HYDROLOGY AND WATER-QUALITY MONITORING CONSIDERATIONS, JACKPILE URANIUM MINE, NORTHWESTERN NEW MEXICO

By Harold H. Zehner

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CONVERSION FACTORS

In this report, measurements are given in inch-pound units only. The following table contains factors for converting to metric units.

Multiply units	By	To obtain units
acre-foot	1233	cubic meter
acre-foot per year	0.001233	cubic hectometer per year
cubic foot per second-day	2447	cubic meter
acre-foot per year per square mile	476	cubic meter per year per square kilometer
inch	2.540	centimeter
inch per year	25.40	millimeter per year
foot	0.3048	meter
square foot	0.09290	square meter
mile	1.609	kilometer
square mile	2.590	square kilometer
foot per day	0.3048	meter per day
foot squared per day	0.0929	meter squared per day
cubic foot	0.02832	cubic meter
cubic foot per second	0.02832	cubic meter per second
gallon	3.785	liter
gallon per minute	0.06309	liter per second
pound	0.4536	kilogram
acre	4047	square meter
ton (short)	0.9072	megagram or metric ton
foot per mile	0.1894	meter per kilometer

Temperature in degrees Fahrenheit (°F) is converted to temperature in degrees Celsius (°C) by $°C = 5/9\,(°F-32)$

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ABSTRACT

The Jackpile uranium mine, which is on the Pueblo of Laguna in northwestern New Mexico, was operated from 1953 to 1980. The abandoned mine consists of underground workings, and the Jackpile, North Paguate, and South Paguate pits, which are 200 to 300 feet deep. The mine and facilities have affected 3,141 acres of land, and about 2,656 acres were yet to be reclaimed in late 1980. The intended use of the restored land is stock grazing. Possible oxidation by ground and surface water in the backfill to be placed in the pits and in the 32 tailings and waste piles may cause increased solution of rock minerals, including radionuclides and trace elements.

The Jackpile sandstone (economic usage), which is an upper unit in the Brushy Basin Member of the Morrison Formation of Jurassic age, is the principal bedrock aquifer in the area, as well as the ore-bearing body. It is a fine- to medium-grained, poorly to moderately well sorted sandstone that ranges in thickness from 40 to 200 feet in the area. Fractured Dakota Sandstone and Mancos Shale of Cretaceous age overlie the Jackpile sandstone and a 200-foot-thick tight mudstone unit of the Brushy Basin Member underlies the Jackpile.

The hydraulic conductivity of the Jackpile sandstone probably is about 0.3 foot per day. The small storage coefficients determined from three aquifer tests indicate that the Jackpile sandstone is a confined hydrologic system throughout much of the mine area. Other water-yielding units include the thin valley alluvium, which had a hydraulic conductivity of 23 feet per day at one test well; colluvium adjacent to the mesas; and basalt flows and pyroclastic rocks west and north of the mine. Seepage from these water-yielding units probably sustains the base flow in the Rio Paguate.

The Rio Paguate flows eastward to near the center of the Jackpile mine, then southward to the Rio San Jose near the village of Laguna. The Rio Moquino is a tributary to the Rio Paguate in the northern part of the mine area. Prior to mining, the Rio Paguate was a gaining stream. During 1977-80, it had a mean daily base flow of about 0.6 cubic foot per second near the mine's south boundary; however, the stream was losing water in its reach between the Paguate pits. Sediment from the Rio Paguate has nearly filled the Paguate Reservoir near Laguna since its construction in 1940. The sediment deposited in the reservoir due to mining is estimated to be very small.

The mean concentrations of uranium, radium-226, and other trace elements generally were less than permissible limits established in national drinking-water regulations or New Mexico State ground-water regulations. No individual surface-water samples collected upstream from the mine contained concentrations of radium-226 in excess of the permissible limits. Radium-226 concentrations in many individual samples collected from the Rio Paguate from near the mouth of the Rio Moquino to the sampling sites along the downstream reach of the Rio Paguate, however, exceeded the recommended permissible concentration of radium-226 for public drinking-water supplies. Concentrations in surface water apparently are changed by ground-water inflow near the confluence of the two streams.

Part of the backfill will become saturated after reclamation. Most discharge from the Jackpile pit backfill probably will be to the Jackpile sandstone, then to the alluvium and the Rio Paguate. Discharge from the backfill in the Paguate pits primarily will be to permeable waste rock and then to the Rio Paguate. The altitude of the water tables in the backfill of the pits will be controlled partly by the water level in the Rio Paguate. Other factors controlling the altitudes of the water tables are the recharge rate to the backfill and the hydraulic conductivities of the backfill, alluvium, Jackpile sandstone, and mudstone unit of the Brushy Basin Member.

Waste piles receive only local recharge, which generally is from precipitation that falls directly on the piles. Saturation of the piles usually is limited and of short duration. Discharge from the piles may be to the land surface or to the underlying alluvium and bedrock.

After reclamation, most of the shallow ground water probably will discharge to the natural stream channels draining the mine area. The remaining ground water probably will flow to the south and east, where erosion has removed the northwest-dipping Jackpile sandstone from the valleys.

Four additional surface-water monitoring stations could be established, and samples initially could be collected about once every 2 months and at different discharges. Constituents that probably would need to be monitored are common ions, dissolved solids, trace elements, gross alpha radioactivity, gross beta radioactivity, and uranium.

Ground-water quality may be monitored as: (1) "Limited monitoring," in which only the change in water quality is determined as the ground water flows from the mine; or (2) "thorough monitoring," in which specific sources of possible contaminants are described. As few as three wells would be needed for limited monitoring; many more wells would be needed for thorough monitoring. Initially, ground-water-quality samples probably would need to be collected initially about once every 3 months.

INTRODUCTION

The area of the Jackpile mine (fig. 1) includes about 7,500 acres of land on the Pueblo of Laguna (Anaconda Copper Co., written commun., 1980). The land was leased from the Pueblo of Laguna by the Anaconda Copper Co. More than 356 million tons of material were moved since mining began in 1953, including 22 million tons of ore from the Jackpile sandstone (economic usage) of the Brushy Basin Member of the Morrison Formation; mining ceased in 1980. The mining has affected 3,141 acres of land, of which 485 acres had been reclaimed in late 1980. All of the remaining disturbed area (2,656 acres) was yet to be reclaimed in late 1980. The reclaimed land will be used for stock grazing. The remaining disturbed area consists of 1,015 acres of open pits, 1,266 acres covered by 32 piles of waste rock, 185 acres underlain by ore stockpiles, and 190 acres of supporting facilities.

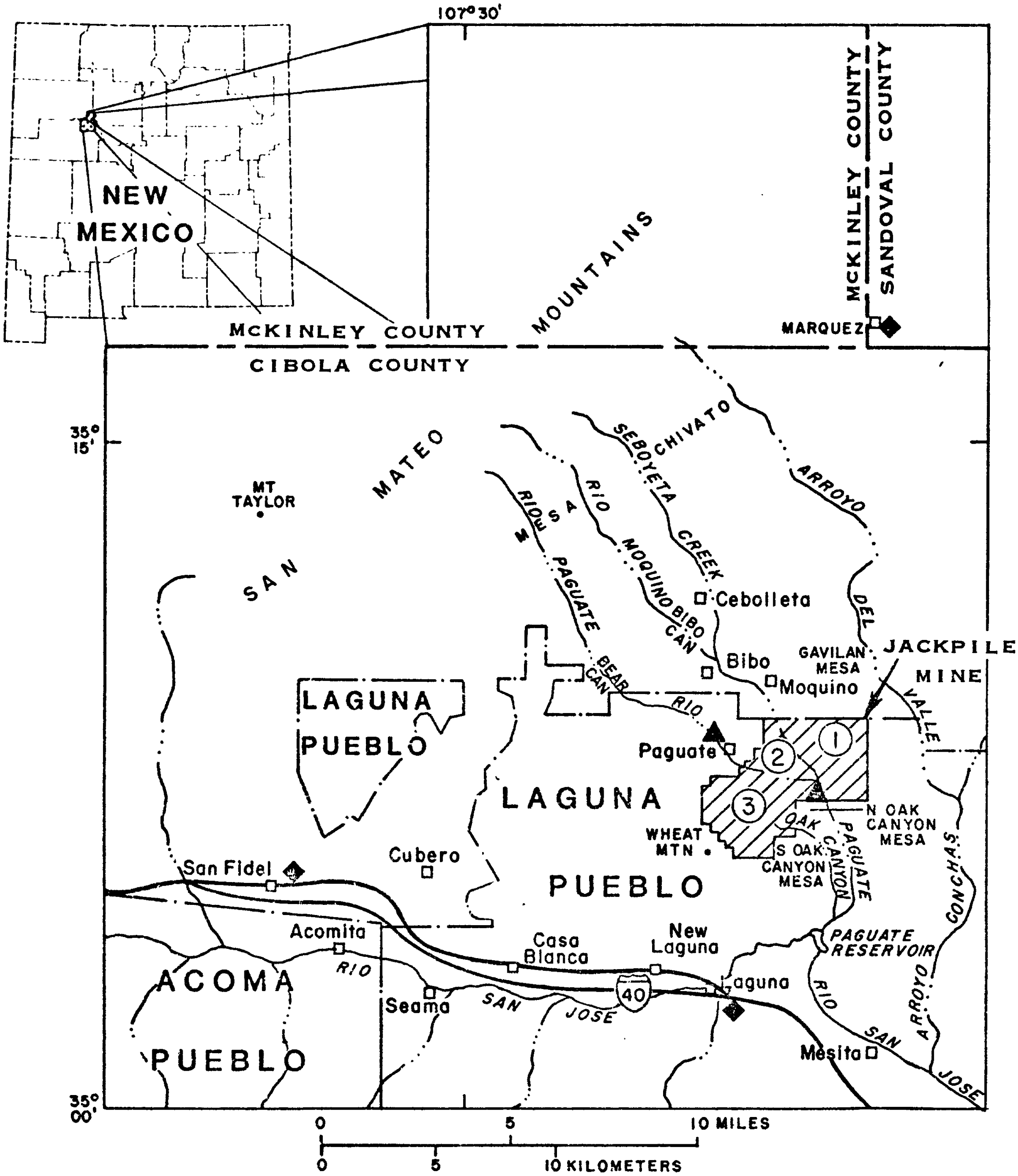
Ore was excavated by the open-pit method from 1953 to late 1980. The open-pit areas consist of the Jackpile pit (first area mined), located in the eastern part of the mine area, and the North and South Paguate pits, located in the northwest and west-central parts of the mine area. Underground mining started in 1974 and continued to late 1980. Most underground workings are located in the southwestern part of the Jackpile mine area.

The population centers nearest to the Jackpile mine are the village of Paguate, about 0.1 mile to the west, and the villages of Bibo and Moquino, 2 miles to the north. Laguna and Mesita, which are 6 to 7 miles south of the mine, are upstream and downstream, respectively, from the confluence of the Rio Paguate with the Rio San Jose (fig. 1). The nearest city is Albuquerque, located about 60 miles (by road) east of the mine.

Surface water from the Rio Paguate is used for irrigation near the village of Paguate. Upstream from Mesita, water from the Rio San Jose is used for irrigation on the Pueblos of Laguna and Acoma.

Ground water on the Pueblo of Laguna is used for public supply, livestock, and industry (F. P. Lyford, U.S. Geological Survey, written commun., 1977). Public supplies are obtained from one well near Mesita and two wells near Paguate. Most wells drilled for individual household use have been abandoned in favor of better quality water from public-supply wells.

The Jackpile uranium mine will be reclaimed by backfilling parts of 3 open pits and recontouring 32 waste piles. The reclaimed land is intended for livestock grazing. Primary hydrologic concerns are that the weathering of exposed backfill and waste rock in the disturbed areas may promote solution of undesirable chemical constituents, such as radionuclides and trace elements, that may move into surface-water or ground-water supplies.



EXPLANATION

(1) JACKPILE PIT

(2) NORTH PAGUATE PIT

(3) SOUTH PAGUATE PIT

▲ STREAMFLOW-GAGING STATION

◆ PRECIPITATION STATION

Figure 1.--Location of the Jackpile uranium mine.

Purpose and Scope

The purposes of this report are as follows:

1. To describe the 1980 hydrologic and water-quality conditions in and near the Jackpile mine that are related to the disturbed surface area of the mine.

2. To describe possible hydrologic flow conditions that might develop after reclamation of the mine and that might affect the quality of surface and ground water.

3. To present reasons for and possible methods of hydrologic monitoring that would be useful in establishing a post-reclamation ground- and surface-water quality monitoring network.

The scope of the report consists of describing the 1980 surface- and ground-water systems, including the rate and direction of flow and the water quality. Possible ground- and surface-water flow conditions after pit backfilling and considerations that may be useful in post-reclamation water-quality monitoring are discussed. Geohydrologic data collected prior to the study and reports were the primary sources of information used in the study. Data collected during the study consisted of streamflow data calculated from channel-geometry techniques; water-level measurements in holding ponds, mine pits, and 34 wells; and aquifer-test data at 5 wells.

The study was conducted during 1981-82 in cooperation with the U.S. Bureau of Land Management. The hydrologic information included in the report may be used in the preparation of an Environmental Impact Statement and the mine-reclamation plans.

Topography and Drainage

Prominent topographic features in the area of the Jackpile mine are the San Mateo Mountains and numerous mesas (fig. 2). Mount Taylor is the highest point in the area at altitude 11,300 feet and is located about 15 miles northwest of the Jackpile mine. Wheat Mountain (altitude 7,140 feet) and the drainage divides southeast of Mesa Chivato are topographically high areas that are fairly close to the mine. Within the lease boundary, altitudes range from 5,820 to 6,910 feet. The prominent features in the mine area are Gavilan Mesa at the northeast corner and North and South Oak Canyon Mesas along the southern edge. Other features include several smaller unnamed mesas and numerous piles of waste rock and stockpiled ore. The mine pits are as much as 200 to 300 feet below the adjacent land surface. The piles of waste rock are as much as 200 feet in height; most are about 50 to 75 feet high.

Drainage through the Jackpile mine is by the Rio Paguate and Rio Moquino, whose headwaters are in the San Mateo Mountains (fig. 2). The Rio Moquino becomes part of the Rio Paguate near the center of the mine. The Rio Paguate flows southeastward into Paguate Reservoir about 3 miles south of the southern mine boundary, then joins the Rio San Jose (altitude 5,700 feet) about 1 mile south of where the Rio Paguate enters the reservoir. The Rio San Jose, the main stream in the Laguna area, flows into the Rio Puerco about 25 miles southeast of its confluence with the Rio Paguate.

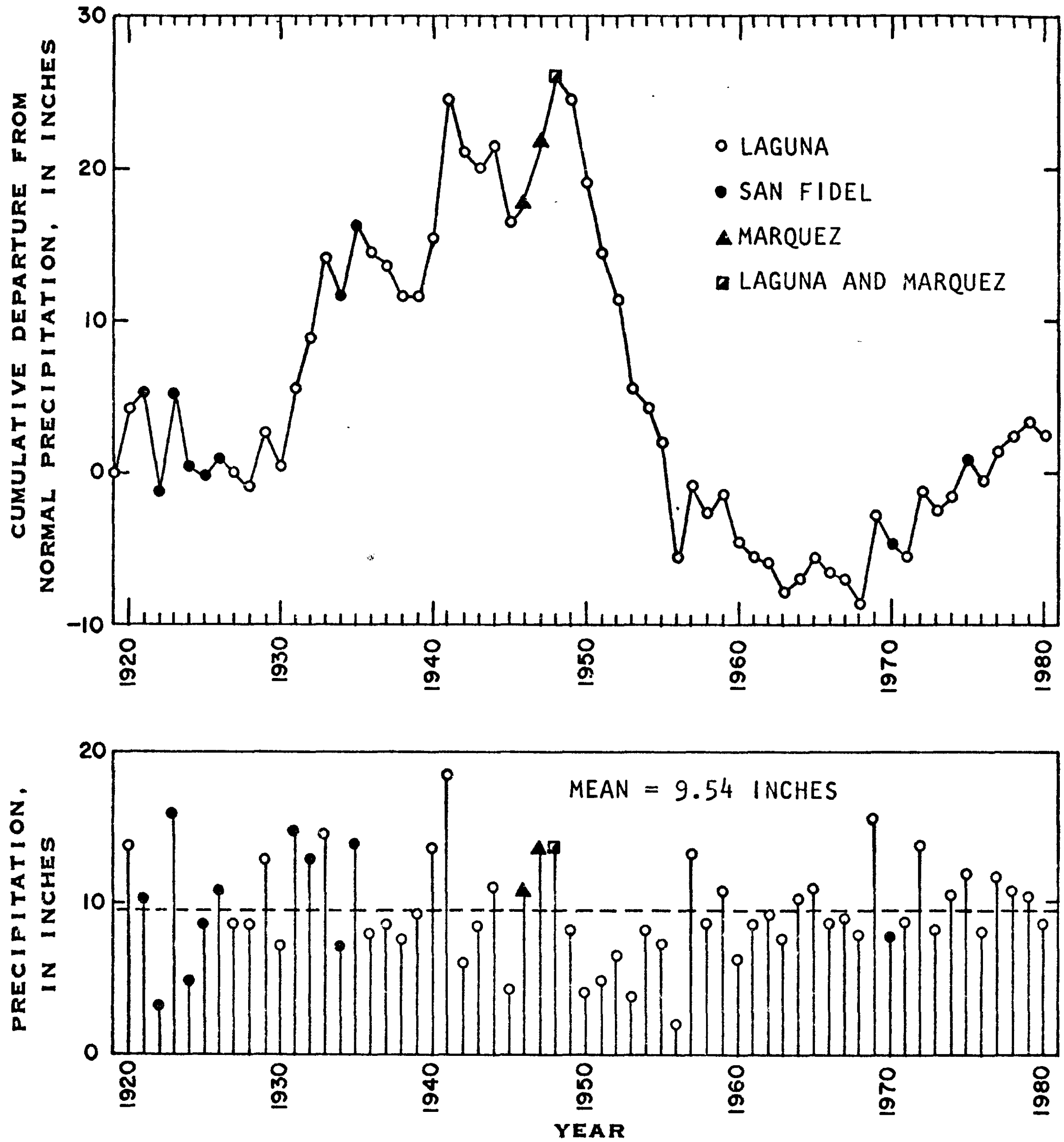


Figure 2.--Annual precipitation and cumulative departure from normal precipitation in the Laguna area.

