,600*	0	
14.09.28	350–400*	0	Most water is recirculated for stope leaching.
14.09.34	350*	0	
14.10.25 14.10.23 14.10.32	2,000*	650	1,200 to 1,300 gal/min used for stope leaching.
13.08.07	1,000*	1,000	Entire discharge diverted for irrigation and stock watering during summer months.
		Church Rock area	
17.16.35	1,250–1,400*	50	Most water used in mill process.
17.16.35	3,750–4,000*	3,750–4,000	
		Smith Lake area	
15.14.12	200–300*	Intermittent	
		San Mateo area	
13.08.24	4,970–5,020*	4,970–5,020	Water provided from shaft and wells. Most of water diverted for irrigation and stock water.
		Laguna–Marquez area	
11.04.19	20–50*	0	Water produced from shaft.
11.05.13	25*	0	
10.05.04	150	0	
11.04.19	25*	0	
13.05.25	1,200*	1,200	
12.03.18	500*	500	
		Crownpoint area	
19.11.31	1,260–1,400*	1,260–1,400	Water produced from shaft and wells during shaft construction.

clear Corporation in 1978 from the old Church Rock mine (16.16.17.2141) show the character of water in a mine after operations cease (Noel Savignac, Manager of Environmental Services, personal communication, 1979). These samples were collected from depths ranging from 427 to 722 ft below the surface; the mine had been abandoned since 1962, and all the underground workings were under water. Total dissolved-solids concentrations ranged from 1,029 to 1,061 mg/L, which is higher than the concentrations (approximately 500 mg/L) of samples from existing mines 3–4 mi to the north. Activity levels of radium-226 (19.3–25.8 pCi/L) (picocuries/liter), gross alpha (74–275 pCi/L), and concentrations of uranium (740–1,630 μg/L) were notably high at all depths, but concentrations of toxic metals were lower than the U.S. Environmental Protection Agency (1977) mandatory limits for drinking water.

In situ extraction of uranium may be more common in the future. Although this method eliminates many of the water-resource impacts associated with conventional mining, it gives rise to some new ones, such as control of the leaching fluid and clean-up of the Morrison aquifer after extraction is terminated. However, a network of monitor wells should permit early detection of any excursion of leaching fluid, and a series of high-capacity wells should permit rapid removal of leaching fluid until the cause of the excursion can be determined. When extraction is complete, repeated flushing and testing should assure that clean-up has been accomplished. Dewatering is still required for in-situ extraction.

Coal

Coal occurs throughout the Cretaceous section of the San Juan Basin, but major deposits are restricted to the Crevasse Canyon Formation, the Menefee Formation, and the Fruitland Formation. Strippable reserves (coal overlain by <250 ft of overburden) occur mainly in the Fruitland Formation and approach 6 billion tons (Sho-