Climate

The climate of northwestern New Mexico is characterized by minimal precipitation and significant evapotranspiration. Precipitation data were used from three stations operated by the U.S. Department of Commerce in the Laguna area. The stations (fig. 2) are located at the following towns: Laguna, about 7 miles south of the Jackpile mine at an altitude of 5,800 feet; San Fidel, about 12 miles west of Laguna at an altitude of 6,100 feet; and Marquez, about 13 miles north of the Jackpile mine at an altitude of 7,800 feet. Climatic data from a long-term station at Los Lunas also were used because several years of pan-evaporation data are available for the station. Los Lunas is located about 45 miles southeast of the Jackpile mine in the Rio Grande valley at an altitude of 4,800 feet.

Annual precipitation and years of record are shown in table 1. The annual precipitation generally is less than 15 inches, but quite variable. For example, the range for Laguna is from 1.96 inches (1956) to 18.42 inches (1941).

Mean monthly and mean annual precipitation at the four stations are presented in table 2. Only complete years of record were used in computing monthly means. About 60 percent of the precipitation occurs during the 5 months from May through September, with the greatest precipitation during July, August, and September. Mean annual precipitation is similar at Laguna and San Fidel. Precipitation at these two stations is about 15 percent greater than at Los Lunas and about 20 percent less than at Marquez.

All data from the Laguna station were used for plotting cumulative departure from mean annual precipitation after 1919 (fig. 2). Some data from other stations were used for years of incomplete record at Laguna. Mostly, data from San Fidel were used to fill in gaps of missing record, but precipitation at Los Lunas and Marquez was used for some years. The 15- to 20-percent differences between the data from Laguna and from Los Lunas-Marquez and the few years of data used from the latter stations are assumed to introduce negligible error in cumulative departure for the Laguna area. Monthly data from Laguna and Marquez were combined to obtain a total of 13.67 inches for 1948.

A 9.54-inch normal was used for 1919-80. This is considered a reasonable approximation for the Laguna area because mean annual precipitation at Laguna is 9.48 inches and the mean for all values on the cumulative departure plot is 9.54 inches. Departure from normal in 1919 is assumed to be zero (fig. 2).

Precipitation frequencies (table 3) range, on average, from 1.2 inches per 24 hours every 2 years to as much as 2.8 inches per 24 hours every 100 years.

Monthly pan evaporation at Laguna is shown in table 4, and that at Los Lunas is shown in table 5. Mean monthly pan evaporation ranged from about 0.5 to about 2 inches more during April through November at Laguna than at Los Lunas. Maximum differences are only 16 percent between monthly means, however, with differences for most months less than 8 percent. In this report, the mean annual pan evaporation at Laguna is assumed equal to that at Los Lunas, which is about 76 inches More than 60 percent of annual pan evaporation occurs during May through September. Months of greatest evaporation correspond to months of greatest precipitation.

Table I.--Annual precipitation at four stations near the Jackpile mine

[All values are in inches. Data from New Mexico State Engineer Office (1956) and annual publications of precipitation data by the U.S. Department of Commerce]

Year	Laguna[1/]	San Fidel	Marquez	Los Lunas	Year	Laguna	San Fidel	Marquez	Los Lunas
1891	--	--	--	16.37	1936	7.88	8.90	--	5.13
1892	--	--	--	6.11	1937	8.59	7.86	--	7.72
1893	--	--	--	8.40	1938	7.55	8.53	--	4.67
1894	--	--	--	4.55	1939	9.37	12.34	--	7.70
1895	--	--	--	--	1940	13.54	14.91	--	11.08
1896	--	--	--	7.65	1941	18.42	22.64	--	--
1897	--	--	--	--	1942	6.00	6.31	10.38	--
1898	--	--	--	--	1943	8.43	9.38	15.51	--
1899	--	--	--	--	1944	11.10	--	14.55	--
1900	--	--	--	8.05	1945	4.43	--	9.69	--
1901	--	--	--	--	1946	--	--	10.85	--
1902	--	--	--	--	1947	--	--	13.46	--
1903	--	--	--	--	1948	--	--	--	--
1904	--	--	--	10.45	1949	8.14	--	13.12	--
1905	--	--	--	--	1950	4.03	--	5.22	5.23
1906	13.05	--	--	11.67	1951	4.75	5.82	8.95	4.80
1907	--	--	--	15.85	1952	6.46	8.90	12.32	6.34
1908	8.35	--	--	5.27	1953	3.73	6.36	9.64	--
1909	10.60	--	--	4.25	1954	8.21	8.72	10.95	--
1910	9.08	--	--	--	1955	7.25	6.78	9.12	7.89
1911	12.90	--	--	11.57	1956	1.96	--	5.21	2.87
1912	--	--	--	5.47	1957	13.12	10.39	19.56	8.18
1913	8.68	--	--	7.77	1958	8.72	9.27	16.05	6.25
1914	--	--	--	10.21	1959	10.74	19.07	12.70	8.74
1915	--	--	--	12.13	1960	6.28	8.49	12.27	7.71
1916	--	--	--	10.14	1961	8.53	8.61	13.08	8.26
1917	--	--	--	2.15	1962	9.19	7.85	11.73	6.36
1918	--	--	--	9.94	1963	7.63	8.10	9.12	6.34
1919	--	--	--	10.84	1964	10.30	7.72	9.45	6.34
1920	13.81	--	--	6.27	1965	10.92	--	13.14	10.17
1921	--	10.35	--	9.26	1966	8.67	7.91	7.90	5.50
1922	--	3.15	--	3.24	1967	8.86	10.16	13.37	8.93
1923	--	15.89	--	9.07	1968	7.83	7.83	7.00	8.43
1924	--	4.93	--	5.83	1969	15.44	10.16	12.67	10.31
1925	--	8.55	--	8.37	1970	--	7.70	6.56	5.90
1926	--	10.78	--	8.11	1971	8.69	7.81	7.18	7.83
1927	8.66	13.06	--	9.40	1972	13.74	13.54	11.44	13.37
1928	8.65	11.10	--	10.26	1973	8.17	7.54	8.59	10.17
1929	12.94	12.25	--	14.07	1974	10.40	10.16	8.17	11.12
1930	7.14	7.95	--	5.08	1975	11.92	8.84	--	5.99
1931	--	14.68	--	10.44	1976	7.95	--	--	5.42
1932	--	12.83	--	10.15	1977	11.57	--	--	8.18
1933	14.64	11.98	--	7.30	1978	10.65	--	--	9.75
1934	--	7.23	--	4.34	1979	10.36	--	--	8.19
1935	--	13.93	--	6.07	1980	8.66	--	--	7.53

[1/]Precipitation recorded prior to 1891: 1850 = 9.69 inches and 1851 = 15.12 inches.

Table 2.--Mean monthly and mean annual precipitation at four stations near the Jackpile mine

[All values are in inches. Data from New Mexico State Engineer Office (1956) and annual publications of precipitation data by the U.S. Department of Commerce]

Station	Jan.	Feb.	Mar.	Apr.	May	June	July	Aug.	Sept.	Oct.	Nov.	Dec.	Annual
Laguna	0.36	0.47	0.43	0.39	0.60	0.60	1.74	1.73	1.40	0.92	0.34	0.50	9.48
San Fidel	.24	.37	.39	.22	.41	.36	1.45	2.12	1.29	1.29	.24	.44	9.36
Marquez	.57	.29	.50	.73	.63	.79	1.56	2.95	1.22	.81	.54	.65	11.22
Los Lunas	.35	.32	.45	.47	.58	.56	1.11	1.50	1.11	.89	.31	.42	8.06

Table 3.--Precipitation frequencies in the Jackpile mine area

[All values are in inches. Data from the U.S. Department of Commerce (1967)]

2-year, 24-hour	5-year, 24-hour	10-year, 24-hour	25-year, 24-hour	50-year, 24-hour	100-year, 24-hour	5-year, 6-hour	10-year, 6-hour	25-year, 6-hour	50-year, 6-hour	100-year, 6-hour
1.2	1.6	1.9	2.3	2.6	2.8	1.3	1.6	1.8	2.1	2.2

Table 4.--Monthly pan evaporation at Laguna

[All values are in inches. Data obtained from annual publications by the U.S. Department of Commerce]

Year	Jan.	Feb.	Mar.	Apr.	May	June	July	Aug.	Sept.	Oct.	Nov.	Dec.
1974	--	--	--	--	--	12.54	10.90	8.92	6.90	3.78	--	--
1975	--	--	--	--	--	13.09	10.19	9.78	--	--	--	--
1976	--	--	--	8.76	11.26	13.09	11.52	9.59	5.88	5.36	--	--
1977	--	--	--	--	10.89	11.22	10.31	9.56	6.77	5.56	--	--
1978	--	--	--	9.33	9.83	12.79	11.98	9.77	7.24	5.92	2.20	--
Mean	--	--	--	9.05	10.66	12.55	10.98	9.52	6.70	5.16	2.20	--

Table 5.--Monthly pan evaporation at Los Lunas

[All values are in inches. Sum of monthly means from all data is 75.52 inches. Data obtained from annual publications by the U.S. Department of Commerce]

Year	Jan.	Feb.	Mar.	Apr.	May	June	July	Aug.	Sept.	Oct.	Nov.	Dec.
1962	--	--	--	--	--	--	--	--	6.79	5.00	--	--
1963	--	--	--	10.34	10.96	11.63	11.25	9.87	7.49	4.61	--	--
1964	--	--	--	8.13	12.13	12.83	11.17	9.89	6.66	--	--	--
1965	--	--	--	8.24	10.82	10.23	10.99	9.02	7.12	4.92	--	--
1966	--	--	5.70	9.04	11.81	11.39	10.28	9.70	6.39	5.40	--	--
1967	--	--	7.02	9.64	10.47	11.00	10.41	7.88	6.36	5.90	--	--
1968	--	--	--	9.19	10.24	13.55	12.07	9.91	7.62	5.01	--	--
1969	--	--	4.00	6.22	9.07	10.77	9.30	11.29	4.91	4.87	1.81	--
1970	--	--	4.94	10.47	10.53	10.29	9.48	9.73	6.90	2.77	--	--
1971	--	--	--	8.27	8.58	11.47	12.07	9.37	7.52	3.01	--	--
1972	--	--	--	7.96	8.23	9.74	10.84	9.22	6.60	2.57	--	--
1973	--	--	2.48	3.79	8.33	10.64	9.73	9.39	6.68	4.54	--	--
1974	--	--	7.17	8.20	10.30	11.91	11.07	8.31	--	4.59	2.57	--
1975	--	--	5.64	7.89	9.09	9.53	8.40	9.15	--	5.56	--	--
1976	--	--	--	7.94	9.32	10.72	9.94	8.50	6.00	4.66	3.04	--
1977	--	2.79	5.75	6.75	9.82	10.18	9.83	9.07	5.88	4.76	3.47	.53
1978	2.00	2.99	5.11	8.99	9.01	10.38	9.90	9.96	7.45	4.71	2.09	--
Mean 1/	2.00	2.89	5.31	8.19	9.92	11.02	10.42	9.39	6.69	4.56	2.60	2.53
Mean 2/	--	--	--	8.47	9.38	10.54	9.83	9.00	6.44	4.86	2.09	-

1/ All months of record, with single values assumed equal to mean.
2/ Only months for which data also were obtained at Laguna.

Acknowledgments

Anaconda Copper Co. personnel provided access and guidance through all areas of the Jackpile mine. William Griego of Anaconda Copper Co. assisted in collecting hydraulic-head data from wells.

Several U.S. Geological Survey personnel made significant contributions to this report and are acknowledged as follows. Jack D. Dewey estimated sediment transport rates in the Rio Paguate drainage basin. Discussions with Richard F. Hadley were helpful in assessing principal factors associated with sediment deposition in reservoirs. John P. Borland estimated flood frequencies for the local streams. Herberto B. Mendieta, with assistance from Kim Ong, summarized the available chemical data and described water quality. Several persons in the Albuquerque office participated in collecting and analyzing aquifer-test data, particularly Paul A. Davis and James A. Basler.

SURFACE WATER

Streamflow data were collected on the Rio Paguate upstream from the village of Paguate (referred to as Paguate Creek near Laguna) from March 1937 through September 1941 and at the southern boundary of the Jackpile mine near Laguna from March 1976 through September 1980 (fig. 1). Discharge was not measured on the Rio Moquino.

A summary of the discharge data by water years (October through September) is shown in table 6. Mean monthly and mean annual discharge are given in Supplemental Information.

Table 6.—Summary of discharge data for Rio Paguate upstream from Paguate (water years 1938-41) and Rio Paguate at the southern boundary of the mine near Laguna (water years 1977-80)

[All values are in cubic feet per second except as indicated]

Water year	Maximum daily	Mean daily	Minimum daily	Total (cubic feet per second-days)
1938	--	0.99	0.20	1/361
1939	--	1.02	.40	1/372
1940	--	1.02	.30	1/372
1941	--	3.80	.40	1/1387
1977	34	1.48	.04	539.07
1978	42	1.08	.07	394.03
1979	14	1.33	.06	485.94
1980	42	.87	.00	316.66
Mean for 1938-41	--	1.71	.32	623
Mean for 1977-80	33	1.19	.04	433.93

1/ Approximated by multiplying mean daily discharge by 365 days.

The mean daily discharge for water years 1938-41 at the gaging station upstream from Paguate was 1.71 cubic feet per second. The value is affected considerably by the unusually large discharge during water year 1941. Precipitation for calendar year 1941 was the greatest recorded at Laguna and caused the anomalously large discharge value. The Rio Paguate usually flows all year. It is occasionally dry at the gaging station at the southern boundary of the Jackpile mine, as shown by the minimum daily discharge in table 6. The mean daily discharge for water years 1977-80 at the southern station was 1.19 cubic feet per second.

The stream discharge is only about 2 percent of the precipitation in the Rio Paguate drainage basin, as will be discussed in the "Water Balance" section of this report. This illustrates the extremely large evapotranspiration in the area.

Base Flow

In humid areas, ground-water discharge to streams (base flow) generally is determined by computing a constant slope from the decreasing limb of the discharge plot (recession), then using this slope as a control for estimating base flow during recessions. In the arid Rio Paguate drainage basin, floods are infrequent during winter months, so that most discharge is base flow during this time. More frequent floods in summer are caused by thunderstorms that are intense, but of short duration. The recessions are, therefore, rapid. Their slopes are difficult to determine, not constant, and not completely controlled by ground-water discharge.

Ground-water gradients near the streams are reversed (hydraulic head is greater in the stream than in the adjacent aquifer) when the stream stage rises and during the early part of the recession. Base flow during this time is zero. The stream may, in fact, be losing water to bank storage. Base flow at the Rio Paguate gaging station was approximated by assuming there is no ground-water discharge during the entire rising and receding stages of the stream. The method is similar to that described by Daniel and others (1970).

Ground-water discharge during recessions was not taken into account for the Rio Paguate, so base-flow values may be too small. The error probably is not significant however, because: (1) Discharge during much of the receding stage of summer floods is low, compared to greater, predominantly base-flow periods in winter; and (2) some of the discharge during receding stages is from temporary ground-water storage very near the stream (bank storage), whereas the flow of primary interest in this study is the regional ground-water discharge to the stream.

Most base flow to the Rio Paguate occurs during winter (table 7) and constitutes a large percent of the total flow in the Rio Paguate. Base flow was 51 percent of total flow in water year 1977, 56 percent in 1978, 35 percent in 1979, and 60 percent in 1980.

Table 7.--Monthly and annual base flow in Rio Paguate below Jackpile mine near Laguna

[All values are in cubic feet per second-days]

Water year	Oct.	Nov.	Dec.	Jan.	Feb.	Mar.	Apr.	May	June	July	Aug.	Sept.	Annual
1977	18.5	29.7	34.1	29.8	37.7	46.1	18.5	38.1	13.8	0.48	0.63	9.10	277
1978	14.1	16.3	29.3	40.0	22.4	43.1	24.1	19.4	7.50	.77	1.46	2.84	221
1979	3.84	12.3	19.5	11.1	16.0	9.7	40.8	28.4	12.9	1.91	4.39	10.6	171
1980	8.56	16.4	17.4	26.7	31.3	55.9	23.7	5.88	3.11	.33	.08	.43	190
Mean	11.2	18.7	25.1	26.9	26.8	38.7	26.8	22.9	9.33	0.87	1.64	5.74	215

The mean of 215 cubic feet per second-day is equivalent to about 426 acre-feet per year or a continuous mean daily discharge of 0.6 cubic foot per second.

Flood Frequency

Flood frequencies were estimated at three locations near the Jackpile mine: on the Rio Paguate 500 feet upstream from the northwest mine-lease boundary; on the Rio Moquino 1,500 feet downstream from the northern mine-lease boundary; and on the Rio Paguate 400 feet upstream from the gaging station near the southern mine-lease boundary. Streamflow data from the gaging station were used to estimate flood frequency by use of the U.S. Geological Survey flood-flow-frequency program (J407). Two other methods were used for all locations: the basin-characteristics method described by Thomas and Gold (1982), and the channel-geometry method described by Scott and Kunkler (1976).

Measurements for use in the flood-frequency methods are given in table 8. Peak discharges were determined for recurrence intervals of 5, 10, 25, 50, 100, 200, and 500 years (table 9). Flood frequencies obtained by using the channel-geometry method are, on average, about three times less than those obtained using the basin-characteristics method. Those values obtained by the latter method are probably more accurate than those from the channel-geometry method because standard estimates of error are smaller for the method, and values obtained by the basin-characteristics method more closely approximate those obtained by use of streamflow data in the flood-frequency program.

Table 8.--Measurements used for estimating flood frequency in the Jackpile mine area

Location	Active channel width (feet)	Contributing drainage area (square miles)	Site altitude (feet)
Rio Paguate upstream from Jackpile mine	10	30.8	6,070
Rio Moquino upstream from Jackpile mine	12	68.6	6,000
Rio Paguate downstream from Jackpile mine	20	107	5,820

Table 9.--Flood frequencies at three locations in the Jackpile mine area

Recurrence interval (years)	Discharge by flood-frequency program (cubic feet per second)	Discharge by basin-characteristics method (cubic feet per second)	Discharge by channel-geometry method (cubic feet per second)
	Rio Paguate upstream from Jackpile mine		
5	--	762	208
10	--	1,180	337
25	--	1,890	558
50	--	2,590	774
100	--	3,370	1,000
200	--	4,260	1,300
500	--	5,780	1,800
	Rio Moquino upstream from Jackpile mine		
5	--	1,140	276
10	--	1,740	442
25	--	2,730	722
50	--	3,700	993
100	--	4,780	1,300
200	--	5,990	1,700
500	--	8,030	2,500
	Rio Paguate downstream from Jackpile mine		
5	1,810	1,520	609
10	2,710	2,310	946
25	4,150	3,610	1,490
50	5,450	4,880	2,000
100	6,940	6,290	2,600
200	8,670	7,860	3,300
500	11,300	10,500	4,400

The estimates of flood frequencies may prove useful for design of structures such as road culverts during reclamation of the Jackpile mine. Flood-prone areas could be outlined by using the flood-frequency values. The areas are partly dependent on existing structures in the mine, however, and probably would be changed considerably during reclamation of roads, culverts, and other stream constrictions such as waste piles presently in the channels.