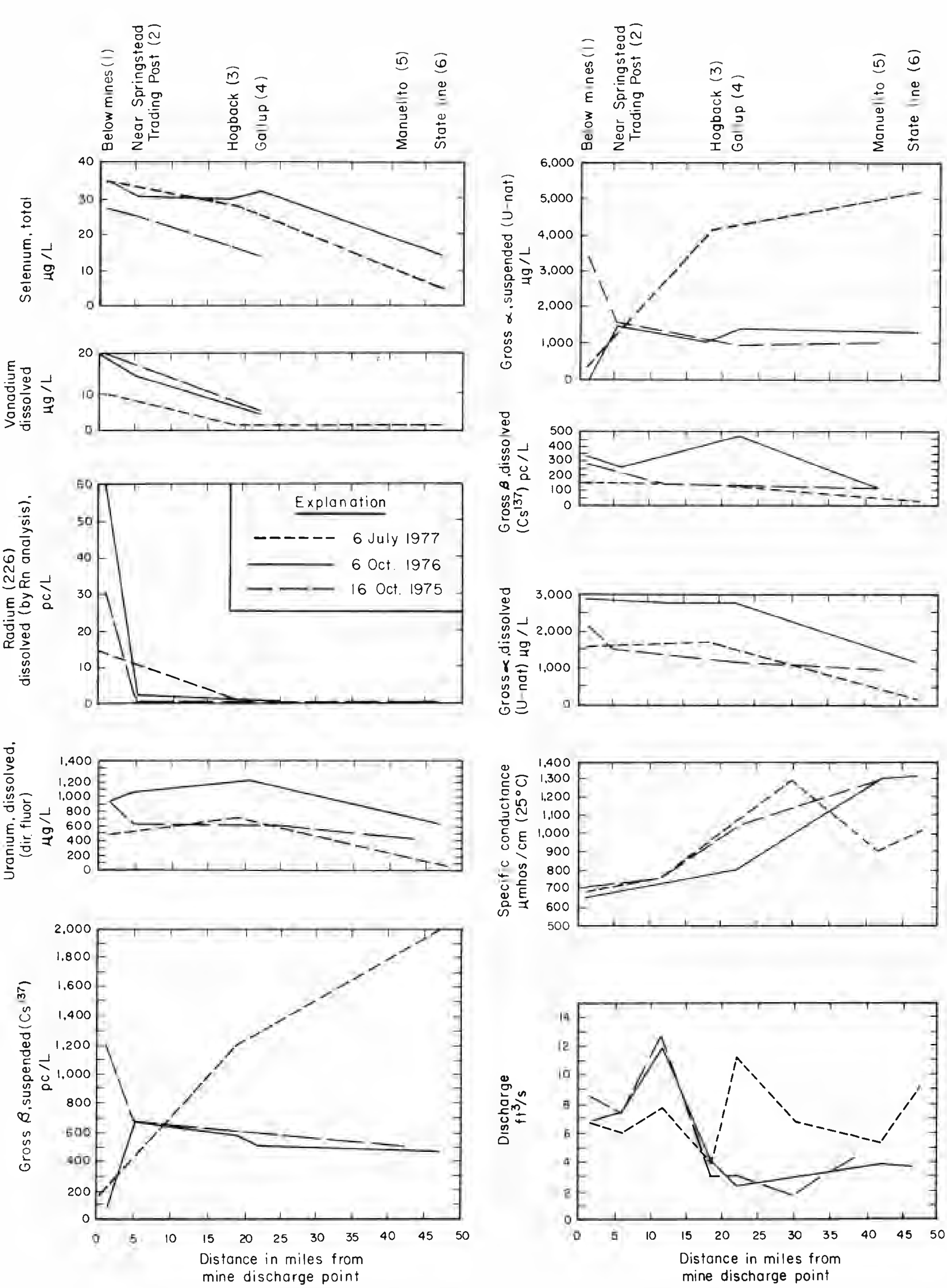


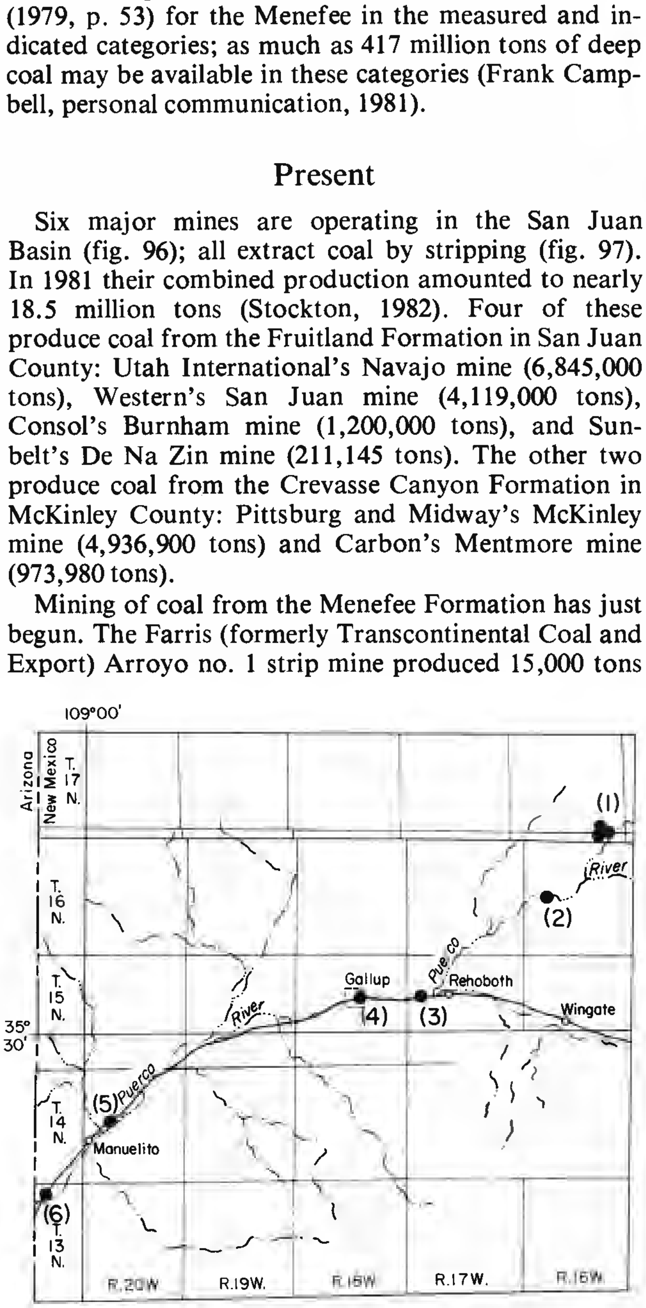
Figure 95—Discharges and concentrations of selected chemical constituents along Puerco River downstream from Church Rock uranium mines (see table 11, microfiche pocket, for detailed information).

maker and others, 1971). Tabet and Frost (1979, p. 52) reported more than 117 million tons of measured and indicated reserves for the Menefee Formation in the Torreon Wash area in the southeast part of the basin; as much as 383 million tons may be available in these categories (Frank Campbell, coal geologist, New Mexico Bureau of Mines and Mineral Resources, personal communication, 1981). Deeper coal accounts for even larger amounts. The Fruitland Formation contains 200 billion tons of coal (in beds >1.2 ft thick) to depths of 4,500 ft, and the Menefee Formation contains 12 billion tons to a depth of 6,000 ft (Shomaker and Whyte, 1977). In the Torreon Wash area, more than 200 million tons of deep coal were reported by Tabet and Frost (1979, p. 53) for the Menefee in the measured and indicated categories; as much as 417 million tons of deep coal may be available in these categories (Frank Campbell, personal communication, 1981).

Present

Six major mines are operating in the San Juan Basin (fig. 96); all extract coal by stripping (fig. 97). In 1981 their combined production amounted to nearly 18.5 million tons (Stockton, 1982). Four of these produce coal from the Fruitland Formation in San Juan County: Utah International's Navajo mine (6,845,000 tons), Western's San Juan mine (4,119,000 tons), Consol's Burnham mine (1,200,000 tons), and Sunbelt's De Na Zin mine (211,145 tons). The other two produce coal from the Crevasse Canyon Formation in McKinley County: Pittsburg and Midway's McKinley mine (4,936,900 tons) and Carbon's Mentmore mine (973,980 tons).

Mining of coal from the Menefee Formation has just begun. The Farris (formerly Transcontinental Coal and Export) Arroyo no. 1 strip mine produced 15,000 tons



Locations of sites sampled

(1) Below mines
(2) Near Springstead Trading Post
(3) Hogback
(4) Gallup
(5) Manuelito
(6) State line

LOCATION MAP FOR FIG. 95

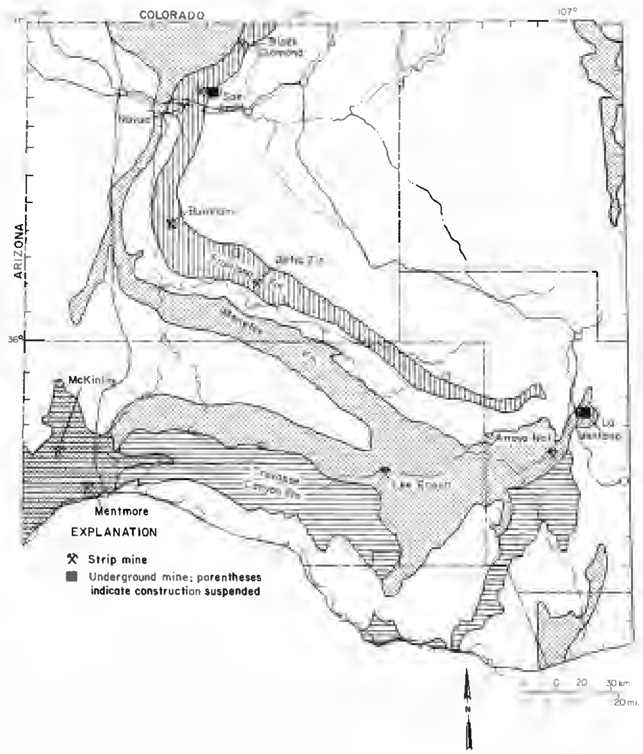


Figure 96—LOCATION OF COAL FIELDS AND ACTIVE MINES IN SAN JUAN BASIN (modified form Kottlowski and others, 1983).

in 1980. Santa Fe's Lee Ranch strip mine went into operation in June, 1982. Work on Ideal Basic's La Ventana underground mine has been suspended.

In strip mining, water is required mainly for irrigating reclaimed lands; more than 2,000 acre-ft/yr have been used at the Navajo mine (Beaumont and others, 1976). In addition, water is used for washing coal and controlling dust on mine roads. The major use of coal is mine-mouth electric-power generation; thus, boiler feed is another major water use. Because water is generally not encountered in stripping, and local, shallow ground water is high in dissolved solids, San Juan River water is utilized for these needs (fig. 98).

Strip mining can have an impact on both the quantity and quality of area water resources. The main impact on

Figure 97—TYPICAL COAL-STRIPPING OPERATION. View to north at San Juan mine, approximately 15 mi west of Farmington and 3 mi north of US-550.