Ponding at Waste Piles

An unnamed valley on the east side of Gavilan Mesa is blocked by waste-rock dumps C, D, E, F, and G (pl. 1). Overland runoff occasionally ponds at the base of the dumps. The ponded water may, therefore, infiltrate both the valley alluvium and the waste rock. The expected depths of water in the pond are discussed in this section.

The initial depths of ponded water after floods were computed by deriving a stage-capacity curve (fig. 3) from a topographic map, then determining discharge in the valley using the streamflow-characteristics method described by Borland (1970). The pertinent factors relating to streamflow characteristics in the unnamed valley and their corresponding values are: drainage area, 0.97 square mile; precipitation from October through April, 3 inches; longitude, 107 degrees 10 minutes; soils infiltration index, 8.5; and mean basin altitude, 6,070 feet.

Flood volumes and depths of ponded water are shown in table 10 for different recurrence intervals. Maximum depth is 3.9 feet for a flood flow of 1 day at a recurrence interval of 50 years. Depths are less than 2 feet for most flow periods and recurrence intervals.

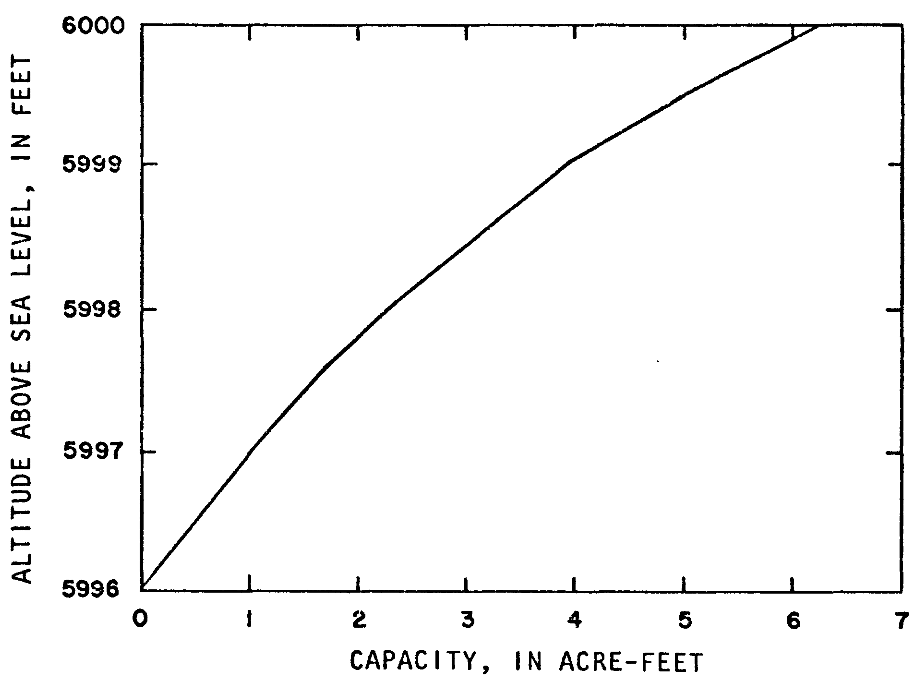


Figure 3.--Stage-capacity curve for the ponding area near waste dumps C, D, E, F, and G at the Jackpile mine.

Table 10.--Flood volumes and depths of ponded water in valley at east side of Gavilan Mesa

Floods and recurrence intervals[1/]	Volume (cubic feet per second-days)	Volume (acre-feet)	SE[2/] (percent)	Altitude of water level (feet)	Depth of water (feet)
$F_{1,2}$	0.29	0.6	59	5,996.6	0.6
$F_{1,5}$	.84	1.7	55	5,997.6	1.6
$F_{1,10}$	1.31	2.6	55	5,998.2	2.2
$F_{1,25}$	2.13	4.2	60	5,999.2	3.2
$F_{1,50}$	2.90	5.8	66	5,999.9	3.9
$F_{3,2}$	.12	.2	62	5,996.2	.2
$F_{3,5}$	.34	.7	56	5,996.7	.7
$F_{3,10}$	.54	1.1	55	5,997.1	1.1
$F_{3,25}$	.88	1.7	56	5,997.6	1.6
$F_{3,50}$	1.17	2.3	60	5,998.0	2.0
$F_{7,2}$	.06	.1	61	5,996.1	.1
$F_{7,5}$	.15	.3	58	5,996.3	.3
$F_{7,10}$	.24	.5	56	5,996.5	.5
$F_{7,25}$	.37	.7	56	5,996.7	.7
$F_{7,50}$	.48	1.0	59	5,997.0	1.0

1/ $F_{n, m}$ is flood volume for flow period n, at recurrence interval m: for example, $F_{1,2}$ means flood volume for 1 day at 2-year recurrence interval.
2/ Standard error of estimate.

Yield and Deposition of Sediment at Paguate Reservoir

Sediment has nearly filled the Paguate Reservoir (fig. 1) since construction of the dam in 1940. At present, ponding occurs only in the immediate vicinity of the dam and spillway. The Pueblo of Laguna is concerned that operation of the Jackpile mine may have increased the volume of sediment deposited in the reservoir. Three principal factors affecting reservoir sedimentation are the rate of sediment transport, the rate of sediment deposition, and the trap efficiency (proportion of sediment inflow retained by the reservoir).

Dames and Moore (written commun., 1980) used sediment volume and rates of sediment deposition, as determined from topographic maps made at different times, to evaluate the effect of the Jackpile mine on sedimentation in the Paguate Reservoir. The mean rates of deposition computed were 71 acre-feet per year from 1940 to 1949 and 22 acre-feet per year from 1949 to 1980. Based on the latter rate, the volume of sediment deposited since mining began in 1953 until 1980 is about 620 acre-feet. This is 47 percent of the total 1,333 acre-feet of sediment accumulated.

The greater rate of deposition during 1940 to 1949 was likely due to: (1) Greater sediment transport in early years due to greater than normal precipitation (fig. 2)--rainfall during 1941 was 18.42 inches, which is the greatest in all 55 years of record at Laguna (table 1); and (2) much greater trap efficiency during earlier years--efficiency would have been 100 percent during the time the reservoir was filling with water.

The rate of sediment transport, which is sediment yield, has not been measured in the Rio Paguate drainage basin. An approximate yield was computed by using a method described by Shown (1970), in which ratings are placed on several characteristics affecting yield (table 11).

Table 11.--Rating ranges of factors used for estimating sediment yields

[Modified from Shown, 1970]

Factor	Rating range	Main characteristics considered
A. Surface geology	0-10	Rock type, hardness, weathering, fracturing.
B. Soils	0-10	Texture, aggregation, salinity, caliche.
C. Climate	0-10	Storm frequency, intensity, duration.
D. Runoff	0-10	Volume per unit area, peak flow per unit area.
E. Topography	0-20	Steepness of upland slopes, relief.
F. Ground cover	-10-10	Vegetation, litter, rocks.
G. Land use	-10-10	Percentage cultivated, grazing intensity, logging, roads.
H. Upland erosion	0-25	Rills and gullies, landslides.
I. Channel erosion and sediment transport	0-25	Bank and bed erosion, flow depths, active headcuts, channel vegetation.

Ratings were made for the entire Rio Paguate drainage basin; the Jackpile mine before mining; and the Jackpile mine in its present (1980) condition (table 12). Drainage is into closed basins (pits) for 5.0 square miles of the 6.0 square miles in the mine area. The ratings for the present (1980) conditions apply to the 1.0 square mile with external drainage.

Shown (1970) described the correspondence of ratings and estimated sediment yields, in acre-feet per year per square mile, as follows: a rating of 25 to 50 gives a yield of 0.2 to 0.5, and a rating of 100 to 125 gives a yield of 3.0 to 7.0. Ratings in table 12 were summed for each drainage area and the corresponding yield computed (table 13). The net sediment yield due to mining operations was estimated as the difference between before and after mining, which is 3.5 - 3.0 = 0.5 acre-foot per year. The estimated present (1980) rate of sediment yield due to mining is only about 1.0 percent of the 46 acre-feet per year total yield in the basin. This percentage may be too large if used to compute total yield since mining started because a smaller mined area was exposed during the early years of operation.

Table 12.--Descriptions of characteristics and ratings for estimating sediment yield in the Rio Paguate drainage basin

Factor*	Rating	Description
		Total Rio Paguate drainage basin upstream from the mine
A	5	Rocks are of medium hardness, moderately weathered, and fractured.
B	5	Soils are medium textured with occasional rock fragments.
C	8	Most runoff is due to intense convective storms, but runoff has small volume.
D	5	Runoff occurs as high peaks, but has small volume.
E	12	The average upland slopes are less than 30 percent, but there is little flood plain.
F	-5	Upper areas have good ground cover and the lower areas have moderate ground cover.
G	-10	Little cultivation, recent logging, and grazing.
H	5	Signs of erosion on less than 25 percent of the land surface.
I	15	Active headcuts and degradation in tributary channels, but flow duration is short.
		Jackpile mine area before beginning mining operations
A thru E		Same as described above.
F	0	Lower areas have moderate ground cover.
G and H		Same as described above.
I	20	Headcuts and degradation are more prevalent in downstream reaches.
		Jackpile mine area in present (1980) condition
A thru D		Same as described above.
E	20	External drainage is mostly from the steep slip faces on the outsides of the waste piles.
F	10	Very little ground cover.
G	10	Land use extensive.
H	25	Rills cover about 50 percent of the land surface.
I	15	Much of the sediment eroded from the slip faces is deposited at the bottoms of the faces.

*Corresponds to factors in table 11.

Table 13.--Estimates of sediment yield in the Rio Paguate drainage basin

Drainage area description	Rating total	Unit yield (acre-feet per year per square mile)	Area (per square mile)	Total yield (acre-feet per year)
Entire Rio Paguate drainage basin	40	0.38	120	46.0
Mine area before mining began	50	.50	6.0	3.0
Mine area at present (1980)	103	3.5	1.0	3.5

Only part of the approximate 0.5 acre-foot per year yield was actually deposited in Paguate Reservoir because trap efficiency was less than 100 percent during mining. Using the deposition rate of 22 acre-feet per year for 1949 to 1980, as determined by Dames and Moore (written commun., 1980), and the total yield in the Paguate drainage basin, the trap efficiency would be about 48 percent (22 acre-feet per year divided by 46 acre-feet per year). Using the 0.5 acre-foot per year (maximum) yield during mining, the mean sedimentation rate during mining would have been less than 0.24 acre-foot per year (0.5 acre-foot per year x 0.48).

Trap efficiency probably would apply equally to both mine sediment and total basin sediment, so the proportion of sediment deposited from mining to that deposited from total basin erosion is the same as the proportion for sediment yield, which is about 1.0 percent. The small percentage results from the fact that the mine area constitutes a small part of the total Rio Paguate drainage basin.

Shown (1970) discussed the magnitude of error in using the rating method for estimating sediment yield at sites in Colorado, New Mexico, and Wyoming. Most estimated yields tended to be less than measured yields, and he attributed this difference to the subjective application of the ratings. The mean sediment-yield estimate for 28 sites was 1.4 acre-feet per year per square mile, whereas the mean determined from reservoir records was 1.73 acre-feet per year per square mile, giving a mean error of -19 percent. The maximum error for all sites studied was about -180 percent.

GEOLOGY AND HYDROLOGIC UNITS

A variety of rocks are exposed in the vicinity of the Jackpile mine. They consist of unconsolidated surficial deposits of Quaternary age, consolidated igneous rocks of Tertiary or Quaternary age, and consolidated sedimentary rocks (fig. 4) that range in age from Cretaceous to Triassic (Schlee and Moench, 1963a, 1963b). Unconsolidated surficial alluvial deposits along the Rio Paguate and Rio Moquino and the Jackpile sandstone of Late Jurassic age are the principal water-yielding units associated with the mine.

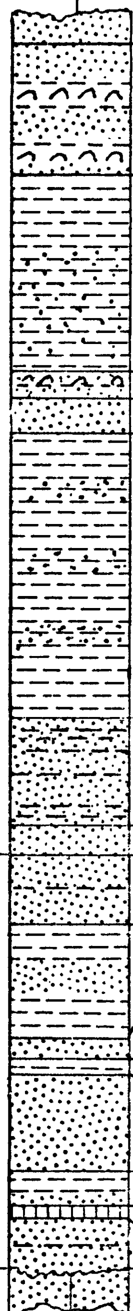
The surficial alluvial deposits, which include considerable amounts of eolian material, are about 80 feet thick locally and consist of clay, silt, sand, and gravel (Anaconda Copper Co., written commun., 1983). Alluvial deposits along the Rio Paguate and Rio Moquino are saturated and yield small quantities of fair-to-good water upstream from the mine.

Additional surficial deposits consist of gravel-covered pediments on the side and base of Mesa Chivato and colluvial deposits on the sides and bases of the mesas. Extensive talus, landslide deposits, and sheets of debris cover the steep hillsides at the western edge of the Jackpile mine and extend continuously along the eastern flanks of Mount Taylor from Wheat Mountain to Mesa Chivato. These deposits also cover parts of North and South Oak Canyon Mesas.

Igneous rocks exposed in the Laguna area are of late Tertiary to Quaternary age and consist of basalt plugs and basalt flows interstratified with alluvial and pyroclastic deposits. Older diabase dikes and sills occur locally, two of which may be clearly seen at the walls of the Paguate pits. Mount Taylor is a stratified volcano and is part of a northeast-trending belt of basaltic cones, plugs, and flows. Interstratified pyroclastic deposits and basalt flows form the cap on Mesa Chivato (Moench and Schlee, 1967) and pyroclastic deposits form the top of Wheat Mountain.

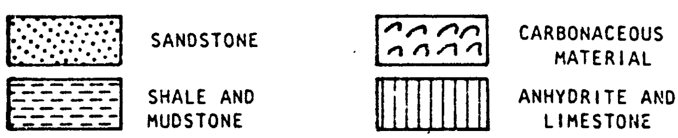
Other hydrologic units are the colluvial deposits and basalt flows and pyroclastic deposits in the Mount Taylor and Mesa Chivato areas. F. P. Lyford (U.S. Geological Survey, written commun., 1977) described springs flowing from the basalt caps on Mesa Chivato at the upper reaches of the Rio Paguate. It is likely that these springs, combined with flow from colluvial debris along the sides of Bear Canyon on Mesa Chivato, sustain base flow in the Rio Paguate. Similar conditions in Seboyeta and Bibo Canyons farther to the north probably produce the base flow in the Rio Moquino.

The consolidated sedimentary rocks shown in figure 4 crop out in an area between a strike line 10 miles southeast of the mine and a strike line 7 miles northwest of the mine. The rock units, which are successively older to the southeast, dip northwestward at about 90 feet per mile (Schlee and Moench, 1963a, 1963b). Few faults are present in the mine area and they have small displacements. The generalized thicknesses of the sedimentary rock units shown in figure 4 are the maximum thicknesses given by Schlee and Moench (1963a, 1963b). Departures from the thicknesses given in figure 4 that are mentioned elsewhere in this report may be more representative of specific localities.



SYSTEM	FORMATION OR GROUP	MEMBER OR TONGUE	THICKNESS (feet)
CRETACEOUS	Point Lookout Sandstone of Mesaverde Group	Hosta Tongue	100
	Crevasse Canyon Formation of Mesaverde Group	Gibson Coal and Dalton Sandstone Members	400
	Mancos Shale	Mulatto Tongue	400
	Crevasse Canyon Formation	Dilco Coal Member	85
	Gallup Sandstone of Mesaverde Group		80
	Mancos Shale		750
	Lower part of Mancos Shale	Includes three sandstone tongues of Mesaverde Group	270
	Dakota Sandstone		50
JURASSIC	Morrison Formation	Jackpile sandstone (economic use)	200
		Brushy Basin Member	270
		Westwater Canyon Member	50
		Recapture Member	40
	Bluff Sandstone		300
	Summerville Formation		90
	Todilto Formation		10
	Entrada Sandstone		120
TRIASSIC	Chinle Formation		

EXPLANATION



Modified from Schlee and Moench (1963a and 1963b). Only maximum thickness given.

Figure 4.--Generalized stratigraphic column of consolidated sedimentary rocks in the vicinity of the Jackpile mine.

Rocks exposed in and immediately around the Jackpile mine are as follows: the Brushy Basin Member, which is the uppermost member of the Morrison Formation and is exposed at the bases of some mesas; the Dakota Sandstone; and the Mancos Shale, which forms the tops of the locally high mesas. The uppermost part of the Brushy Basin Member is predominantly sandstone in the mine area. It is called the Jackpile sandstone (economic usage) and is both the ore-bearing body and the principal local bedrock aquifer. The Brushy Basin Member is underlain by the middle and lowest members of the Morrison Formation, which are the Westwater Canyon and Recapture Members, respectively.

The Jackpile sandstone is mostly fine to medium grained, poorly sorted to moderately well sorted, and friable. It is predominantly detrital quartz and has a chalky white cast due to kaolinization of feldspars prior to deposition of the Dakota Sandstone. Moench and Schlee (1967) observed discontinuous strata of greenish-gray bentonitic mudstone in most exposures of the Jackpile sandstone. They also stated that it is predominantly calcite cemented in its lower part and becomes increasingly clay cemented toward the upper part. Its thickness in the Jackpile mine ranges from 40 to 200 feet with an average of about 100 feet (Hydro-Search, Inc., written commun., 1981).

The Jackpile sandstone is overlain by tightly cemented sandstone in some areas, but elsewhere it is overlain by black shale. The black shale may represent a facies change in the Dakota Sandstone, or it may be a tongue of the Mancos Shale. In this report it will be called a shale in the Dakota Sandstone. The Dakota Sandstone is overlain by beds of tightly cemented sandstone and black shale in the Mancos Shale. Both formations overlying the Jackpile sandstone are extensively fractured. Fracture spacing at outcrops is only a few feet. Underlying the Jackpile sandstone is a mudstone unit in the Brushy Basin Member. In some areas, the mudstone is composed of fine sand- to silt-size fragments embedded in a clay matrix, but in other areas it is predominantly composed of swelling-type clays (Moench and Schlee, 1967).

The Dakota Sandstone and Mancos Shale vary in thickness in the Jackpile mine, depending mostly on the topography. The Dakota Sandstone averages about 45 feet thick. The Mancos Shale is not present on lower mesas, but is about 50 to 75 feet thick at the northwest and west-central part of the mine, and as much as 300 feet thick near Gavilan Mesa. The mudstone unit in the Brushy Basin Member is about 200 feet thick.

The lower hydrologic boundary in the local ground-water system probably is the mudstone unit underlying the Jackpile sandstone, as will be discussed later in the report. Recharge through fractures may occur in the otherwise almost impermeable rocks overlying the Jackpile aquifer. The recharge may occur locally in the mine area, as well as at higher altitudes where these rocks are buried beneath other sedimentary rocks and more permeable colluvial debris and pyroclastic deposits. Most recharge probably occurs at the higher altitudes north and west of the mine, where there is likely to be more precipitation and less evapotranspiration. Few data, however, are available regarding recharge in the Laguna area.

GROUND WATER

Underflow and Recharge

An estimate was made of the recharge rate in the Rio Paguate drainage basin by summing base flow and underflow and assuming that change in ground-water storage is negligible. Underflow may occur in the vicinity of the downstream Rio Paguate gaging station via the alluvium, Jackpile sandstone, and underlying rocks (bedrock other than Jackpile sandstone).

Alluvial underflow cannot be determined at the exact location of the gaging station because data are insufficient. Data are used from wells located near the confluence of the Rio Paguate and Rio Moquino for estimating underflow at the downstream station. An aquifer test at well M4C (described in a later section) indicated hydraulic conductivity (K) of the alluvium to be 23 feet per day. Saturated thickness (b) is about 20 feet and width (w) is about 1,000 feet. Hydro-Search, Inc. (written commun., 1979) determined the gradient of the stream to be about 0.02 at this location. The hydraulic gradient (I) is approximated by assuming it is equal to the gradient of the stream. Underflow is approximated as $Q = KIbw = 9{,}000$ cubic feet per day, which is equivalent to an annual flow of about 40 cubic feet per second-days. Annual base flow is 215 cubic feet per second-days (table 7). Base flow plus underflow through alluvium is, therefore, about 250 cubic feet per second-days annually.

Underflow through bedrock cannot be determined because data are insufficient. Saturated zones and hydraulic gradients are not known, and hydraulic conductivities of bedrock other than the Jackpile sandstone are not known. Positions of ground-water divides may not correspond to topographic divides, so interbasin flow may occur. For purposes of this report, it is assumed that neglecting underflow through bedrock does not introduce significant error in estimating the recharge rate in the Rio Paguate drainage basin. This assumption probably is reasonable because: (1) The mudstone strata underlying the Jackpile sandstone form the lower hydrologic boundary throughout much of the southeastern part of the basin; and (2) the top of the mudstone generally crops out northeastward across the basin in the vicinity of the Rio Paguate stream-gaging station (located near the south edge of the mine), so that much of the water in the Jackpile sandstone probably discharges to the alluvium or to streams upgradient from the station.

The recharge rate is estimated as the sum of base flow and underflow through alluvium, which is about 250 cubic feet per second-days (about 500 acre-feet) annually in the Rio Paguate drainage basin upgradient from the gaging station. This is equivalent to about 0.1 inch per year throughout the 107-square-mile drainage area. Rates probably are greater at higher altitudes on Mount Taylor and Mesa Chivato and may be less at lower altitudes. Recharge probably is greater in colluvium on the flanks of mesas and in alluvium at valley bottoms than it is on exposed bedrock.

Wells in the Jackpile Mine

Most wells in the Jackpile mine are open to one or the other of the two principal aquifers in the area, which are the alluvium and the Jackpile sandstone (figs. 5-8). None are completed solely in bedrock overlying the Jackpile sandstone. Well M25 near the North Paguate pit is completed in the mudstone unit of the Brushy Basin Member underlying the Jackpile sandstone. Wells M17 and M24 are drilled into mine waste rock.

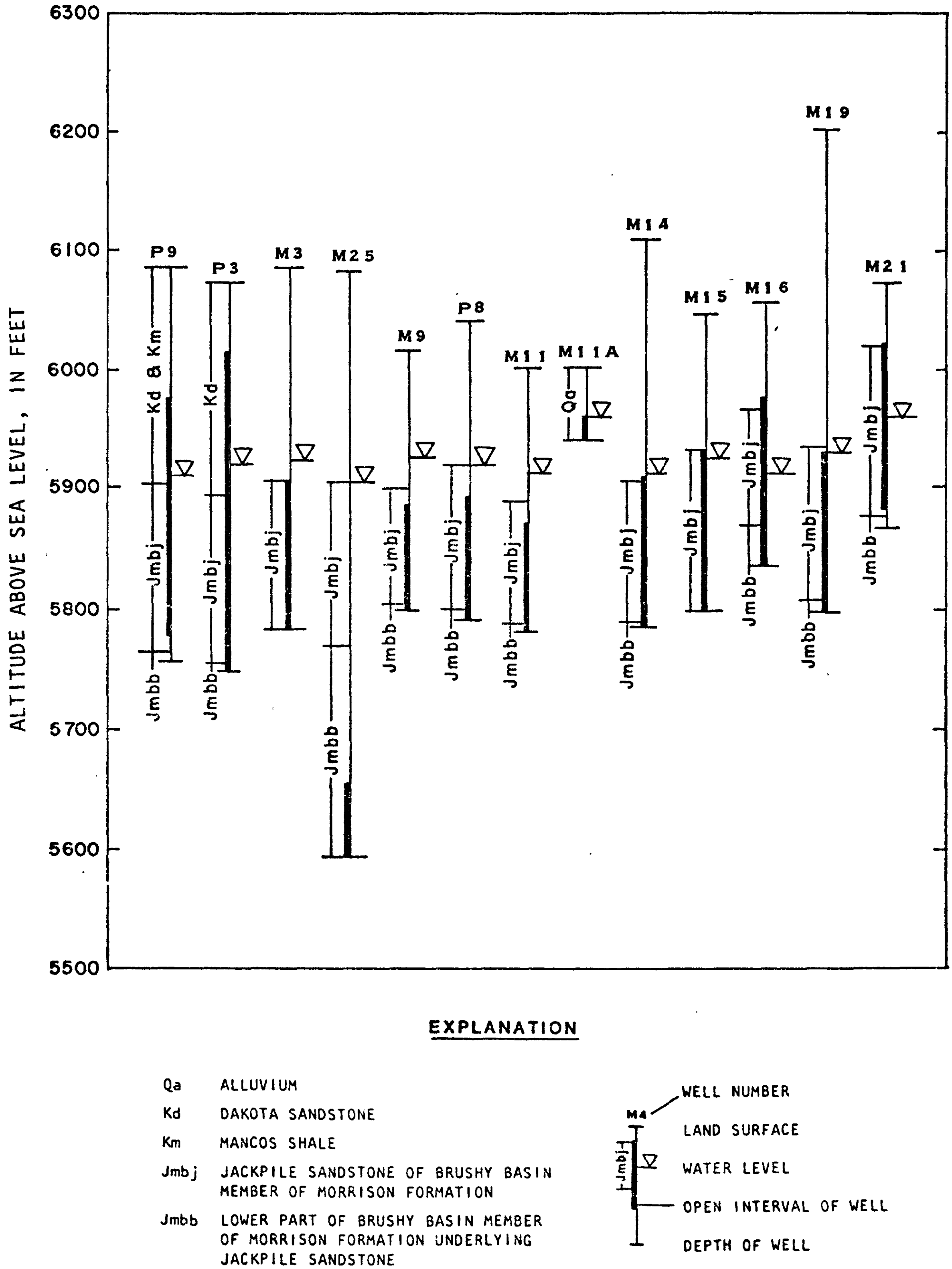
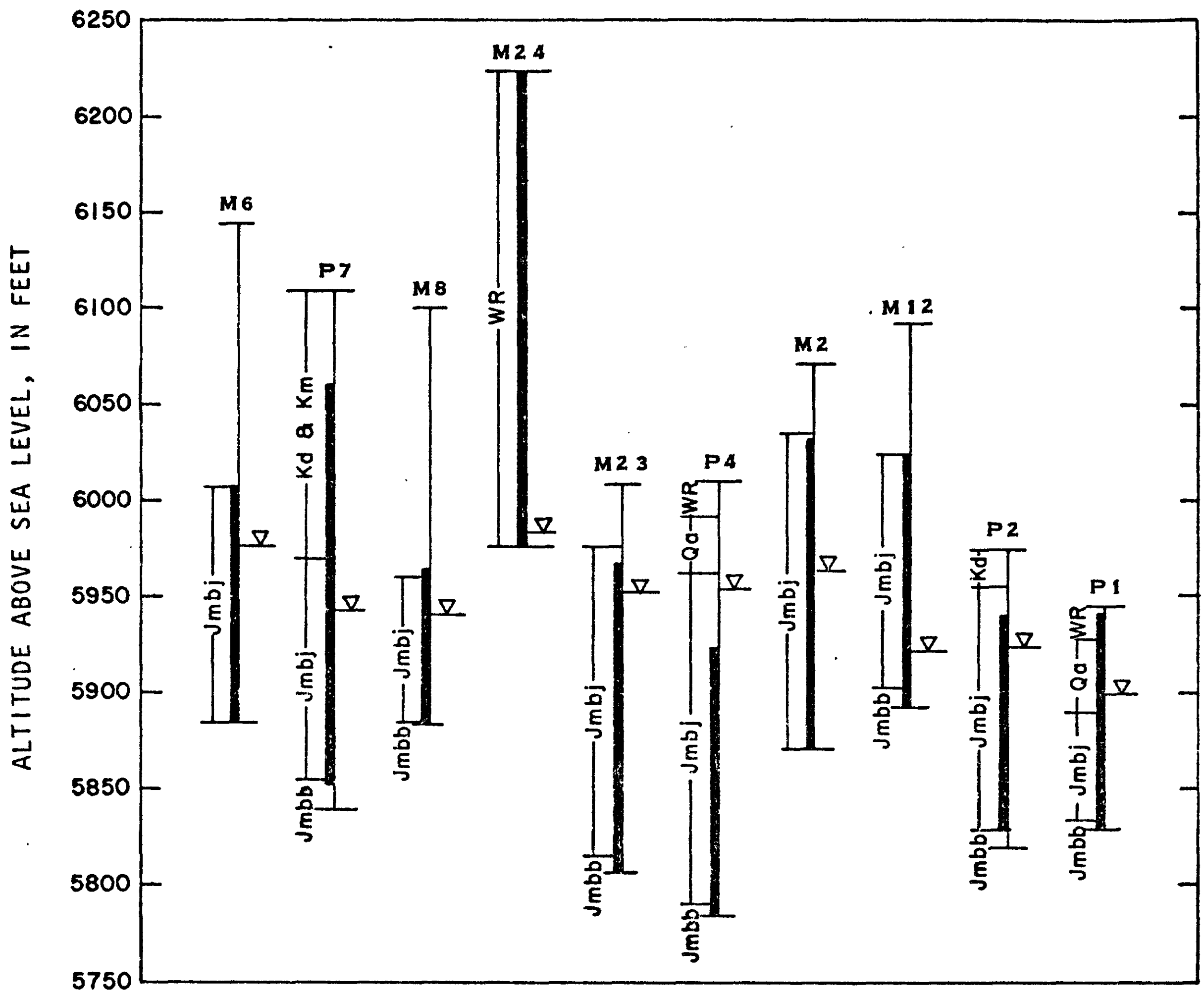


Figure 5.--Well construction and water levels in wells, northern part of the Jackpile mine area.



EXPLANATION

WR	WASTE ROCK
Qa	ALLUVIUM
Kd	DAKOTA SANDSTONE
Km	MANCOS SHALE
Jmbj	JACKPILE SANDSTONE OF BRUSHY BASIN MEMBER OF MORRISON FORMATION
Jmbb	LOWER PART OF BRUSHY BASIN MEMBER OF MORRISON FORMATION UNDERLYING JACKPILE SANDSTONE

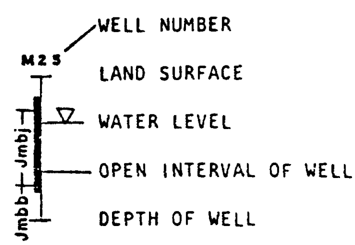


Figure 6.--Well construction and water levels in wells, west-central part of the Jackpile mine area.

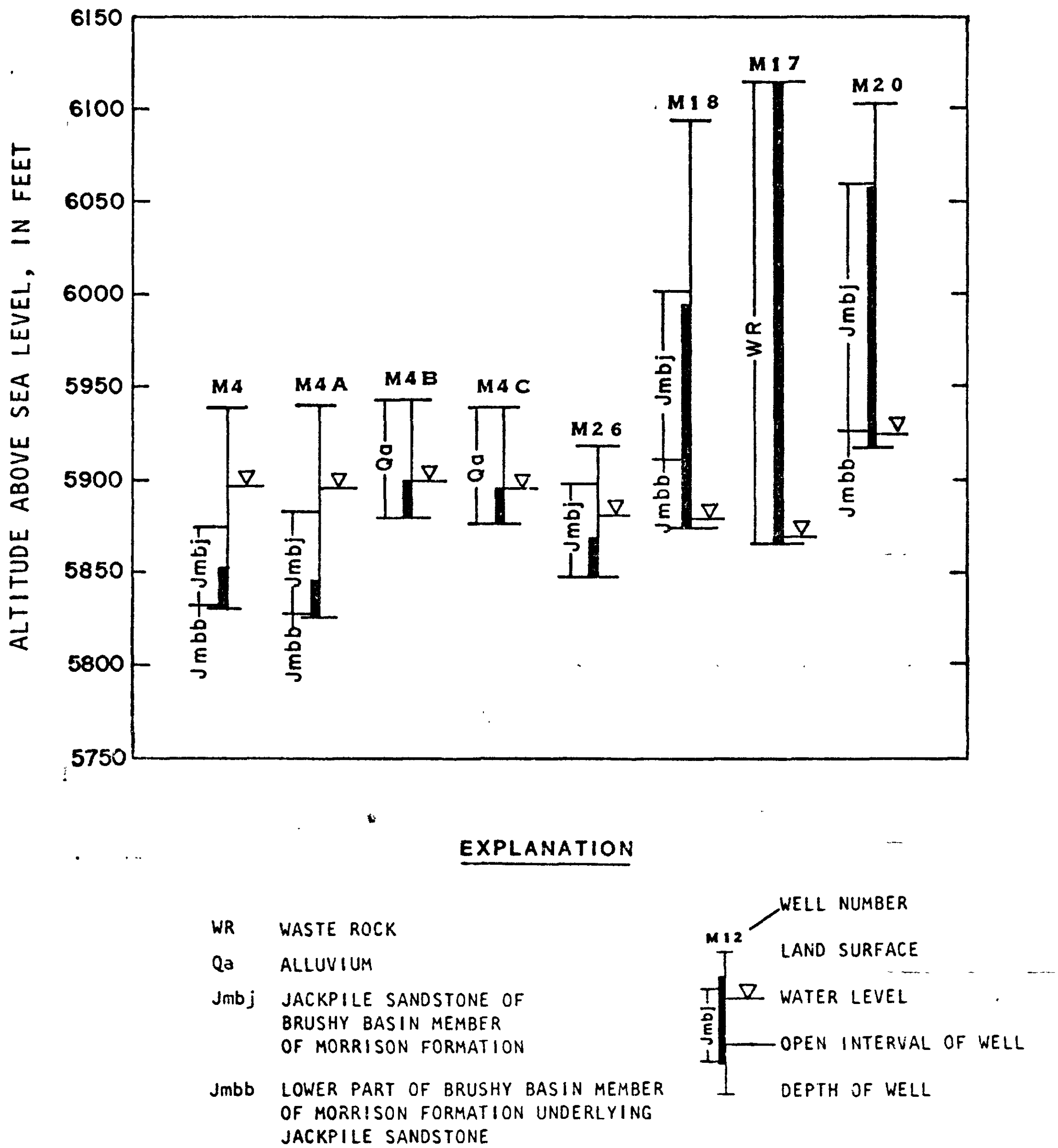
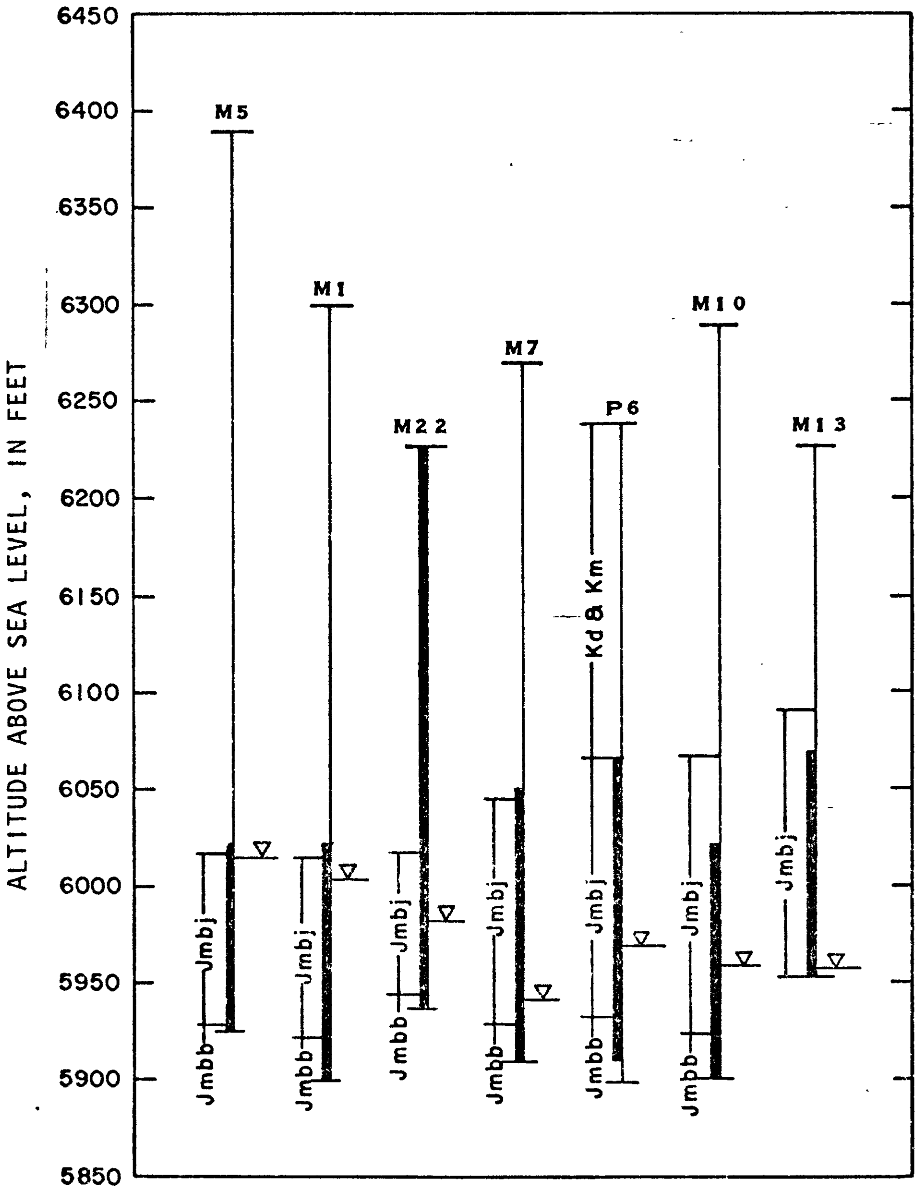


Figure 7.--Well construction and water levels in wells, east-central part of the Jackpile mine area.