Figure 98—VIEW TO WEST ALONG SOUTH BANK OF SAN JUAN RIVER TOWARD FOUR CORNERS POWERPLANT IN DISTANCE.

quantity is the vast amount of water required for reclamation in this arid setting. Such water is extracted from one area and source and introduced into another area and aquifer; however, the impact of such water transfer has not been specifically studied. Depending on the salinity of both the irrigation and local ground waters, this may have an impact on water quality as well. Mining brings aquifers closer to the surface, increasing the chances for pollution. Evaporation of stored water increases its salinity; leakage of impounded saline water can contaminate local surface and ground waters. Fly ash, returned to pits and added to soils in reclamation, also may be a salinity and trace-metal source (Cherkauer, 1980). Similarly, spoil piles are both potential salinity and sediment sources for surface runoff. The U.S. Geological Survey, in cooperation with the U.S. Bureau of Land Management, is collecting data on suspended-sediment loads and chemical quality of runoff from unreclaimed and reclaimed spoil piles of various ages at the San Juan and Navajo mines in the northwest part of the basin.

Future

Numerous new mines are planned and two mines just beginning operation will have greater production in the future. Ten new mines have been permitted but will probably not go into production until railroad spurs are constructed into the Star Lake area and along the west side of the basin. The Black Diamond mine, in northern San Juan County, extracts only humate now but plans call for stripping coal from the Fruitland in the future. Santa Fe's Lee Ranch strip mine will produce approximately 3 million tons of Menefee coal per yr when in full operation.

The major water problem of new mines will be one of supply. San Juan River water is fully appropriated, so future operations must either purchase existing water rights or look elsewhere. Three alternatives are recognized. One is ground water in aquifers lying beneath the coal (Shomaker and Stone, 1976). The Morrison Formation, for example, underlies the Fruitland coal belt at a depth of approximately 5,000 ft and contains water having a dissolved-solids content of 1,000–4,000 mg/L. The sandstones of the Mesaverde Group lie at shallower depths (less than 3,200 ft) and contain waters of comparable quality, but transmissivities are lower (50 ft^2/d or less). A second alternative is to transport ground water of suitable quality from the sandstone aquifers in the Tertiary deposits lying to the north and east of the Fruitland coal belt. These aquifers occur within 2,000 ft of the surface and contain water having dissolved-solids contents of 1,000 mg/L or less. Transmissivities of 100 ft^2/d are probable; Brimhall (1973) reported values in excess of 150 ft^2/d locally. The third alternative is use of excess uranium-mine water (Hiss, 1977) as allowed by statute 72-12-7 NMSA 1978.

Deep coal will no doubt be extracted only by underground and in-situ methods, such as gasification or liquefaction. The major water problems in these methods will be dewatering. This report should provide adequate geologic and hydrologic data for at least preliminary planning of such operations.

Petroleum

Petroleum occurs in both Paleozoic and Mesozoic strata of the San Juan Basin. Mississippian rocks produce gas and Pennsylvanian rocks produce oil at Tocito Dome in western San Juan County. The Entrada Sandstone (Jurassic) yields oil in an area covering the southeast corner of San Juan County, northwest McKinley County, and the adjacent part of Sandoval County. Both oil and gas are produced from the various Cretaceous sandstones in numerous pools throughout the basin.

Present

Crude-oil production (Pennsylvanian and Cretaceous) in northwest New Mexico for 1981 was 4,485,639 bbls (barrels), or about 6% of the state's total production. Gas production (Cretaceous) was about 559 mcf (million cubic feet), or about 50% of the state's production (Energy and Minerals Dept., 1982, tables 8 and 9, p. 20–21).

Many of the oil and gas wells in the San Juan Basin also produce water having a high dissolved-solids concentration. Most of this water is reinjected to help maintain reservoir pressures or as a means of disposal. The quantity of water produced varies with oil and gas production and is reported monthly by operators to the New Mexico Oil Conservation Commission, which in turn publishes these quantities in its Monthly Statistical Report. Based on data in the monthly summary for April 1978 (New Mexico Oil Conservation Commission), a production rate of about 8.2 ft^3/s is obtained; of this, 8.1 ft^3/s was produced from oil wells and 0.1 ft^3/s was produced from gas wells. About 6 ft^3/s was reinjected, and the rest presumably evaporated from small disposal ponds. The principal water-producing units at that time were the Entrada Sandstone (about 3.5 ft^3/s), the Gallup Sandstone (Hospah sand of informal usage) at Hospah (about 2.0 ft^3/s), and the Gallup Sandstone at the Horseshoe Canyon field northeast of Shiprock (about 1.3 ft^3/s). The rest was produced from the Gallup Sandstone in other fields, the undivided Mesaverde Group, the Dakota Sandstone, and Pennsylvanian strata.

Future

The number of well completions in the San Juan Basin in 1981 increased over those in 1980 by 33.1%, but much of this activity was infill drilling to more fully develop known gas fields (fig. 99). Exploration will undoubtedly continue, but significant increases in oil and gas production are not expected. Petroleum production from Paleozoic units in the central and northern parts of the basin is unlikely, based on the thermal history of the region (Reiter, in preparation).

Any expansion of natural-gas development in the San Juan Basin will cause only minor increases in water production. Although additional oil wells, particularly in the Entrada Sandstone, will probably cause an increased rate of water production, this will have little impact on regional water resources if the water is reinjected into the producing formations. Removal of oil and gas will cause head declines in producing formations.

Figure 99—Typical drilling rig in operation in San Juan Basin gas field (southeast quarter of Aztec 15′ quadrangle).

Water for other uses

In evaluating the impact of energy development on the water resources of the San Juan Basin, other water-resource needs also must be considered. Sizable herds of livestock are grazed in the San Juan Basin, but irrigation and municipal supply are the other main water uses.

Navajo Indian Irrigation Project

Water for the Navajo Indian Irrigation Project (NIIP) is diverted from the San Juan River at Navajo Dam (fig. 9) and is transported via Cutter Dam and canals to the project area (fig. 100). Between 1976, when irrigation began, and the spring of 1979, 21,677 acres of irrigated land were placed in production. Eventually a total of 100,630 acres will be irrigated as part of NIIP (fig. 101).

The project will require water diversions of 3.14 acre-ft/acre, of which 1.88 acre-ft will be consumed by evapotranspiration and the remaining 1.26 acre-ft will flow into surface channels or will infiltrate and contribute to subsurface water (U.S. Bureau of Reclamation, Regional Director, personal communication, 1975). The infiltrated water must eventually discharge to streams; however, because of the great depth to the water table (more than 200 ft in most places), the large storage capacity in the unsaturated zone, and the relatively low permeabilities, the effects of this recharge may not be apparent for many years.

Increased ground-water-discharge rates will undoubtedly affect surface-water quality because of the high dissolved-solids concentrations (generally greater than 4,000 mg/L) of water in rock units adjacent to the river. Arroyos draining irrigated lands, such as Gallegos Canyon and tributaries of the Chaco River, may eventually flow perennially in their lower reaches because of increased ground-water-inflow rates.

Other irrigation

Prior to the Navajo Indian Irrigation Project, extensive irrigation was practiced only along the valleys of major surface-water courses (fig. 102). These included the San Juan, Animas, and La Plata Rivers in the San Juan River drainage basin and the Rio San Jose in the Rio Grande drainage basin. In 1975, 62,180 acres of cropland were irrigated or temporarily fallow in the San Juan River drainage basin and 11,200 acres were irrigated or temporarily fallow in the Rio San Jose drainage basin (Sorensen, 1977, table 9).