EXPLANATION

Kd	DAKOTA SANDSTONE
Km	MANCOS SHALE
Jmbj	JACKPILE SANDSTONE OF BRUSHY BASIN MEMBER OF MORRISON FORMATION
Jmbb	LOWER PART OF BRUSHY BASIN MEMBER OF MORRISON FORMATION UNDERLYING JACKPILE SANDSTONE

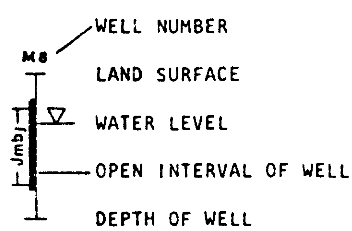


Figure 8.--Well construction and water levels in wells, southwestern part of the Jackpile mine area.

Wells were installed for two hydrologic studies at the Jackpile mine. The "P" series of 11 wells was constructed in 1977 by Hydro-Search, Inc., in order to examine water-quality effects of holding ponds on the ground-water system. The "M" series of 30 wells was constructed about 1980 by Hydro-Search, Inc., as part of a general hydrogeologic study. Locations are shown on plate 1 for wells completed in bedrock and waste rock. Seven observation wells also were constructed for aquifer tests at several of the M wells. Well M4C is an observation well drilled near well M4 (pl. 1).

The P-series wells have 2-inch-diameter PVC casing in the drillholes, which is slotted and gravel packed through the aquifers. Cement depths are not reported for P wells. Well P5 presently is inaccessible, and well P11 has been destroyed. The M-series wells have 5 9/16-inch-diameter steel casing, which is slotted and gravel packed through the aquifers. The wells were cemented from the tops of the gravel packs to ground surface, except for wells completed in waste rock and well M22 (Anaconda Copper Co., written commun., August 1981).

Diagrams showing well construction, formations penetrated, and positions of water levels are shown in figures 5-8. The diagrams show equal spacing between wells. They are intended to illustrate relative positions of strata contacts and water levels and should not be construed as geologic sections. Water levels were measured in June 1981.

Wells in the northern and east-central parts of the mine (figs. 5 and 7) generally have water levels above the top of the Jackpile sandstone, whereas wells in the west-central and southwestern parts of the mine area generally have water levels within this stratum (figs. 6 and 8). The dip of the rocks causes the Jackpile sandstone to be below land surface north and west of the mine. In these areas, it is completely saturated.

Potentiometric Surface and Directions of Ground-Water Flow

Regional ground-water flow in the Laguna Pueblo is southward toward the Rio San Jose and eastward toward the Rio Puerco (F. P. Lyford, U.S. Geological Survey, written commun., 1977). The emphasis of this report is on local flow, and descriptions are based primarily on a potentiometric-surface map of the Jackpile mine.

Water levels and well depths were measured in all wells reported as being open to the Jackpile sandstone, two wells completed in waste rock, and one well completed in the lower part of the Brushy Basin Member (table 14). Measurements were made with steel tape from June 10 through June 12, 1981. Accuracy is about ± 0.05 foot for most wells. It is about ± 0.2 foot for well M20, and about ± 3 feet for well P6. Water-level altitudes are given in tenths of a foot for P wells because only ground-surface altitudes at the wells are available. Altitude differences for previously measured water levels and those measured for the present study are shown in table 14.

The water levels represent composite hydraulic heads because the wells are open to many feet of saturated rocks. Wells open to the Jackpile sandstone only are used to indicate general directions of ground-water flow and general ground-water gradients in that stratum because most are open to the entire thickness of the stratum. A water level at altitude 5,960 feet was measured in well P11 (now destroyed) in March 1979, and this measurement also was used in constructing a potentiometric-surface map for the present report.

Well locations and the potentiometric surface for the Jackpile sandstone in June 1981 are shown on plate 1. Flow into the mine area primarily is from high areas on the flanks of Mount Taylor to the west and probably from Mesa Chivato to the north. Much of the flow from the west is intercepted by the North and South Paguate pits and by pumpage from the P10 underground mine.

Seepage faces are obvious on the walls of the North and South Paguate pits. The top of a seepage face was at altitude 5,948 feet on a waste-covered section of bedrock at the north side of the South Paguate pit, and a pond in the lowest part of the pit had a water-surface altitude of 5,927 feet (pl. 1). The altitudes were measured in June 1981. They were below water-level altitudes measured in nearby wells. Water-surface altitudes were not measured in other pits, but the lowermost pond in the North Paguate pit was observed to be below the top of seepage faces. Closed potentiometric contours were therefore drawn around all pits and indicate ground-water discharge into the pits. Water loss is by evaporation and use of pond water for dust suppression on roads.

The approximate position of the top of the Jackpile sandstone at the edge of the pits is shown on plate 1. Topographic contours could not be used because some high areas at pit edges are extensive piles of waste rock. Most cross sections drawn by Anaconda Copper Co. (written commun., 1980) show "edges of excavation," and these are shown on plate 1. The top of the Jackpile sandstone at the approximate pit edge is illustrated where the edges of excavation are not shown on the cross sections. Where neither of the boundaries were reported, the edge is not shown. Both the "edges of excavation" and the edge of the Jackpile sandstone are shown at the northeast end of the Jackpile pit because the top of the stratum underlies much of the excavated surface at this location. Few detailed cross sections are available for the North Paguate pit, so its boundaries are not shown.

The positions are approximate for the ground-water divides near the pits because there are few wells at pit edges. Potentiometric contours at pit edges are simplified. With extensive data-point control, many closely spaced contours would have to be drawn near seepage faces.

Table 14.--Water levels in wells at the Jackpile mine

[All values are in feet. All wells are open to the Jackpile sandstone except for those noted]

Well	Height of casing above ground level	Depth to water in June 1981 1/	Altitude of water level in June 1981	Difference from previous levels 2/	Depth of well 1/
M1	2.0	298.59	6003.61	- 3.01	403.1
M2	1.6	110.30	5962.61	+ 2.18	201.6
M3	1.7	162.68	5924.04	+ .22	302.7
M4	2.3	44.83	5896.77	+ .65	110.7
M5	2.8	378.52	6014.57	- 1.30	467.7
M6	2.2	170.21	5976.08	-18.66	261.8
M7	2.5	327.59	5940.96	- .05	360.1
M8	2.1	162.18	5940.29	- 3.05	217.8
M9	2.2	90.94	5926.98	- .29	219.9
M10	2.6	231.47	5959.33	.00	289.9
M11	2.5	90.93	5912.95	- .35	222.4
M12	2.4	173.74	5920.86	- .24	201.5
M13	2.5	270.37	5955.53	-	270.8
M14	2.5	199.13	5912.76	- 1.44	324.2
M15	2.3	123.12	5925.70	- 5.22	251.3
M16	2.1	147.47	5911.51	- .72	219.4
M17 3/	2.7	249.02	5867.86	-	254.1
M18	2.2	217.31	5878.95	-	219.3
M19	2.7	274.85	5930.21	+ .27	406.9
M20	2.5	180	5925.2	- .2	188.4
M21	2.4	114.43	5961.17	- .14	204.0
M22	2.8	244.77	5982.64	+ 1.04	290.7
M23	2.3	58.61	5951.52	- .93	202.9
M24 3/	3.0	244.40	5981.45	-	246.9
M25 4/	1.6	179.34	5906.06	-	-
M26	1.8	38.79	5881.11	- .26	67.1
P1	0.5	45.98	5897.9	- 1.8	86.2
P2	2.1	52.70	5923.1	+ 1.3	143.2
P3	0.5	151.93	5921.5	- 2.9	313.4
P4	1.6	57.08	5953.0	- 3.0	171.6
P6	1.4	270	5969	-23	-
P7	1.7	168.52	5942.5	-40.3	269.9
P8	0.7	122.19	5920.5	- 2.0	250.8
P9	2.4	177.33	5912.2	- 9.0	332.7

1/ Depth referenced to top of casing.
2/ Water levels measured in December 1980 (M wells) and March 1979 (P wells) subtracted from those measured in June 1981.
3/ Completed in backfill.
4/ Completed in Brushy Basin Member of the Morrison Formation below Jackpile sandstone.

Water-table surfaces could not be drawn inside pits due to lack of data. A pond in the South Paguate pit, with water-surface altitude measured at 5,976.3 feet (pl. 1) in June 1981, is higher than the pond in the deeper part of the pit and higher than water levels in some wells. The higher ponds probably are due to surface runoff and water from near-surface infiltration discharging into them. Infiltrating water from the higher ponds probably flows through backfill material toward the lower ponds.

Water-level differences shown in table 14 generally show lower hydraulic heads for the later measurements. Differences of about 2 to 3 feet probably are not significant. They may be due to different measuring techniques or seasonal changes. Significant hydraulic-head declines in wells M6 (18 feet), P7 (40 feet), and P6 (23 feet) probably result from discharge into the North and South Paguate pits. Hydraulic-head changes in well M1(-3 feet), M22(1 foot), and M7(-.05 foot) are small, indicating that pumpage from the P10 underground mine presently has less effect on hydraulic heads near wells M6, P7, and P6 than does discharge into the Paguate pits. Discharge into the North Paguate pit probably caused the hydraulic-head declines in wells P3 (3 feet), P9 (9 feet), and M8 (3 feet).

Well M25 is 50 feet from well M3 and is completed in a sandstone bed underlying a mudstone unit approximately 100 feet thick. The mudstone underlies the Jackpile sandstone in which well M3 is completed. The water level in well M3 was 17.1 feet higher than that in well M25 in August 1981, indicating potential for downward flow at this location. Well M25 penetrates about 180 feet more strata than well M3, indicating a gradient of about 0.1 in the vertical.

The local flow system probably is more complex than is shown on plate 1. Even though 33 wells are available for control in drawing potentiometric contours in the Jackpile sandstone, data are insufficient to show the following: effect of local topographic and mining features; gradients near streams, particularly the Rio Moquino and the downstream reach of the Rio Paguate; and flow in the northern, northwestern, and southeastern parts of the mine.

Potentiometric contours at Gavilan Mesa are highly interpretive, with only wells M19, M20, and M21 available for control. Because Gavilan Mesa is the highest area at the eastern part of the mine, contours were drawn as indicating local recharge through the extensively fractured rocks comprising Gavilan Mesa.

The gradients drawn around the northwest and west side of Gavilan Mesa are about 1 to 2 orders of magnitude greater than would be expected if a hydraulic conductivity of 0.3 foot per day were used for the Jackpile sandstone (explained in the following section), with a recharge-discharge rate of 0.1 inch per year. The water level in well M19 (fig. 5) shows nearly complete saturation of the sandstone at this location at an altitude of 5,930.2 feet. Contours from 5,930 to 5,960 feet on plate 1 represent saturation of the Dakota Sandstone on the mesa. Observations of outcrops showed the rocks to be tightly cemented; the most effective porosity apparently is due to fracturing. Hydraulic conductivity could be 2 orders of magnitude less than that in the Jackpile sandstone, thus producing gradients approximating those shown.

A well on Gavilan Mesa completed in the Jackpile sandstone would show whether or not the interpretation illustrated on plate I is correct. Wells at the same location, open only to fractures in the Dakota Sandstone and in the Mancos Shale, might show one or more water tables higher than that in the Jackpile sandstone. If so, local recharge might be expected in other areas of the mine, including waste dumps.

The ground-water divide indicated by the 5,970-foot potentiometric contours south and east of the South Paguate pit probably is either due to: (1) Nonequilibrium conditions resulting from withdrawal in the P10 underground mine and losses to the South Paguate pit, thus lowering a potentiometric surface that was higher when hydraulic heads were greater at the western part of the mine; or (2) equilibrium conditions that reflect local recharge. Similar explanations may be made for the ground-water divides indicated by the 5,920-foot contours east of the North Paguate pit, and perhaps some areas around the Jackpile pit. Nonequilibrium conditions are likely to prevail in some of the mine area, however, as indicated by the recent large changes in some ground-water levels described earlier in this section.

Well M17 is in a waste dump at the southwest end of the Jackpile pit (pl. I). The dump extends southward to a small mesa on which well M18 is located. Data are insufficient to determine whether flow in the vicinity of well M18 is toward the dump or toward the Rio Paguate. Potentiometric contours between wells M16 and M18 were, therefore, truncated.

Streams gain water near the center of the mine, as indicated by the potentiometric contours. Gains of about 20 gallons per minute were estimated near the confluence of the Rio Moquino and Rio Paguate, whereas losses were estimated in the Rio Paguate from the western edge of the mine to a point about 1,000 feet above its confluence with the Rio Moquino.

The potentiometric surface shown on plate I does not reflect losing areas, which would be expected to result in ground-water mounding along the stream. Contours could not be drawn with available data to reflect ground-water mounding without producing unreasonably large gradients. The stream channel was changed during mining in the vicinity of wells M23 and P4 and is now underlain by about 40 feet of waste rock. The waste probably is permeable enough so that there is little ground-water mounding.

In summary, normal ground-water flow has been changed in the Jackpile mine by pit excavations, pumpage from underground mines, and probably by streambed alteration. Natural variations in hydraulic conductivity are likely to also produce local changes in flow. Extensive well control would be needed to define the ground-water system accurately. In general, ground water enters the mine primarily from the west and north and flows mostly toward pits, the P10 underground mine, and the Rio Paguate and Rio Moquino. Flow in the southeastern part of the mine is not defined, but is probably toward the Rio Paguate or toward the southeast.

Aquifer Tests

Water-transmitting characteristics of aquifers were determined at five sites in the Jackpile mine. A submersible pump was installed in four wells, and constant-rate pumping continued until completion of tests. A fifth well (M25) was "slug tested," using a piston to increase the hydraulic head in the well. Hydraulic-head data were collected continuously at each site from both the pumped well and a nearby observation well. Pressure transducers were used, and readings were checked at various intervals by measurements with steel tape.

Strata and sites tested were the following: the alluvium at the confluence of the Rio Paguate and Rio Moquino; the Jackpile sandstone at the northwest, northeast, and southwest parts of the mine; and a sandstone bed in the predominately mudstone part of the Brushy Basin Member at the northwest part of the mine. Test data were analyzed as follows: well M2 by the nonequilibrium method with allowance for delayed yield from storage (Boulton, 1963); wells M4C and M3 by the curve-matching nonequilibrium method (Theis, 1935); well M21 by the nonequilibrium method with allowance for water stored in the finite-diameter well bore (Papadopulos and Cooper, 1967); and well M25 by the instantaneous-charge method (Cooper, Bredehoeft, and Papadopulos, 1967).

Description and results of the tests are given in table 15. Distances between discharge and observation wells were obtained from Hydro-Search, Inc., (written commun., 1981). Well locations are shown on plate 1. The hydraulic conductivity of the Jackpile sandstone throughout much of the mine probably is about 0.3 foot per day, as indicated by the tests at wells M2 and M3. Hydraulic conductivity of the alluvium is almost 2 orders of magnitude greater than the bedrock strata tested, probably because of larger interconnected pore size and lack of cementation between grains.

The hydraulic conductivity of 0.33 foot per day for the sandstone bed in the Brushy Basin Member at well M25 probably is much larger than that for the mudstone part of the member. Mudstone beds about 100 feet thick separate the sandstone bed from the overlying Jackpile sandstone (Hydro-Search, Inc., written commun., 1981). Maximum water-level change was 0.03 foot in well M25 when 61.6 feet of drawdown was produced in the Jackpile sandstone after 4 days of pumping at well M3. The wells are 50 feet apart. The small hydraulic-head change in well M25 may have been mostly due to a change in barometric pressure during the test. The predominantly mudstone part of the Brushy Basin Member, which underlies the alluvium and stream channels in the area, probably forms the lower hydrologic boundary in the mine, as indicated by the lack of hydraulic connection with the Jackpile sandstone.

The small storage coefficients for the Jackpile sandstone may indicate a confined system. However, water levels in wells M2 and M21 were below the top of the aquifer, so the Dakota Sandstone did not cause the confined conditions at the well sites. The Jackpile sandstone contains discontinuous strata of bentonitic mudstone, and clay content increases upward in the stratum (Moench and Schlee, 1967). The mudstone and clay cement probably cause locally confined conditions.

Table 15.--Summary of aquifer tests at five wells in the Jackpile mine

Well	M2	M3	M21	M4C	M25
Strata tested	Jackpile sandstone	Jackpile sandstone	Jackpile sandstone	Alluvium	Sandstone 1/
Distance, in feet, between discharge and observation wells	54	44	57	2/ 52	--
Date test began	8/19/81	8/24/81	8/18/81	8/22/81	8/19/81
Altitude of water level before test (feet)	5964.6	5924.5	5961.3	5897.4	5907.4
Maximum drawdown (feet)	37.0	61.6	36.7	1.9	--
Duration of test (hours)	43	88	24	17	2
Pumping rate (gallons per minute)	5.1	15.3	0.25	8.6	--
Saturated thickness (feet)	93	120	81	19	60
Transmissivity (feet squared per day)	24	47	2.0	430	20
Hydraulic conductivity (feet per day)	0.28	0.39	0.024	23	0.33
Storage coefficient X 10^4 (dimensionless)	1.9	2.9	0.20	19	1.0

1/ Sandstone bed in predominantly mudstone part of the Brushy Basin Member of the Morrison Formation.