Irrigation in the San Juan drainage basin in 1975 depleted 97,650 acre-ft of water, all from surface-water diversion. Irrigation in the Rio San Jose drainage basin in 1975 depleted 14,510 acre-ft of water that was derived from both surface- and ground-water sources (Sorensen, 1977, table 9). Here, some of the irrigation water was pumped from the Glorieta Sandstone–San Andres Limestone aquifer and the shallower alluvium and basalt aquifers.

Water diverted for irrigation in the San Juan River drainage basin in 1975 totaled 222,300 acre-ft (Sorensen, 1977, table 1). Of this quantity, almost 125,000 acre-ft returned to the river courses either by direct runoff or by flow through valley-fill deposits. The specific conductance of water returning to the rivers in the subsurface increases from less than 500 μmhos, when applied, to 2,000 μmhos or more by the time the water reaches the river. The increase in specific conductance is caused by the concentration of salts by evapotranspiration, the dissolution of soluble minerals in the soils, and the mixing with water from bedrock sources.

Irrigation in the Grants–Bluewater area contributes little if any water to the Rio San Jose. Return flow in this area recharges shallow aquifers and is reused for irrigation or other purposes. Possible adverse effects of irrigation on water quality in this area have not been studied. Water-level declines caused by pumping, however, may reduce flow in the Rio San Jose downstream from irrigated areas (Gordon, 1961, p. 77).

The Animas–La Plata project may eventually add 47,000 acres of irrigated land in Colorado and New Mexico north of the San Juan River. Diversions will be from the Animas and La Plata Rivers. No other major irrigation projects in the project area are anticipated. Irrigation acreage along the major valleys will probably decrease as water rights are transferred to other uses, such as energy-resources development.

Municipal supply

Most municipalities in the San Juan Basin have experienced growth as a result of energy development in the region. Medium-level projections of growth for some towns suggest that populations may roughly double by the year 2000 and triple by the year 2020 (table 12). In many cases, this growth will require additional ground-water supplies. Because such ground-water production may compete with that associated with energy development, it is useful to examine the present and potential future water-resource situations of the major communities in the basin. The official declarations by the State Engineer of the San Juan Underground Water Basin (July 29, 1976) and the Gallup Underground Water Basin (March 5, 1980) ensured the protection of existing water rights from possible impairment by new withdrawals.

In the following discussion, towns on Indian reservations are omitted because of the difficulty in obtaining information for them. These towns are, however, included in the overview of water supplies in northwest New Mexico prepared by Dinwiddie and others (1966) and the County Profile series by the New Mexico Interstate Stream Commission and New Mexico State Engineer's Office (1974, 1975).

Figure 100—Typical conveyance canal, pumping station, and water tower used to distribute water in Navajo Indian Irrigation Project. Photo taken in block 1, west of NM-44 and south of Bloomfield.

Figure 102—View to west across valley of Animas River, showing irrigated croplands near Cedar Hill.

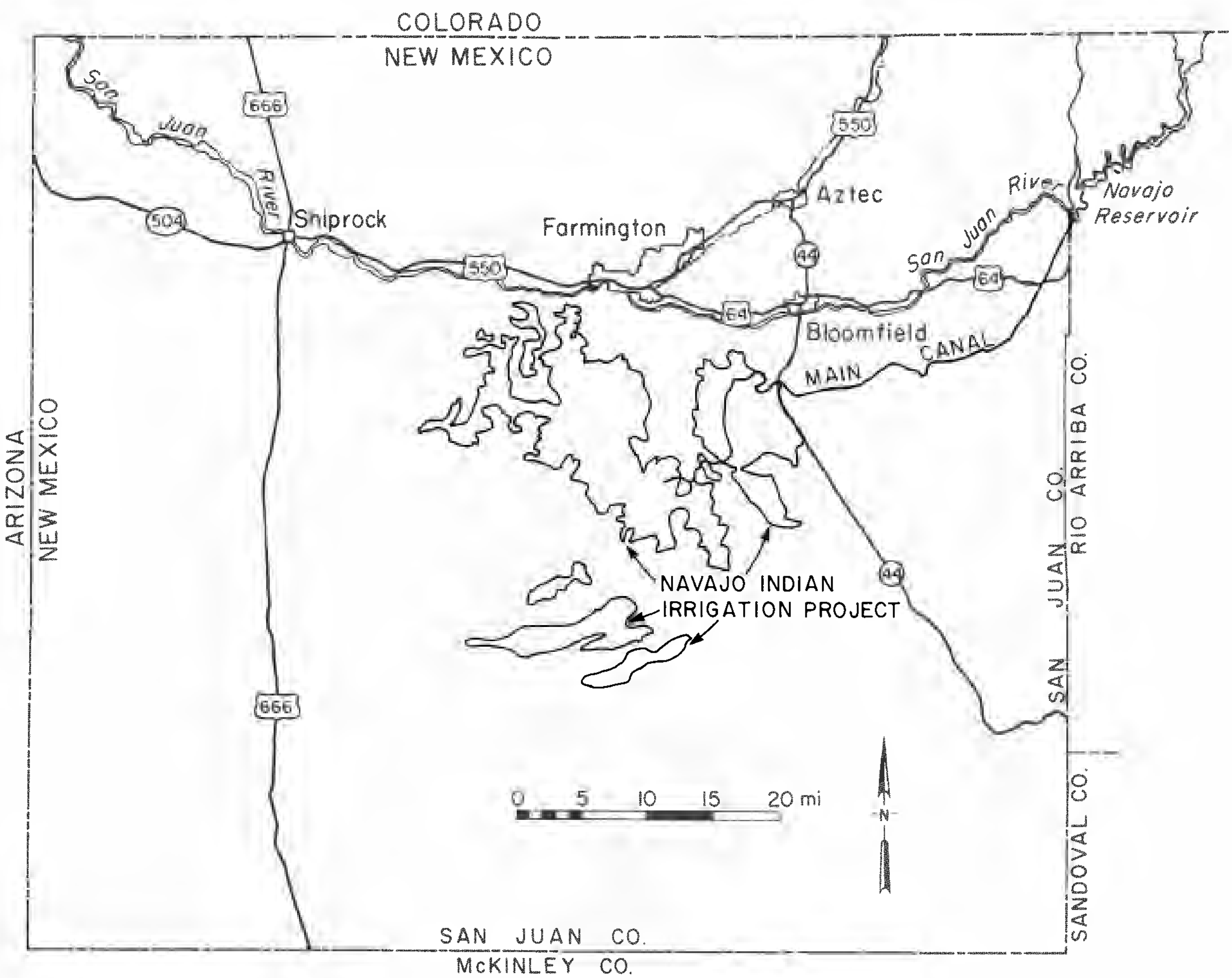


Figure 101—Location and extent of Navajo Indian Irrigation Project.

TABLE 12—PROJECTED GROWTH FOR YEARS 2000 AND 2020 FOR TWO MAJOR TOWNS IN THE SAN JUAN BASIN (Earl Sorensen, State Engineer's Office, personal communication, 1980); Low projections from U.S. Bureau of Economic Analysis and Bureau of Business Research, University of New Mexico, 1972; Medium projections from Office of Business Economics, U.S. Dept. of Commerce, 1968; High projections from Bureau of Business Research, University of New Mexico, 1968.

Town	1970 Census	Year 2000 projections			Year 2020 projections		
		Low	Medium	High	Low	Medium	High
Farmington	21,979	35,000	35,000	60,000	46,000	60,000	124,000
Gallup	14,956	28,000	31,700	54,800	35,000	52,300	100,000

Aztec

Aztec, the county seat of San Juan County, has a population of nearly 6,000. The source of municipal water is the Animas River. The capacity and consumption associated with this system are summarized in table 13. Numerous private wells tap the alluvium of the Animas River valley in areas bordering the town.

Aztec has always been a center of activity for oil and gas development in the San Juan Basin. Although the current wave of in-fill drilling has been healthy for the town's economy, major growth as a result of energy development is not anticipated.

Brown and Stone (1979) suggested several possible sources for additional water should it be needed. Collector wells or a field of shallow wells constructed in the valley fill could supplement the surface-water supply system during times of peak consumption or low river discharge. It may also be advisable to store river water underground for use in low-flow periods. Such storage could result in degradation of quality of the stored water, but this alternative deserves further study. The shallowest bedrock aquifer from which potable water might be obtained is the Nacimiento Formation. Exploratory drilling would be necessary to locate sandstone bodies within this formation and to evaluate their aquifer potential. Deeper wells might produce from the Ojo Alamo Sandstone. Water quality may not permit use without treatment (figs. 22 and 30).

Bloomfield

The population of Bloomfield is 4,881 according to the 1980 census. This community derives its water from the San Juan River and one well that taps the valley fill. The characteristics of the Bloomfield public water system are summarized in table 13. Like Aztec, Bloomfield also has been a center for oil and gas production in the basin, but will probably not grow significantly in response to other energy development activities in the region.

Should additional water supplies be needed, the alternatives listed for Aztec should also apply to Bloomfield. If suitable aquifers cannot be located in the alluvium or Nacimiento Formation, wells might be extended to the underlying Ojo Alamo Sandstone, which dips easterly below the surface a short distance west of town.

Cuba

The population of Cuba is 609 according to the 1980 census. The village obtains its water from a well on Mesa de Cuba, northwest of town. The system is summarized in table 13. The source of the water is the Cuba Mesa Member of the San Jose Formation. Although this water has a total dissolved-solids content of only 566 mg/L, it is high in sulfate, calcium, iron, manganese, and magnesium, making it unpalatable (Anderholm, 1979, p. 74). Residents haul water for culinary purposes from Horseshoe Spring, which issues from the lower Cutler/Abo, southeast of town.

When the coal in the Torreon Wash and Star Lake areas to the southwest is mined, Cuba will no doubt experience a boom in population and a corresponding need for additional or more suitable water. According to Anderholm (1979), existing wells may produce significant quantities for some time, but the quality will have

TABLE 13—CHARACTERISTICS OF PUBLIC WATER SYSTEMS OF MAJOR MUNICIPALITIES IN THE SAN JUAN BASIN (compiled from county profiles prepared by the New Mexico Interstate Stream Commission and State Engineer's Office, 1975); capacity of Aztec municipal reservoir is as of 1975 (Brown and Stone, 1979).

Town	County	Population	Water source	System capacity (gpd)	Average consumption (gpd)	Storage capacity (gal)
Aztec	San Juan	5,512	Animas River	2,880,000	1,500,000	7,000,000
Bloomfield	San Juan	4,881	1 well San Juan River	300,000	190,000	150,000
Cuba	Sandoval	609	1 well	50,000	30,000	305,000
Farmington	San Juan	31,222	Animas River	24,200,000	8,000,000	10,500,000
Gallup	McKinley	18,161	9 wells	3,750,000	1,700,000	13,600,000
Grants–Milan	Valencia (now Cibola)	15,186	3 wells	4,600,000	1,000,000	4,500,000

to be improved. Tests to treat the present water supply by reverse osmosis and electrodialysis have been encouraging (Folster and Wilson, 1979). If such treatment proves uneconomical, wells could be drilled to the Point Lookout or Dakota Sandstones near the mountain front (Anderholm, 1979). Mountain runoff also might be harvested to some advantage.

Farmington

According to the 1980 census, the population of Farmington is 31,222. The major source of municipal water is the Animas River, which joins the San Juan River here. Private wells tap the alluvium outside the city limits. Farmington has been through previous boom cycles associated with oil and gas development activity and, as shown in table 12, could grow substantially again in the next 20–40 yrs, mainly in response to increased coal production.

Additional demands for water may be met by several ground-water alternatives: shallow wells drilled in the valley fill, deeper wells in the Nacimiento Formation, or still deeper wells to the Ojo Alamo Sandstone. Wells in the bedrock aquifers should be located some distance east of the town to take advantage of greater saturated thicknesses. Water quality may not permit use of these waters without treatment.

Gallup

The 1980 census showed that Gallup had a population of 18,161. Although several wells open to both the Gallup Sandstone and Morrison Formation are in the municipal supply system (William Petranovich, City Engineer, Gallup, personal communication, 1981), nine wells tapping the Gallup Sandstone provide the main source of water for this community (table 13). Private wells in alluvium and various Cretaceous deposits occur in the area surrounding the town. As shown in fig. 103, the demand for water has more or less steadily increased over the past 40 yrs. Gallup lies adjacent to both coal- and uranium-mining areas. The projected growth shown in table 12 is mainly associated with anticipated expansion of uranium production.

Additional water supplies may be obtained from new wells to the Gallup Sandstone or shallower Cretaceous deposits, but deeper aquifers may have to be explored eventually. The potential of the Westwater Canyon Sandstone Member of the Morrison Formation in the Church Rock area as a source of water for Gallup was evaluated by Hearne (1977). The use of treated uranium-mine effluent also has been suggested (Hiss, 1977). The piping of San Juan River water to Gallup has also been addressed; this would be done in conjunction with the delivery of Indian water from the Navajo Dam