2/ Observation well used was M4B.

Flow through Backfill and Waste Piles

Few data are available to accurately describe flow through backfill (in pits) and waste piles (located outside pits) because of the problems involved in well completion. Two wells, M17 and M24, were drilled into backfill, but difficulties in completing them prevented proper grouting of the annuli.

Well M17 was drilled into backfill at the southwest end of the Jackpile pit (pl. 1). The water-surface altitude was 5,968 ± 1 feet at a pond about 500 feet north of the well in August 1981. This was within 1 foot of the water level in the well. The greater hydraulic head at these sites was not determined because of the large error range in pond-surface altitude. Water may be flowing through backfill northward toward the pond or from the pond toward lower areas to the west or south.

Well M24 is located at the north end of the South Paguate pit (pl. 1) and had a water-level altitude of 5,981 feet in June 1981. The water-level altitude is higher than that of the water surface in the lowermost pond in the pit and higher than hydraulic heads in the Jackpile sandstone near the well. Well M24 was drilled through backfill into what was formerly a holding pond for water pumped from mine workings. The water level may represent ground-water mounding (or perched water) due to the holding pond, local recharge to the backfill, or surface flow down the well annulus.

Flow from the Rio Paguate to well M24 is not likely because the water table in the alluvium was at an altitude of 5,970 feet in March 1979 (Hydro-Search, Inc., written commun., 1979) at a point about 1,500 feet downstream from wells M23 and P4. Discharge from the backfill at well M24 probably is toward the South Paguate pit, toward the Rio Paguate, or both. A hydraulic conductivity of 190 feet per day was reported for backfill at well M24 by Hydro-Search, Inc. (written commun., 1981).

No wells are completed in waste piles, so it is not known if the piles are unsaturated, periodically saturated, or constantly saturated. Runoff was observed flowing into small cavities atop two waste piles during intense rainfall, indicating much of the recharge probably is through very permeable vertical channels below surface depressions rather than uniform infiltration over the surface of the piles. No seepage faces were observed at the bases of the piles during dry weather because saturation may be limited and of short duration or flow may be downward through the bases of the piles to the underlying bedrock or alluvium. The waste piles may have large enough hydraulic conductivity so that infiltrating water is discharged rapidly, preventing long-term saturation.

WATER BALANCE

A water balance is useful for estimating evapotranspiration in the Rio Paguate drainage basin. A general form of the water-balance equation may be written as:

$$P = R + \Delta GW + U + ET$$

where:

P is precipitation;
R is runoff;
ΔGW is change in ground-water storage;
U is underflow; and
ET is evapotranspiration.

The change in ground-water storage is assumed to be negligible on an annual basis. Total underflow is about equal to underflow through alluvium, as described previously. Therefore, the underflow is about 40 cubic feet per second-days annually, which is equivalent to about 0.01 inch per year over the 107-square-mile drainage area upstream from the gaging station near the southern boundary of the mine area. The underflow was added to runoff and the sum subtracted from precipitation to estimate evapotranspiration for water years 1977 through 1980 (table 16). Water losses by evapotranspiration are very large, constituting about 98 percent of precipitation.

Table 16.--Water balance for the Rio Paguate drainage basin upstream from the gaging station at the southern boundary of the Jackpile mine

[Values are in inches, except numbers in parentheses are percent of precipitation]

Water year	Precipitation	Runoff plus underflow	Evapo-transpiration
1977	8.38	0.197	8.2 (98)
1978	7.90	.147	7.7 (97)
1979	11.60	.179	11.4 (98)
1980	9.85	.120	9.7 (98)
Mean	9.43	.161	9.2 (98)

WATER QUALITY

This description of water-quality conditions within and in the vicinity of the Jackpile uranium mine is based on a review of chemical analyses performed on water samples collected by Anaconda Copper Co., the U.S. Bureau of Indian Affairs, and the U.S. Geological Survey. The surface-water and ground-water sampling sites are shown in figure 9.

More than 500 samples were collected by Anaconda Mining Co. for analyses of major dissolved constituents at several surface sites from 1962 to 1981. Surface-water samples were collected on the Rio Paguate and the Rio Moquino at the following locations: (1) on each stream upstream from the mine area, (2) on each stream just inside the mine area's upstream boundary, (3) on each stream within the mine area just upstream from the confluence, (4) on the Rio Paguate within the mine area but downstream from the mouth of the Rio Moquino, and (5) at Paguate Reservoir about 5 miles downstream and outside the mine area. A few additional surface-water samples were collected from miscellaneous locations in the vicinity of the mine, including pools within the mine pits.

Ground-water samples selected for this description were collected by Anaconda Copper Co. periodically from water-supply wells within the mine area from 1976 to 1981 and also from each of the 11 P-series test wells during 1977 and 1978. The P-series wells were installed in 1977 as water-quality sampling wells to study ground-water interactions with the holding ponds.

About 150 water analyses performed by the Bureau of Indian Affairs and about 20 selected samples from the files of the Geological Survey were reviewed and used collectively with Anaconda Copper Co.'s data for this study. The water analyses of the Bureau of Indian Affairs and Geological Survey were performed mainly on water samples collected from outside the mining area. Because of the large number of analyses and the small ranges of chemical concentrations found at each site, it was possible to judge and to select typical samples to represent the water-quality conditions at the different sites for the period sampled. No obvious trends were detected after examining the data, so the typical samples represent prevailing conditions.

Chemical analyses of water samples collected within the mined area before the mining began in 1953 were not found in the data search, so the water-quality conditions described are for the mining period between 1962 and 1980.

Dissolved Solids and Dominant Ions

Stiff diagrams (Stiff, 1951) were used to compare the differences in major dissolved-ion concentrations among the selected sampling sites shown in figure 9. The Stiff diagrams are not included in this report but are available in the files of the U.S. Geological Survey in Albuquerque, New Mexico.

An arithmetic average of the specific conductances measured during the sampling period at each site was used as a guide to select chemical analyses to represent the water at each site. The analyses selected had specific-conductance values similar to these averages and were assumed to approximate the average concentrations of the chemical constituents that would be computed for the sites for the periods the sites were sampled. The Stiff diagrams were constructed using the ionic concentrations of these selected analyses.

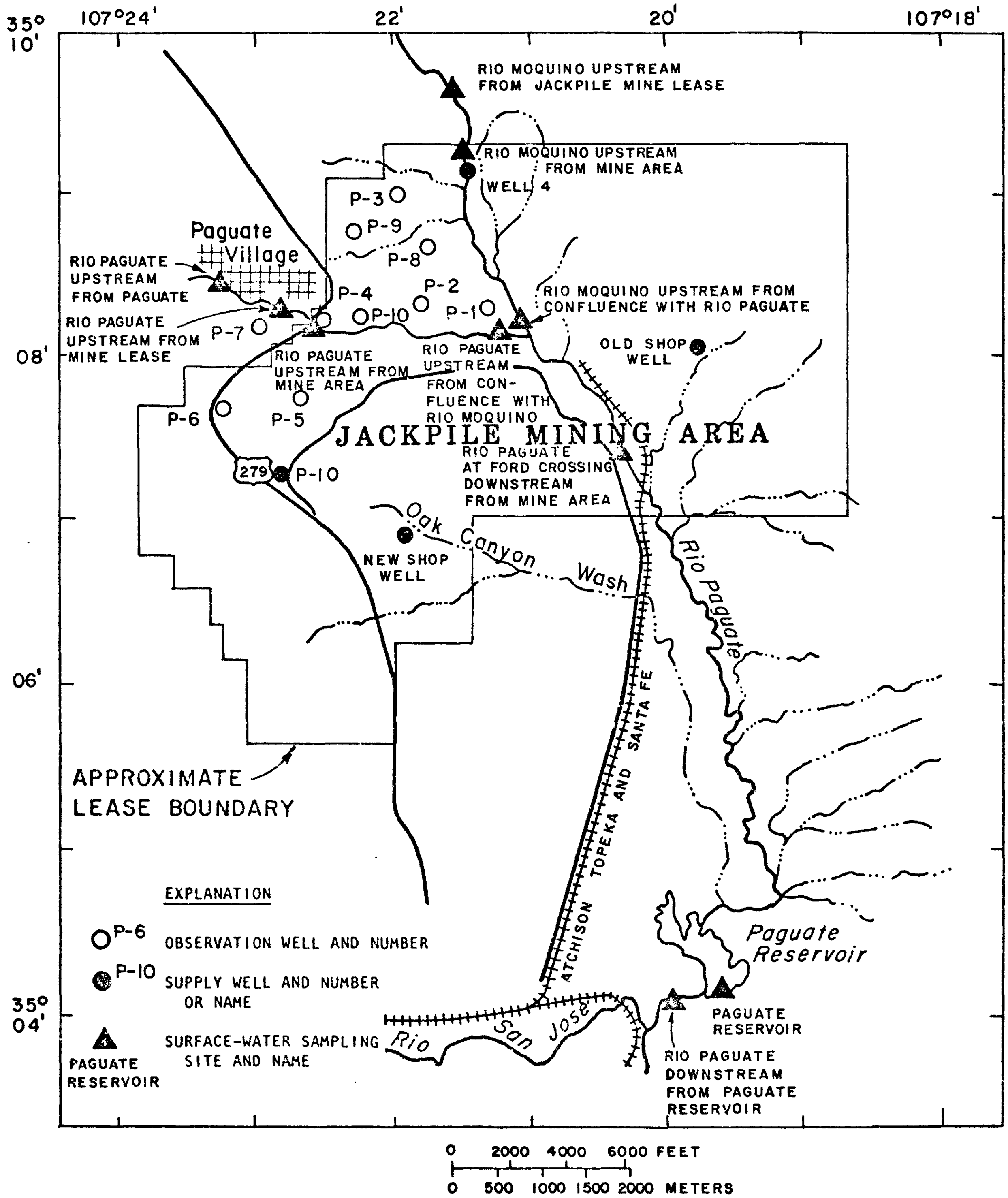


Figure 9.--Location of wells and selected water-quality sampling sites, Jackpile mine area and vicinity.

The average specific conductance for each of the sampling sites and the collection dates of single samples that are representative of the typical water-quality condition at each site are given in table 17.

Table 17.--Average specific conductance in water at each sampling site, Jackpile mine area and vicinity

Sampling site (fig. 9)	Average specific conductance (microsiemens per centimeter at 25°Celsius)	Analysis selected (month-day-year)
Rio Paguate upstream from Paguate	344	10-30-78
Rio Paguate upstream from Jackpile mine lease	708	03-03-80
Rio Paguate upstream from mine area	788	10-02-80
Rio Paguate upstream from confluence with Rio Moquino	1,040	11-06-79
Rio Paguate at ford crossing downstream from mine area	2,240	02-24-71
Paguate Reservoir	2,190	11-11-75
Rio Paguate downstream from Paguate Reservoir	2,310	01-10-78
Rio Moquino upstream from Jackpile mine lease	2,010	05-21-79
Rio Moquino upstream from mine area	1,870	05-19-71
Rio Moquino upstream from confluence with Rio Paguate	2,460	11-06-79
Well 4	1,266	05-19-71
New shop well	2,014	12-04-80
Old shop well	2,183	06-03-80

The streamflow in the Rio Paguate upstream from the Rio Moquino contains concentrations of dissolved solids that average from less than 575 mg/L (milligrams per liter) upstream from the community of Paguate to about 700 mg/L upstream from the confluence with its main tributary, the Rio Moquino (table 18). The dominant ions are calcium and bicarbonate, indicating dissolution of calcareous minerals in the streamflow. The Stiff-diagram analysis shows a gradual increase in the downstream direction of calcium, magnesium, bicarbonate, and sulfate, which indicates dissolution of gypsum and dolomite minerals.

Table 18.--Mean concentrations of dissolved solids in water from the Jackpile mine area and vicinity

Sampling site	Dissolved solids (milligrams per liter)
Rio Paguate upstream from mine area	less than 575
Rio Paguate upstream from the confluence with Rio Moquino	700
Rio Moquino upstream from mine area	1,600
Rio Moquino upstream from confluence with Rio Paguate	1,900
Rio Paguate at ford crossing downstream from mine area	2,000
Paguate Reservoir	2,000
Well 4	900
New shop well	1,400
Old shop well	1,500

The streamflow in the Rio Moquino contains greater concentrations of dissolved solids than does the Rio Paguate. The mean dissolved-solids concentrations in the Rio Moquino range from 1,600 mg/L upstream from the mine area to 1,900 mg/L just upstream from its confluence with the Rio Paguate.

The flow in the Rio Moquino contains calcium, magnesium, and sodium concentrations in nearly equal proportions and sulfate concentrations that are greater than bicarbonate or chloride concentrations. A mixture of weathered shale and sandstone is the probable source of these ions. These water-quality characteristics prevail in the Rio Paguate downstream from the mouth of the Rio Moquino. The average dissolved-solids concentration increases to about 2,000 mg/L in the downstream reach of the Rio Paguate.

On the basis of the concentrations of dissolved solids, flow in the upstream reach of the Rio Paguate is considered to be fresh, whereas the flow in the Rio Moquino and the downstream reach of the Rio Paguate is considered to be slightly saline according to the U.S. Geological Survey's salinity classification (table 23 at back of report).

The degree of salinity in these two streams generally is acceptable for the local irrigation, livestock, and domestic uses according to criteria set by the U.S. Environmental Protection Agency (1972, 1977b). The sulfate concentrations exceed the recommended criterion of 250 mg/L (U.S. Environmental Protection Agency, 1972, 1977b) for drinking-water supplies in the Rio Moquino and in the downstream reach of the Rio Paguate; however, this criterion is set to prevent undesirable odors or taste and to prevent temporary laxative effects on humans.

The Stiff-diagram analysis for ground water from well 4 and wells P3 through P8 indicates one pattern in which the concentrations of sodium, bicarbonate, and sulfate predominate. This may indicate that the ground water was in contact with clay and shale. The Stiff diagrams for the ground water from the New shop well, the Old shop well and wells P9 and P10 indicate another pattern in which the proportions of sodium and sulfate are much greater than those proportions in water from the first group of wells. This may indicate that the ground water may be associated with more oxidized clay and shale. The Stiff-diagram patterns for wells P1, P2, and P10 indicate greater proportions of calcium and magnesium. This may indicate the presence of gypsiferous or dolomitic minerals in the water-bearing zones in which these wells are completed.

This entire group of wells produces waters with dissolved-solids concentrations between 900 and 1,500 mg/L (table 18). The water is either fresh or slightly saline and is considered acceptable for the local customary irrigation, livestock, and domestic uses.

The slightly saline water in the Rio Moquino and downstream reach of the Rio Paguate, as compared to areas of greater rainfall, is less saline than the water found in certain other streams within a 60-mile radius of the mine. Water-quality data have been collected downstream from the Rio Puerco near Bernardo for 34 years, and the data show that the water at this station is usually more saline than the water in the Rio Moquino and the downstream reach of the Rio Paguate, but still only slightly saline. The Rio Paguate joins the Rio San Jose 5 miles downstream from the Jackpile mining lease, and the Rio San Jose flows into the Rio Puerco about 25 miles southeast of the mouth of the Rio Paguate. The Rio Puerco ultimately flows into the Rio Grande near Bernardo.

Specific-conductance hydrographs were made for four Rio Paguate sampling sites and for three Rio Moquino sampling sites. The hydrographs are not included in this report but are available in the files of the U.S. Geological Survey. The specific conductances were determined in samples collected monthly or less frequently. These hydrographs do not indicate any consistent increasing or decreasing trends for the short periods covered between 1971 and 1980. The fluctuations in specific conductance at each of these sites can be attributed to dilution of the dissolved-solids concentration by large volumes of snowmelt or rainstorm runoff, concentration of dissolved solids by evaporation during periods of low flow, or the flushing of soluble salts into the streamflow during initial storm runoff. It cannot be determined from these graphs that mine-wastewater discharges contributed to these fluctuations.

Specific-conductance hydrographs also were made for samples collected from production wells at the Jackpile mine. The fluctuating specific-conductance measurements may not be necessarily representative of the formation water because of insufficient pumpage to purge the well of water that was standing in the well bore. The fluctuations in the hydrographs are caused by specific-conductance differences generally of about 500 microsiemens per centimeter at 25° Celsius or less. These production-well hydrographs indicate a slight increasing trend for specific conductances beginning in 1978.

Radiochemicals

The mean concentrations of dissolved uranium and dissolved radium-226 in water supplies from the Jackpile mine area and vicinity are listed in table 19. These are arithmetic-mean concentrations at selected surface-water and ground-water sampling sites. Estimated values or values less than analytical detection limits were not used to determine these mean concentrations.

All of the mean concentrations in table 19 are less than the maximum permissible concentration of 5 mg/L for uranium listed in the New Mexico State Ground Water Regulations (New Mexico Water Quality Control Commission, 1982) and of 5 pCi/L (picocuries per liter) for radium-226 listed by the U.S. Environmental Protection Agency (1981). All individual uranium concentrations were less than the permissible limit of 5 mg/L. Although mean concentrations of radium-226 were less than the 5-pCi/L limit, many individual radium-226 concentrations exceeded this limit in the Rio Paguate near the mouth of the Rio Moquino and in the downstream reach of the Rio Paguate. A slight increase in streamflow in this reach is attributed to ground-water seepage, which may be the source of the greater uranium and radium-226 concentrations. The uranium can be expected to remain in solution in oxygen-saturated water, whereas most of the radium-226 will be adsorbed on suspended sediments or the sediments of the channel's bank or bottom because of the alkalinity in the streamflow.