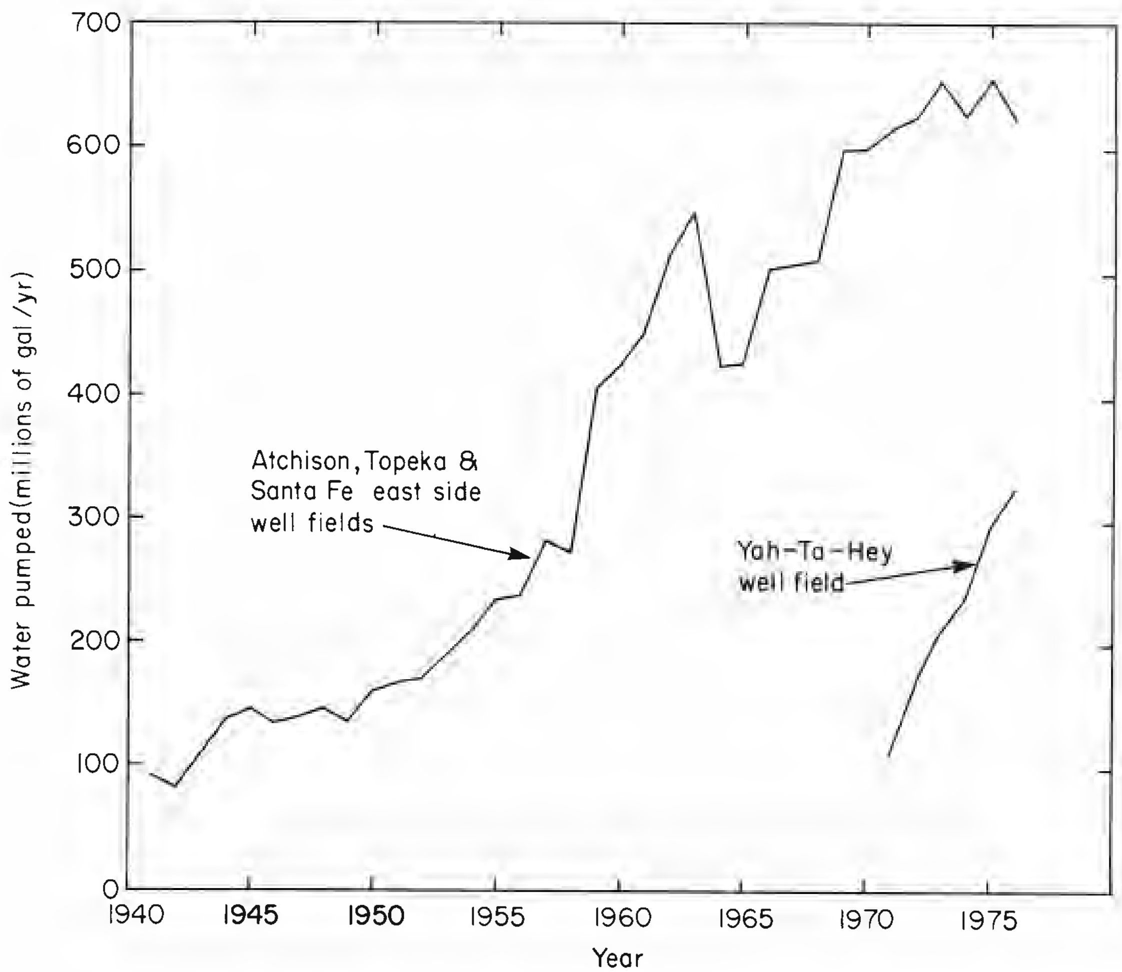


Figure 103—HISTORY OF PUMPAGE FROM CITY OF GALLUP WELL FIELD (data from West, 1961, p. 2, and Gallup City Water Department, personal communication, 1978).

to various villages on the Navajo reservation (Jerry Butler, Navajo Tribal Utility Authority, personal communication, 1978).

Grants–Milan

The population of Grants is 11,439 and that of Milan is 3,747, according to the 1980 census. The main source of municipal water for Grants is a well to the Glorieta–San Andres; Milan obtains its water from three wells constructed in valley fill (Gordon, 1961). The characteristics of the system serving these communities are given in table 13.

Grants and Milan, at the heart of the uranium-mining area, are expected to grow at a rate similar to that projected for Gallup (table 12). The major source of additional ground water is the Glorieta–San Andres aquifer. Like Gallup, Grants and Milan may also be able to utilize mine-dewatering product.

Summary and conclusions

The limited surface-water resources of the San Juan Basin are fully appropriated, and any new water supplies must be obtained from either negotiated surface-water resources or from ground-water resources. In northwest New Mexico, ground water is obtained from Quaternary valley-fill deposits and from sandstones of Tertiary, Cretaceous, Jurassic, and Triassic age (table 14, inside front cover). The Glorieta Sandstone–San Andres Limestone (Permian) combine to form a significant aquifer along the southern margin of the basin. Older strata are too deep or too poorly known to be used in any but basin-margin areas.

Although the term "aquifer" may not be appropriate in areas where ground water flows across stratigraphic and structural boundaries, the term is relevant in the San Juan Basin because the major component of ground-water flow is through sandstones of relatively higher hydraulic conductivity than adjacent rock units. Recharge of these aquifers generally occurs in topographically high outcrop areas around the basin margin and in the broad upland in the northeast part of the basin. Discharge occurs in topographically low areas, most notably in the San Juan River valley in the northwest and the Rio Puerco valley in the southeast. Minor discharge is associated with the deep tributary canyons of the San Juan River and the Puerco River in the southwest. Steady-state analysis gives inflow and outflow rates of less than 20 ft^3/s for the Tertiary aquifers and approximately 40 ft^3/s for the Cretaceous and Jurassic aquifers.

The aquifers in the San Juan Basin are artesian because of the regional geologic structure and confinement by overlying mudstones of relatively lower hydraulic conductivity. Confinement is not absolute and interaquifer movement (leakage) of ground water does occur. Rates of such leakage, however, are very low except in areas of intense fracturing. Some 2 million acre-ft of fresh to slightly saline water could be released from storage in the confined aquifers with a water-level decline of 500 ft.

Sandstone aquifers in the San Juan Basin that have transmissivities between 100 and 200 ft^2/d throughout large areas include the Ojo Alamo Sandstone, Gallup Sandstone, Morrison Formation, and Entrada Sandstone. Other aquifers that are used for low-yield (10 gpm or less) sources of domestic and stock water, but which may have relatively high transmissivities in areas of small extent, include the valley-fill alluvium, San Jose Formation, Nacimiento Formation, Cliff House Sandstone, Menefee Formation, Point Lookout Sandstone, Crevasse Canyon Formation, and Dakota Sandstone.

The specific conductance of water in aquifers varies widely from less than 500 μmhos to more than 30,000 μmhos. Extensive areas of fresh water (less than 1,500 μmhos) occur in the San Jose Formation, Ojo Alamo Sandstone, Gallup Sandstone, and Morrison Formation; the potential exists for additional development of these resources. Limited quantities of fresh water can be found in or near outcrops of the other sandstone aquifers and in valley-fill alluvium. Pre-Jurassic rocks generally yield only small amounts of water to wells and contain saline water. Saline springs along fault zones marking the boundary between the San Juan Basin and Rio Grande valley may be evidence of ground-water discharge from older rocks in the basin.

The occurrence, movement, and quality of ground water in the San Juan Basin are subject to considerable geologic control. Occurrence is controlled mainly by the distribution of sandstone aquifers. Their distributions are in turn a result of their origins; the Tertiary sandstones are alluvial and fluvial in origin, the Cretaceous sandstones are the result of marine and nonmarine coastal deposition, and the Jurassic sandstones are partly eolian and partly alluvial in origin.

Ground-water movement consists of recharge, flow, and discharge. Recharge of all aquifers in the region is controlled by the geomorphic setting. Because geologic structure and stratigraphy strongly influence the geomorphology, and because structure and stratigraphy vary across the basin, the specific nature of the controls also varies. Flow direction and location of discharge areas are largely factors of topography, but are locally controlled by the geometry and orientation of zones of higher conductivity within the sandstone aquifers. This is most apparent in the case of the coastal marine Cretaceous sandstones. Flow direction in the Gallup Sandstone, for example, generally parallels 1) the basinward pinch-out of the unit, 2) the long axis of the sandstone bodies within the unit, and 3) the ancient shoreline trend.