Table 19.--Mean concentrations of uranium and radium-226 in water from the Jackpile mine area and vicinity

Sampling site (fig. 9)	Uranium (milligrams per liter)	Radium-226 (picocuries per liter)
Rio Paguate upstream from mine area	0.008	0.36
Rio Paguate upstream from confluence with Rio Moquino	.160	3.89
Rio Moquino upstream from mine area	.007	.34
Rio Moquino upstream from confluence with Rio Paguate	.051	1.73
Rio Paguate at ford crossing downstream from mine area	.266	4.31
Paguate Reservoir	.210	1.18
Well 4	.005	.54
New shop well	.008	2.19
Old shop well	.112	2.13
Well P10	.0036	.82

The mean concentrations for uranium and radium-226 in water from the wells listed in table 19 also are less than the maximum permissible concentrations; however, the larger concentrations found in the shop wells indicate that the ground water withdrawn from these wells may have flowed from a disturbed orebody or a mined-out area. The use of water from any of the stream sites or wells with the greater uranium or radium-226 concentrations for drinking or other consumptive uses needs to be discouraged. Although mean concentrations in water from these wells are less than maximum permissible limits, they are several orders of magnitude greater than the concentrations found in most natural waters. The concentration of uranium in most natural waters usually is less than 0.01 mg/L, and the concentration of radium-226 usually is less than 0.10 pCi/L. Two other measurements that indicate radiochemicals in solution, gross-alpha and gross-beta radioactivity, had the same concentration patterns in water from the Jackpile mine area and vicinity as described for uranium and radium-226. Uranium isotopes, uranium-238 and uranium-234, and radium-226 account for most of this radioactivity; the radioactive decay products of natural uranium such as thorium-230, lead-210, and radon-222 contribute to the remainder of this radioactivity. Thorium-230 has chemical characteristics similar to those of uranium and would be expected to remain in solution in streamflow, whereas lead-210, like radium-226, is not as soluble. Radon is a gas and would readily escape from solution in an open atmosphere. Radioactive decay of radium-226 produces radon-222 gas, which is almost 100 times more radioactive than an equal weight of radium-226.

Trace Elements

Trace-element data collected from the Jackpile mine area are very limited. Total recoverable concentrations of 18 trace elements in a sample collected on January 24, 1977, from the Rio Paguate at the southern boundary Jackpile mine area are shown in table 20. Trace-element concentrations in water samples from this site may represent cumulative effects of the Jackpile mine area on water quality in the Rio Paguate and Rio Moquino. Also listed in table 20 are the National Primary Drinking Water Regulations limits for trace elements (U.S. Environmental Protection Agency, 1977a) considered to be health risks in water supplies. The other list of trace-element concentration limits in table 20 are those in the New Mexico State Ground Water Regulations (New Mexico Water Quality Control Commission, 1982), which were developed to prevent contamination of ground-water supplies.

Table 20.--Trace-element concentrations in the Rio Paguate at the southern boundary of Jackpile mine

[Concentrations are in micrograms per liter unless otherwise indicated]

Trace element	Total recoverable concentration	Federal limit[1/]	State limit[2/]
Arsenic (As)	5	50	100
Barium (Ba)	100	1,000	1,000
Cadmium (Cd)	10	10	10
Chromium (Cr)	0	50	50
Fluoride (F), milligrams per liter	.6	[3/]1.8	1.6
Lead (Pb)	100	50	50
Mercury (Hg)	.0	2.0	2
Selenium (Se)	8	10	50
Silver (Ag)	10	50	50
Boron (B)	120	--	750
Cobalt (Co)	50	--	50
Copper (Cu)	10	--	1,000
Iron (Fe)	7,500	--	1,000
Manganese (Mn)	180	--	200
Molybdenum (Mo)	2	--	1,000
Vanadium (V)	.3	--	--
Radium (Ra), picocuries per liter	1.7	5.0	30
Uranium (U), milligrams per liter	0.072	--	5

1/National Primary Drinking Water Regulations (U.S. Environmental Protection Agency, 1977a)

2/New Mexico State Ground Water Regulations (New Mexico Water Quality Control Commission, 1982)

3/For annual average maximum air temperature between 63.9° and 70.6° Fahrenheit

HYDROLOGIC CONDITIONS AFTER RECLAMATION

Part of the pit backfill will saturate after reclamation. Saturation eventually will result from the cessation of pit-water use for road conditioning, a decrease in evaporation of pit water, a possible increase in discharge from bedrock to backfill, and a possible increase in local recharge to the permeable backfill. The water will discharge to streams and to adjacent strata. The water in backfill at the North and South Paguate pits will discharge primarily to the Rio Paguate because only permeable waste rock separates the pits from the stream. Discharge from the Jackpile pit will be to the Jackpile sandstone because the backfill is enclosed by this stratum. Hydraulic heads in the Jackpile sandstone will increase due to saturation of backfill and the end of pumping from underground mines. Pit backfilling is necessary in order to decrease radon formation from the part of the Jackpile sandstone exposed by mining.

Waste piles, which are located primarily on undisturbed areas outside of the pits, are different hydrologically from backfill because the waste piles receive only local recharge. Discharge from the piles may be along the ground surface or into underlying alluvium or bedrock.

Flow through both backfill and waste piles is considered particularly important because: (1) Water flowing through waste rock may contain increased concentrations of dissolved materials due to increased surface area exposed on the rock as the result of mining and due to increased solubility of minerals in the rock as a result of their oxidation; (2) if ponding in the backfill persists, animals using the ponds could injest abnormally large quantities of dissolved materials; and (3) increased concentrations of dissolved materials could enter aquifers and streams.

Flow through Backfill

The Rio Paguate gains water from the alluvium both upstream and downstream from the Paguate pits. A well used for public supply at Paguate village is completed in alluvium of the Rio Paguate and occasionally flows (F. P. Lyford, U.S. Geological Survey, written commun., 1977), indicating discharge to the stream upstream from the mine. Gains in streamflow downstream from the Paguate pits and losses between the pits are described by Hydro-Search, Inc. (written commun., 1979). The present (1980) loss of stream water between the two pits probably is due to infiltration into the permeable backfill underlying the stream. It is, therefore, reasonable to assume that prior to mining, the Rio Paguate was a gaining stream along its length from Paguate village at least to its confluence with the Rio Moquino.

Ground-water levels will approach (or will be similar to) premining levels after reclamation. The downstream part of the backfill underlying the Rio Paguate probably will saturate to stream level. The stream would then be the direct hydraulic control for discharge from backfill in the Paguate pits. Discharge from backfill in the Jackpile pit would be through the Jackpile sandstone, and most of the water probably will enter the alluvium and the Rio Paguate west, and possibly south, of the pit. The level of the Rio Paguate would be the ultimate hydraulic control for water levels in backfill at the Jackpile pit.

Diagrammatic hydrologic models are shown for the South Paguate pit (fig. 10) and the Jackpile pit (fig. 11). Flow through the North Paguate pit would be similar to that for the South Paguate pit except that discharge toward the stream would be southward. The generalized section through the South Paguate pit is from the southernmost edge of the pit (southeast of well P6) to the Rio Paguate upstream from well P4. The generalized section through the Jackpile pit is from the west edge of Gavilan Mesa through well site M18 to the Rio Paguate.

Positions for the water table, level of proposed backfill, and, particularly, the bedrock surface beneath backfill are approximate in figures 10 and 11. Mean thickness of backfill beneath the Rio Paguate is assumed to be about 30 feet. Cross section 12 prepared by the Anaconda Copper Co. (written commun., 1982) shows backfill under the stream to be 40 feet deep. Well site P4 is underlain by 16 feet of fill (Hydro-Search, Inc., written commun., 1979). The contact of the Jackpile sandstone and the underlying mudstone unit of the Brushy Basin Member is at ground level west of the Jackpile pit near the Rio Paguate. The Jackpile sandstone has been removed by erosion near the south end of the Jackpile pit.

Infiltration of backfill will be from runoff, direct precipitation, and discharge from bedrock, particularly the Jackpile sandstone. Discharge will be to the Rio Paguate at the Paguate pits; discharge will be to the Jackpile sandstone, alluvium, and the Rio Paguate at the Jackpile pit. Discharge at the south end of the Jackpile pit also could be through the mudstone unit of the Brushy Basin Member.

Ponding probably will result if backfill in the Paguate pits is below the level of the Rio Paguate adjacent to the pits. Evapotranspiration may be sufficient to prevent long-term ponding if the level of backfill is at stream level, but occasional ponding could occur during periods of minimal evapotranspiration or intense rainfall. Little or no ponding will occur if the backfill is several feet above stream level. The altitude of the stream is about 6,010 feet at the upstream end of the backfill and at about 5,975 feet at the downstream end of the backfill. The height of the water table in backfill will be determined by recharge to the pits and discharge to the Rio Paguate.

Assuming inflow is equal to outflow at the Paguate pits, the general equation for recharge-discharge may be written as:

$$K_j I_j A_j + P = K_b I_b A_b + ET,$$

where:

K is hydraulic conductivity;
I is hydraulic gradient;
A is cross-sectional area perpendicular to flow;
P is water added to the pit by direct precipitation and runoff;
ET is evapotranspiration; and

subscripts "j" refer to the Jackpile sandstone, subscripts "b" refer to the backfill; A linear approximation of the height of the water table is described by the product $I_b D$ for given distances D upgradient from the stream.

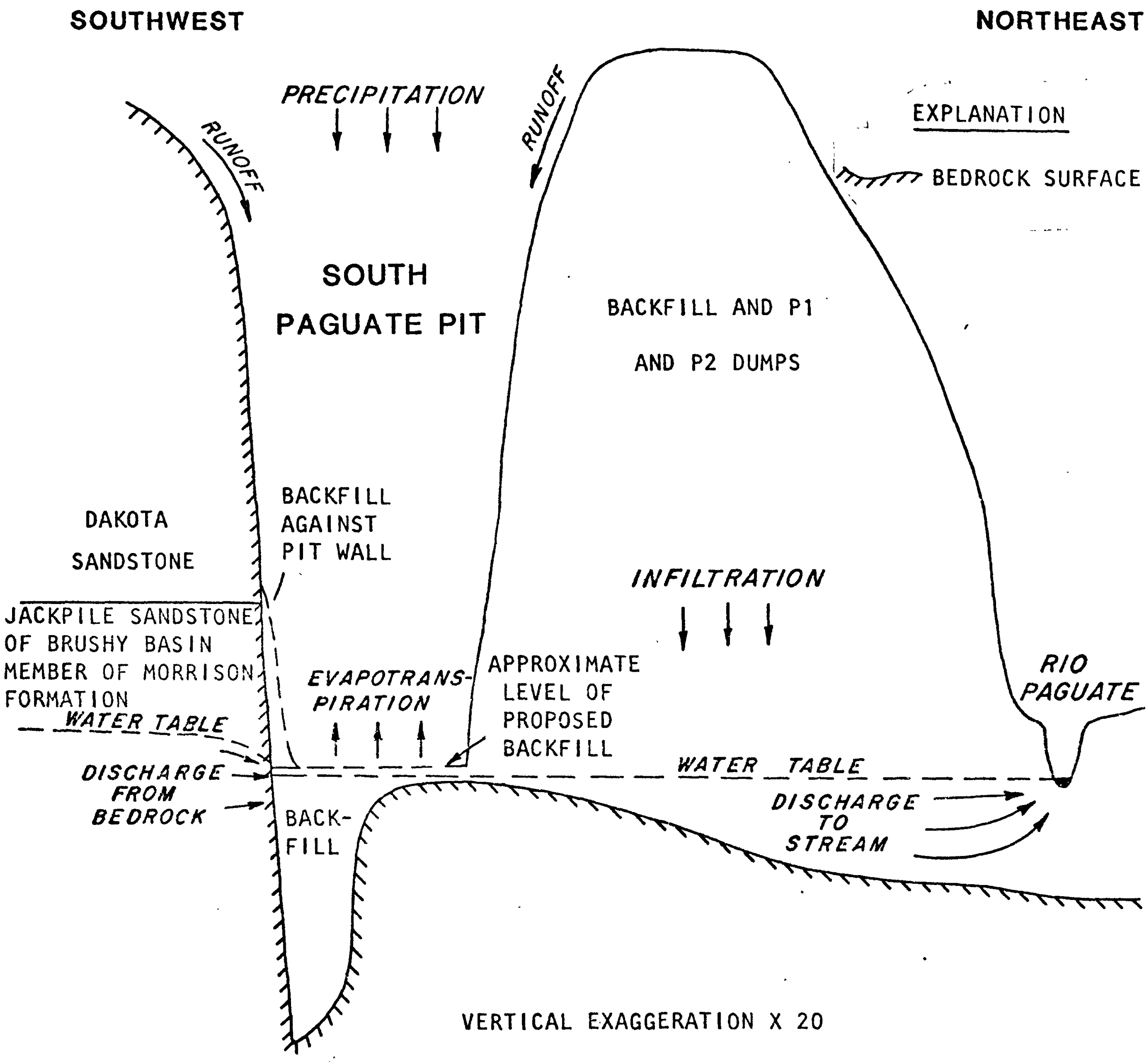


Figure 10.--Diagrammatic hydrologic model of the South Paguate pit.

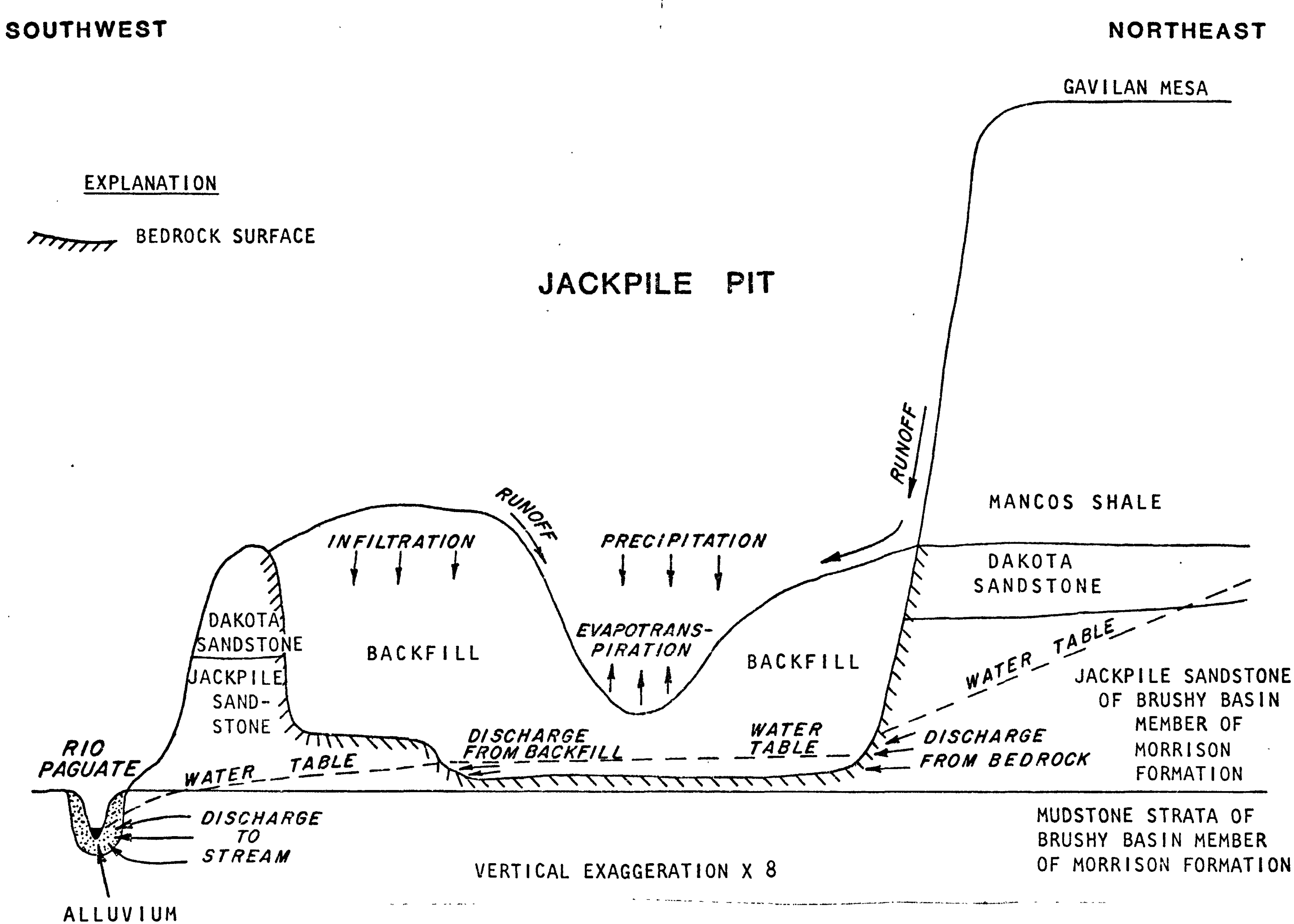


Figure 11.--Diagrammatic hydrologic model of the Jackpile pit.

Values for most factors in the equation above are known or can be reasonably estimated. Little data, however, are available regarding ET. The average ET for the entire Rio Paguate drainage basin may be about 98 percent of precipitation, as described in a previous section. This percentage could be quite different locally, particularly where direct precipitation and runoff from steep pit walls may quickly infiltrate permeable backfill.

The position of the water table in backfill at the Jackpile pit will be controlled by factors described for the Paguate pits, and also by discharge through the Jackpile sandstone, the alluvium, and possibly the mudstone unit in the Brushy Basin Member. Flow may be across at least four boundaries compared to two in the Paguate pits. After reclamation, ground-water levels in backfill will tend to reach equilibrium between hydraulic heads in rocks underlying Gavilan Mesa and the levels of the streams adjacent to the pit. The Rio Moquino is at an altitude of about 5,925 feet west of the Jackpile pit, and the Rio Paguate is at an altitude of about 5,850 feet near the southwest end of the pit.

Flow through Waste Piles

The unnamed valley on the east side of Gavilan Mesa is dry except for short periods after intense rainfall. At least the upper part of the alluvium is, therefore, unsaturated. The waste piles blocking the valley probably also are dry much of the time because no discharge is visible at their downstream end. Water infiltrates the alluvium and waste rock, partly because of occasional ponding at the faces of the piles.

Wetting fronts move more rapidly through fine-grained materials than through coarse-grained materials. Therefore, ponded water at the waste piles may enter the alluvium more rapidly than the waste rock. The volume of water entering alluvium and waste rock and the extent of saturation of the waste rock at the blocked valley probably would be determined best by constructing a flow model of the site.

Numerous waste piles are located outside of valleys and are not part of pit backfill. Recharge to these piles will be from direct precipitation. Reclamation plans call for the piles to be flat topped with terraced sides and berms to decrease erosion. The proposed design might promote infiltration of precipitation.

Assuming waste piles are reclaimed as flat-topped structures with terraces and berms, infiltration of precipitation will be greatest in the basins formed by the structures. Waste piles presently reclaimed have very transmissive vertical channels at the lower parts of the basins. Runoff from adjacent higher areas rapidly infiltrates these vertical channels.

Infiltrating rainfall and runoff may flow through the piles so rapidly that saturation of the waste either does not occur or is short term. The time of water contact with the waste may, therefore, be short, so that solution of minerals from the waste will be minimal if minerals in the waste rock are not greatly soluble. No data, however, are available regarding extent of saturation or water quality in waste piles.