Residence time is a major control of ground-water quality. In addition to mere distance from recharge area, residence time also is influenced by geologically controlled hydrologic properties of the aquifer. In the case of the Gallup Sandstone, the distribution of dissolved-solids concentrations generally coincides with the distribution of transmissivity, fresher water being associated with zones of higher transmissivity. Solids are readily dissolved along sandstone/shale contacts. The uptake of dissolved solids is thus enhanced by intertonguing of the sandstone and shale units. Because the stratigraphic column is characterized by complex intertonguing of such units, especially in the Tertiary and Cretaceous sections, this intertonguing is an important geologic control of water quality.

Dewatering of uranium mines has lowered water levels in the Morrison Formation. Pumpage of water for uranium exploration drilling has caused water-level declines in the Gallup Sandstone. More widespread and greater declines can be expected as deeper mines are constructed.

Water quality is altered in the vicinity of mines because oxidation at the mine face makes some radionuclides soluble, and the collapse of abandoned workings allows inflow of poorer quality water from overlying rocks. The persistence of toxic substances and radiochemicals after mining ceases is not known, but studies suggest that these materials may not migrate much beyond the mine cavity because of water-rock interactions and other geochemical processes there. Contamination of shallow ground water by leakage from tailings ponds has been documented in the Grants area; such contamination may be an increasing threat as development continues.

The major water-resource problem associated with coal development in the San Juan Basin is one of supply. Large quantities of water are required for boiler feed in the associated powerplants and for irrigation in mine reclamation. However, little water is encountered in mining, surface water is fully appropriated, and shallow aquifers are not likely to produce water of sufficient quantity and quality. In some areas, it may be as feasible to transport excess uranium-mine water or ground water from well fields in the Tertiary aquifers as it is to drill to the deeper aquifers in the coal-mining areas.

Significant quantities of saline water are produced with oil and gas, particularly from oil wells in the Gallup Sandstone and Entrada Sandstone. This production is not likely to affect ground-water resources as long as the current practice of reinjecting the water is maintained.

Return flow and related increases in ground-water discharge from the Navajo Indian Irrigation Project area eventually may have a significant impact on water quality in the San Juan River. However, this impact may be difficult to distinguish from the impacts of energy-resource and municipal development. Historical applications of irrigation water in valleys of the San Juan, Animas, La Plata, and San Jose Rivers have contributed to the dissolved-solids concentrations in these rivers. The amount of irrigated acreage along the rivers may decrease as water rights are transferred to other uses, such as energy-resource development.

Most municipalities in the San Juan Basin have experienced growth as a result of energy-resource development and are expected to continue to do so. Present and future water supplies for these towns may, however, be impacted by this development. Uranium-mine dewatering lowers water levels in the Westwater Canyon Sandstone Member of the Morrison Formation, and municipalities depending on this aquifer for their water supply will be affected. Alternative supplies may be obtained from deeper aquifers or excess mine water. Towns along the San Juan River will have to look toward bedrock ground-water sources as they grow beyond the capacity of present supplies.

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Glossary

Hydrogeology has a language all its own. The following list includes terms most likely to be unfamiliar to the nonspecialist as well as terms having more than one meaning. Definitions of most geologic terms are modified from those given in the American Geological Institute glossary (Gary and others, 1974). Definitions of hydrologic terms are modified from Lohman and others (1972) or Freeze and Cherry (1979). Other sources are identified where used.

ALLUVIAL—deposited by running water on broad slopes or aprons, or in valleys adjacent to uplands.

ALLUVIUM—alluvial deposit; usually unconsolidated mixture of gravel, sand, silt, and clay.

AQUIFER—consolidated or unconsolidated deposit having sufficient saturated permeable material to yield significant quantities of water to wells or springs; a material which both stores and transmits water.

AQUIFER TEST (also WELL TEST)—test of a well to determine the hydrologic properties of the aquifer penetrated; involves pumping to remove (or injection to add) a known volume of water; accompanied (drawdown or pumping test) or followed (recovery test) by monitoring the water level at selected time intervals to determine the rate of the aquifer's response to the induced change.

ARKOSE—feldspar-rich sandstone; more specifically, a sandstone composed of <75 percent quartz, and having a feldspar-to-rock-fragment ratio of >3:1 (Folk, 1974, p. 129).

ARTESIAN (also CONFINED)—term applied to ground water that rises above the level at which it is encountered in constructing a well; also applied to wells in which this rise occurs and to aquifers that produce it. The rise is not necessarily to the ground surface.

BRINE—see TOTAL DISSOLVED SOLIDS

CALCITE—mineral consisting of calcium carbonate ($CaCO_3$); main mineral in limestone.

CARBONACEOUS—said of a rock containing carbon or carbonized organic (mainly vegetal) material.

CLASTIC ROCK—rock composed of fragments of preexisting rocks.

CLAYSTONE—a clastic sedimentary rock composed mainly of clay, but lacking fissility.

COAL MEASURES—succession of sedimentary rocks associated with coal; in the San Juan Basin includes mainly coal, mudstone (often carbonaceous), and sandstone.

COLLUVIAL—deposited on or at the base of slopes by gravity or unconcentrated slope runoff.

COLLUVIUM—colluvial deposit; usually unconsolidated rock fragments and soil.

CONFINED—see ARTESIAN

CONFINING BED—material of relatively low hydraulic conductivity overlying an aquifer and responsible for the confinement of water within it.

CONFORMABLY OVERLIES—overlies without a break in the rock record at the contact.

CONTACT—boundary between vertically adjacent stratigraphic units.

DARCY'S LAW—flow through porous media is proportional to the hydraulic head loss (h_1-h_2) and inversely proportional to the length of the flow path (L). Expressed mathematically as: $Q = KA(h_1-h_2)/L$, where Q is discharge in volume per unit time, K is hydraulic conductivity, A is cross-sectional area of discharge site; $(h_1-h_2)/L$ is the hydraulic gradient.

DISCHARGE—loss of water from, or movement of water out of, an aquifer; the process by which ground water is depleted.

DISCONFORMABLY OVERLIES—overlies with obvious erosional relief along the contact.

DRAWDOWN—lowering of the water table or potentiometric surface for an aquifer in response to pumpage or artesian flow from wells.

DRAWDOWN TEST—see AQUIFER TEST

ELEVATION HEAD—hydrostatic pressure due to the elevation of the point in question above a datum.

EOLIAN—deposited by the action of the wind.

EPHEMERAL—said of a stream that flows only in direct response to precipitation in the vicinity and whose channel is at all times above the water table; also the flow of such a stream.

EVAPOTRANSPIRATION—combined loss to the atmosphere of ground water from an area through processes of evaporation from soil and transpiration by plants.

FELDSPAR—common mineral composed mainly of potassium, sodium, or calcium aluminum silicate.

FISSILITY—tendency of a rock to split into thin platy layers.

FLUVIAL—deposited by running water in discrete channels as associated with rivers and streams.

FORMATION—fundamental unit used in the local stratigraphic classification of rocks, as on geologic maps.

FRESH—see TOTAL DISSOLVED SOLIDS

GEOLOGY—study or science of the natural processes and products of the earth.

GROUND WATER—subsurface water, especially water in saturated materials that exist below the water table.

GROUP—combination of two or more formations.

GYPSUM—common mineral composed of hydrous calcium sulfate ($CaSO_4$); may occur in layers with limestone, shale, or other evaporites.

HYDRAULIC CONDUCTIVITY—volume of water (at existing viscosity) that will move in unit time, under a unit hydraulic gradient, through a unit area of saturated material. Sometimes reported as gpd/sq ft; if gals are converted to cubic ft (ft^3), unit becomes ft/day, as a result of algebraic cancellation.

HYDRAULIC GRADIENT—change in static head per unit of distance in a given direction; see DARCY'S LAW.

HYDRAULIC HEAD (also TOTAL or STATIC HEAD)—height (above a datum) of a column of water that can be supported by the static fluid pressure at a given point; the sum of the elevation head and the pressure head, if velocity head is negligible.

HYDROGEOLOGY—study or science of the geologic controls of hydrologic phenomena.

HYDROLOGY—study or science of the occurrence and behavior of water in nature.

IGNEOUS—formed by cooling from molten material.

INFILL DRILLING—drilling, at allowed spacing, between existing wells in established oil or gas fields to optimize yield.

INTERMITTENT—said of a stream along which perennial flow is restricted to certain reaches; also the flow of such a stream.

LIMESTONE—sedimentary rock consisting of >50 percent calcite.

LITHIC ARKOSE—sandstone composed of <75 percent quartz, and having a feldspar-to-rock-fragment ratio between 1:1 and 3:1 (Folk, 1974, p. 129).

LITHOLOGY—physical character of a rock expressed in terms of texture, mineralogy, color, and structure.

MEMBER—subdivision of a formation.
METAMORPHIC—formed by metamorphism, that is, alteration of preexisting rock through changes in temperature, pressure, and chemical conditions.
MINERAL—naturally occurring, inorganic substance, with a characteristic set of physical properties, and a fixed chemical composition or fixed range of composition.
MUDSTONE—used herein as a general term for the entire family of fine-grained clastic rocks regardless of fissility (siltstone, shale, claystone, and various mixtures thereof).
PERENNIAL—said of a stream that flows year round; also the flow of such a stream.
PERMEABILITY (also INTRINSIC PERMEABILITY, SPECIFIC PERMEABILITY)—measure of the relative ease with which a porous medium transmits a liquid; as used herein, a property of the medium alone and independent of liquid properties or forces causing movement.
PLAYA—flat-floored, unvegetated, periodically flooded area in a desert region.
POPCORN WEATHERING—tendency of swelling clays to form a weathered surface whose texture resembles that of popcorn.
POROSITY—percent of total volume of a rock, soil, or unconsolidated sediment taken up by pores; equal to the sum of specific retention and specific yield.
POTENTIOMETRIC SURFACE—surface that represents the static head for a given aquifer.
PRESSURE HEAD—hydrostatic pressure expressed as the height of a column of water the pressure can support relative to a datum.
PROGRADATION—seaward build-up of a shoreline as a result of sedimentation along the coast.
PUMPING TEST—see AQUIFER TEST
QUARTZ—common mineral composed of crystalline silica (silicon dioxide, SiO_2).
RECHARGE—addition of water to, or movement of water into, an aquifer; the process by which ground water is replenished.
RECOVERY TEST—see AQUIFER TEST
REGRESSION—seaward migration of a shoreline and associated environments as a result of progradation, sea-floor subsidence, land uplift, or worldwide sea-level drop.
ROCK—naturally occurring aggregate of minerals.
SALINE—see TOTAL DISSOLVED SOLIDS
SANDSTONE—clastic sedimentary rock composed mainly of sand-sized particles.
SEDIMENTARY—formed by deposition of sediment.
SHALE—clastic sedimentary rock composed mainly of clay and displaying fissility.
SILTSTONE—clastic sedimentary rock composed mainly of silt-sized particles.
SLIGHTLY SALINE—see TOTAL DISSOLVED SOLIDS
SPECIFIC CAPACITY—relationship of discharge of a well and the drawdown of the water level in it. Measured as gpd/ft of drawdown; if gals are converted to ft^3, unit becomes ft^2/d.
SPECIFIC CONDUCTANCE—electrical measure of salinity; the reciprocal of resistance. Theoretically measured as μmhos/cm, but instruments generally give readings simply as μmhos (micromhos); the mho is ohm (the resistance unit) spelled backward. Specific conductance times 0.7 gives general approximation of the total dissolved solids in mg/L.
SPECIFIC RETENTION—volume of water a porous medium will retain after drainage by gravity flow; equal to porosity minus specific yield.
SPECIFIC STORAGE—volume of water released from or taken into storage per unit volume of porous medium, per unit change in head.
SPECIFIC YIELD—volume of water that will drain from a porous medium under the influence of gravity; equal to porosity minus specific retention.
STATIC HEAD—see HYDRAULIC HEAD
STORAGE COEFFICIENT—volume of water released from or taken into storage per unit surface area of porous medium, per unit change in hydraulic head.
SUBARKOSE—sandstone composed of >75 percent quartz, and having a feldspar-to-rock-fragment ratio of greater than 1:1 (Folk, 1974, p. 129).
TOTAL DISSOLVED SOLIDS—physical measure of salinity; amount (mg/L) of residue obtained by oven drying a water sample. Water is often classified by this parameter:

<1,000 mg/L	=	fresh
1,000–3,000 mg/L	=	slightly saline
3,000–10,000 mg/L	=	saline
10,000–35,000 mg/L	=	very saline
>35,000 mg/L	=	brine

TOTAL HEAD—see HYDRAULIC HEAD
TRANSGRESSION—landward migration of a shoreline and associated shorezone environments as a result of sea-floor uplift, land subsidence, or worldwide sea-level rise.
TRANSMISSIVITY—rate at which water (at existing viscosity) is transmitted through a cross section of material having the dimensions unit width and total thickness as height, under a unit hydraulic gradient; hydraulic conductivity times the thickness of material. Sometimes reported as gpd/ft of thickness; if gals are converted to ft^3, unit becomes ft^2/d through algebraic cancellation.
UNCONFINED—term applied to ground water in a water-table aquifer or one not overlain by a confining bed; also applied to such an aquifer.
UNCONFORMABLE—said of a contact between stratigraphic units across which the rock record is incomplete or which marks a gap in the rock record.
VELOCITY HEAD—energy of flow expressed as vertical distance through which a fluid would fall in order to attain the given velocity.
VERY SALINE—see TOTAL DISSOLVED SOLIDS
VISCOSITY—property of a fluid that determines its ability to resist flow; dependent on temperature and density.
WATER TABLE—that surface in an unconfined aquifer at which water stands in wells; roughly corresponds to the top of the saturated zone. Specifically, the surface formed by points at which water pressure equals atmospheric pressure.
WELL TEST—see AQUIFER TEST

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