SURFACE-WATER MONITORING CONSIDERATIONS

Sampling sites presently (1980) used for surface-water quality (fig. 9) could continue to be used, except possibly for the one at the "ford crossing." They are properly located for determining water quality at hydrologically important points and probably will monitor changes in quality as water moves through the mine. Four additional locations would be useful for sampling. One of these may be substituted for the ford crossing sampling point. Their location and reasons for sampling them are described below.

The U.S. Geological Survey gaging station at the southern boundary of the mine area, where the Rio Paguate flows beneath the railroad spur, would make a good sampling station for the following reasons: (1) Some water from waste dumps C, D, E, F, and G, and possibly some water from the Jackpile pit, may discharge to the Rio Paguate downstream from the ford crossing sampling point; (2) discharge data from the gaging station may be used to compute a dissolved-constituent load from the mine; and (3) the location is sufficiently far from disturbed areas so that samples from the site may be considered as reflecting most effects from mining activity (except possibly for some flow from the Jackpile pit via alluvium). This sampling point could be substituted for that at the ford crossing.

A sampling point could be established upstream from Paguate Reservoir, north of where swamplike conditions exist due to sedimentation in the reservoir. No data are available regarding flow through alluvium to the Rio Paguate downstream from the mine, but ground-water could discharge to the stream between the southern mine boundary and Paguate Reservoir. The ground-water discharge could change ion concentrations in surface water discharging from the Jackpile mine. The samples presently (1980) collected at the dam of Paguate Reservoir probably reflect considerable evapotranspiration and probably are not representative of freely flowing water to the north of the reservoir.

Two sampling points could be located on the Rio San Jose: one immediately upstream from and one immediately downstream from its confluence with the Rio Paguate. Results of analyses from these samples could be compared to determine the effects of flow from the Rio Paguate on quality of water in the Rio San Jose.

Water-quality samples probably would need to be collected initially about once every 2 months. If trends can be established for a given discharge, sampling frequency might later be extended to once every 3 or 4 months.

Surface-water quality is expected to be much more variable than ground-water quality due to the changes caused by rainfall and evapotranspiration. Care would need to be taken to collect samples at various stream discharges. Minimum concentrations of dissolved ions may be expected during the peak stage or recession of high discharge and maximum concentrations during the initial flush of a storm or during sustained periods of low discharge. Loads of dissolved constituents could be computed by using stream-discharge data.

The same types of analyses as presently established for samples collected from the mine would be useful, that is, analyses for common ions and dissolved solids. Additional analyses are needed, however, for trace elements, gross alpha and gross beta radioactivity, radium-226, and uranium. If significant radioactivity is detected, the radioactive isotopes would need to be identified. Measurement of water temperature, specific conductance, pH, and titration for alkalinity are best done at the sampling site. Duplicate samples may need to be collected occasionally, possibly 1 or 2 per 20 samples collected, and analyzed by a laboratory independent from that normally used in order to compare laboratory results.

GROUND-WATER MONITORING CONSIDERATIONS

Water-quality data collected from existing wells in the Jackpile mine probably will be of limited use because: (1) Many of the wells are not appropriately located; and (2) water-quality data may not be representative at the intended sampling point due to shrinkage of casing cement and resultant leakage of water from upper to lower zones. Cement shrinkage in well annuli may have occurred because several feet of void annular space near the ground surface was observed at some wells. If some existing wells are to be used for monitoring, the wells would need to be pumped until pH and specific conductance of the water have stabilized before samples are collected.

One of two methods may be used to monitor ground-water quality at the Jackpile mine. The first is to determine only the change in quality of ground water that has flowed through the mine. This method is referred to as limited monitoring in this report. This method would neither monitor the sources of possible contaminants nor measure areal changes in water quality. A second method would be to monitor the ground water in such a way that specific sources of possible contaminants are determined and spatial distributions of the possible contaminants are described. This method is referred to as thorough monitoring in this report.

Limited Monitoring

As few as three well sites may be sufficient to monitor only the change in quality of ground water flowing from the open-pit mining area. One well site could be at the southern perimeter of the mine about 2,000 feet east of the stream-gaging station shown on plate 1. One well could be completed in alluvium, and a second well could be completed in the sandstone unit of the Brushy Basin Member at this location. The second site could be at the southeast corner of the mine about 3,000 feet southeast of waste dumps C, D, E, F, and G. Two wells would be needed at this location, and they also could be completed in the alluvium and the Brushy Basin Member. A third site could be at the north end of the mine for the purpose of determining natural water quality. A suitable site probably would be near the Rio Moquino about 1,000 feet north of well M9 (pl. 1). Again, one well completed in alluvium and one well completed in the sandstone unit of the Brushy Basin Member would be useful. In addition, a well could be completed in the sandstone unit of the Brushy Basin Member in Oak Canyon to monitor possible flow from the underground mining area.

Thorough Monitoring

Thorough monitoring would require a greater well density than needed in limited monitoring. Not only would more wells be required, but difficulties can be expected during construction of wells to be completed in backfill.

Monitoring wells would need to be constructed in pit backfill after all planned backfill has been emplaced. Water-quality data from the wells can be used to describe probable maximum concentrations of dissolved substances in water that result from reclamation and that discharge to adjacent rocks and streams. At least one well could be located at each of the following sites: the north side of the South Paguate pit, the south side of the North Paguate pit, and the west side of the Jackpile pit, where the contact of the Jackpile sandstone and mudstone unit of the Brushy Basin Member is below ground level. Ideally, the wells could be positioned at the downgradient end of the backfill. Gradients could be determined by installing several small-diameter wells in each pit and periodically measuring the water levels in these wells. Because pit backfill may not saturate to equilibrium levels for several years, additional monitoring wells may need to be constructed later at the downgradient areas.

Locations of multiple-well sites are described in the following paragraphs. It would be helpful if the wells at any one location were spaced not more than about 30 feet apart in order to observe water-quality changes in aquifers at different depths at essentially the same geographic locations.

Wells for monitoring quality of water discharging from the Jackpile and Paguate pits probably would be needed at the following sites: (1) Three wells west of the Jackpile pit near the Rio Moquino (one well completed in each of the alluvium, the upper part of the Jackpile sandstone, and the base of the Jackpile sandstone); (2) two wells could be about 2,000 feet east of the gaging station and completed as described in the previous section; (3) two wells could be installed at the southeast corner of the mine and completed as described in the previous section; and (4) four wells could be near existing wells M23 and P4 (one well completed in each of the backfill, the alluvium, near the top of the Jackpile sandstone, and near the base of the Jackpile sandstone).

If the water quality in the backfill of the South Paguate and the North Paguate pits is similar, the proposed wells near existing wells M23 and P4 should suffice. If the water quality is different, an additional set of four wells could be constructed north of the Rio Paguate at the south end of the North Paguate pit. These wells would need to be completed in the same strata as described for the proposed wells near M23 and P4.

From an economic viewpoint, waste piles are too numerous to monitor separately. The reclaimed part of "T" dump (pl. 1) could be a representative site. Four wells could be installed at the east side of the dump near the Rio Moquino. One well could be completed in each of the waste rock, the underlying alluvium (if present), the upper part of the Jackpile sandstone, and the base of the Jackpile sandstone.

At least one monitoring well could be installed at the waste piles blocking the valley east of Gavilan Mesa because water occasionally ponds in this area. The well could be located in the valley, immediately downstream from the piles, and completed a few feet below the water table. The water table may be in the alluvium or in the underlying bedrock. Ideally, two other wells could be located at the upstream end of the dumps near the area of ponding. One of the wells could be completed in waste rock, and the other completed a few feet below the water table.

Natural water quality could be determined by installing three wells about 1,000 feet north of existing well M9. One well could be completed in alluvium, one in the Jackpile sandstone, and one in the sandstone unit of the Brushy Basin Member.

Sampling Frequency and Types of Analyses

Initial sampling frequency could be about once every 3 months. If trends can be established after several sampling periods, the frequency could be changed to about twice yearly. If samples are collected two times a year, one sampling period could be in late winter and the other in late fall. Local recharge in the mine area probably is least in winter and greatest in summer.

Types of analyses could be the same as presently done for samples from the mine, as explained in the section regarding proposed surface-water monitoring. Temperature, specific conductance, pH, and titration for alkalinity would best be measured at the sampling site. Duplicate samples probably would need to be collected at least once a year for the purpose of comparing laboratory results.

SUMMARY AND CONCLUSIONS

About 2,656 acres of land are to be reclaimed at the Jackpile mine, which is located on the Pueblo of Laguna in northwestern New Mexico. Uranium was surface mined from the Jackpile sandstone (economic usage) in the Brushy Basin Member of the Morrison Formation from 1953 to late 1980. Reclamation plans probably will include partial backfilling of three open pits to decrease radon formation and modifying the shape of waste-rock piles located outside of the pits.

The pits are as much as 200 to 300 feet below the adjacent ground surface and have an area of 1,015 acres. Piles of waste rock are as much as 200 feet in height; most are about 50 to 75 feet high. Thirty-two piles of waste rock cover 1,266 acres. Reclamation probably will include making waste piles flat-topped in order to resemble the mesas in the area. Terraces and berms are to be constructed on the sides of the piles to decrease erosion.

Primary hydrologic concerns are that oxidation and the large surface area of rock fragments in backfill and waste piles may cause greater than normal dissolution of rock minerals, including radionuclides and trace elements, by water flowing through the waste. Virtually no data exist regarding quality of water passing through the waste rock. Water from waste rock will discharge to adjacent streams and adjacent aquifers, principally the alluvium and the Jackpile sandstone.

The topography of the Laguna area is mountainous with numerous mesas. Altitudes range from 11,300 feet at Mount Taylor to 5,700 feet on the Rio San Jose south of the Jackpile mine. The climate is arid, with mean annual precipitation of 9.5 inches. Surface-water evaporation is about 76 inches per year as measured by the pan-evaporation method. Evapotranspiration losses are estimated to be about 98 percent of precipitation.

The Rio Paguate flows through the Jackpile mine, and the Rio Moquino is tributary to the Rio Paguate in the northern part of the mine. The Rio Paguate flows into Paguate Reservoir about 3 miles downstream from the southern mine boundary, then enters the Rio San Jose about 1.0 mile south of where the Rio Paguate enters the reservoir. Mean daily discharge of the Rio Paguate for water years 1977-80 was 1.19 cubic feet per second at the south end of the mine, about 50 percent of which was base flow. Peak discharge during large floods ranges from about 1,520 cubic feet per second once every 5 years to about 10,500 cubic feet per second once every 500 years, as estimated by the basin-characteristics method.

The Rio Paguate flows over waste rock between the North and South Paguate pits. Present (1980) loss of stream water between the Paguate pits is caused by infiltration into the backfill, pumpage from underground mines, evapotranspiration, and lowering of the water table in the area due to loss of water from pits by pumpage for road conditioning.

Ponding may occur where waste dumps block an arroyo at the east side of the Jackpile mine. Maximum depth of ponded water is estimated to be 4 feet for a flood flow of 1 day at a recurrence interval of 50 years. Depths probably are less than 2 feet for most flow periods and recurrence intervals. Water from the pond will infiltrate underlying alluvium and waste rock at the upstream end of the dumps.

Sediment has nearly filled the Paguate Reservoir since construction of the dam in 1940. Sediment yield due to mining is less than about 1 percent of total sediment yield in the basin, and sediment deposited in the reservoir due to mining is estimated to be less than 0.24 acre-foot per year. The sediment contribution resulting from mining is small because the externally draining area of the mine constitutes only about 1 percent of the 107-square-mile drainage area in the Rio Paguate basin upstream from the southern boundary of the mine.

The recharge rate in the Rio Paguate drainage basin is estimated to be about 0.1 inch per year, based on the sum of base flow and underflow through alluvium. Rates may vary locally with altitude, ground slope, rock type, and distribution of alluvium and eolian deposits. Recharge to rocks in the Jackpile mine is from high areas on the flanks of Mount Taylor to the west and probably from Mesa Chivato to the north. Some recharge may occur locally in the mine. Regional ground-water flow is southward toward the Rio San Jose and eastward toward the Rio Puerco. Most of the local flow in alluvium and in the Jackpile sandstone discharges to mine pits, to underground mines presently being dewatered, and to the Rio Paguate and Rio Moquino. Some ground water may flow from the mine via alluvial and eolian deposits and from rocks in the Brushy Basin Member.

The hydraulic conductivity is about 23 feet per day for the alluvium and about 0.3 foot per day for the Jackpile sandstone and for a sandstone bed in the underlying part of the Brushy Basin Member. Mudstone beds approximately 100 feet thick separate the deeper sandstone from the Jackpile sandstone. Minimal hydraulic connection between the two sandstone strata indicates that the mudstone unit is the lower boundary of the hydrologic system in the mine area. Hydraulic-head differences between the two sandstone beds, however, indicate downward flow of some water from the Jackpile sandstone.

Water in the Rio Moquino is a mixed-ion type, with dissolved solids ranging from about 1,600 mg/L upstream from the mine to about 1,900 mg/L at its mouth. Water in the Rio Paguate upstream from the confluence with the Rio Moquino is a sodium bicarbonate type, with dissolved solids ranging from 575 to 700 mg/L. Downstream from the confluence of the streams, the water in the Rio Paguate is of the same type as in the Rio Moquino, with dissolved solids of about 2,000 mg/L. Mean concentrations of dissolved solids in samples of ground water range from 900 to 1,500 mg/L.

Concentrations of uranium, radium-226, and other trace elements generally were less than permissible limits established in national drinking-water regulations or New Mexico ground-water regulations. Trace elements that could pose water-quality problems because of their association with uranium ores are lead, selenium, iron, manganese, molybdenum, vanadium, radium, and uranium.

Mean concentrations of uranium and radium-226 increase through the mine area at various surface-water sampling sites. None of the mean concentrations exceeded permissible concentrations for public use. No individual stream-water samples collected upstream from the mine contained radium-226 concentrations in excess of permissible limits. However, many individual radium-226 concentrations in the Rio Paguate from near the mouth of the Rio Moquino and along the downstream reach of the Rio Paguate exceeded the permissible concentration of radium-226 for public drinking-water supplies. Concentrations in surface water apparently are changed by ground-water inflow near the confluence of the two streams.

Part of the backfill in the pits will become saturated after reclamation. The water will discharge to adjacent strata and to streams. Discharge from the Paguate pits primarily will be from backfill in the pits to permeable waste rock and to the Rio Paguate. Most discharge from the Jackpile pit probably will be from backfill to the Jackpile sandstone, then to alluvium and to the Rio Paguate. Some discharge from the Jackpile pit could be to strata underlying the Jackpile sandstone. Previous studies determined that the backfill has a hydraulic conductivity of 190 feet per day at well M24.

The depth to the water table in pit backfill will be partly controlled by the water level in the Rio Paguate adjacent to the pits. Other factors controlling the altitude of the water table will be the recharge rate to the backfill and the hydraulic conductivity of the backfill, alluvium, Jackpile sandstone, and mudstone unit of the Brushy Basin Member. Computer flow models of the pits could be made to estimate post-reclamation water levels in the backfill for given conditions.

Waste piles are different hydrologically from backfill, in that they receive only local recharge. Recharge principally will be from direct precipitation on most piles. The basins formed by berms constructed around terraces will promote infiltration. Recharge to the upstream part of the backfill blocking the arroyo east of Gavilan Mesa will be caused by temporary ponding at the faces of the dumps. Virtually no information, however, exists regarding extent of saturation in waste piles. The waste rock may be permeable enough so that saturation is limited and of short duration. Discharge from the piles may be to ground surface or to underlying alluvium and bedrock. Computer flow models could be made of a typical waste pile and of the waste piles blocking the arroyo east of Gavilan Mesa.

After reclamation, most of the shallow ground water probably will discharge to the natural stream channels draining the mine area. The remaining ground water probably will flow to the south and east, where erosion has removed the northwest-dipping Jackpile sandstone from the valleys.

Four surface-water monitoring stations could be established in addition to those presently sampled. Their locations could be as follows: at the gaging station on the Rio Paguate at the south end of the mine area, on the Rio Paguate immediately north of Paguate Reservoir, on the Rio San Jose immediately upstream from the Rio Paguate, and on the Rio San Jose immediately downstream from the Rio Paguate. The present sampling station at the ford crossing could be discontinued.

Surface-water-quality samples could be collected about once every 2 months and at different stream discharges. If water quality can be mathematically related to given discharges, sampling frequency could later be changed to once every 3 or 4 months. Loads of dissolved constituents could be computed using stream-discharge and water-quality data collected at the gaging station. Duplicate sampling could be done at least once a year to compare results from different laboratories. Types of analyses that probably would be needed are common ions, dissolved solids, trace elements, gross alpha radioactivity, gross beta radioactivity, and uranium. Measurements of water temperature, specific conductance, pH, and alkalinity could be made at the sampling sites.

Quality of ground water could be monitored as: (1) "Limited monitoring," in which only the change in water quality is determined as the ground water flows through the mine; or (2) "thorough monitoring," in which specific sources of possible contaminants are determined, and spatial distributions of the possible contaminants are described. As few as three well sites are needed for limited monitoring; one could be located at the northern part of the mine for determining natural water quality and one each at the south and southeast ends of the mine to determine changes in water quality (which would likely be due to mining). Paired wells could be completed at each site as follows: one in alluvium, and one in the sandstone strata below the mudstone unit in the Brushy Basin Member. Many more well sites would be required for thorough monitoring, and they are described in the text of this report.

Ground-water-quality samples probably need to be collected about once every 3 months initially. If trends can be established, the frequency could be changed to twice yearly. Types of analyses, field measurements at the sampling sites, and duplicate sampling could be the same as described above for surface water.

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SUPPLEMENTAL INFORMATION

Table 21.--Mean monthly and mean annual discharge for Paguate Creek near Laguna, New Mexico

[All values are in cubic feet per second]

Water year	Oct.	Nov.	Dec.	Jan.	Feb.	Mar.	Apr.	May	June	July	Aug.	Sept.	Annual
1937	-	-	-	-	-	1.45	1.77	0.73	0.61	0.66	0.77	0.70	-
1938	0.78	0.98	1.15	1.16	1.07	1.18	1.24	1.21	.91	.82	.35	1.03	0.99
1939	.76	.92	1.04	1.06	1.04	1.58	2.09	.85	.48	.93	.88	.62	1.02
1940	.85	1.10	1.22	1.16	1.62	1.18	1.14	.92	.47	.80	.76	1.06	1.02
1941	.84	1.67	1.42	1.18	1.59	5.92	12.6	14.7	1.51	.71	.93	2.42	3.80

Table 22.--Mean monthly and mean annual discharge for Rio Paguate downstream from Jackpile mine near Laguna, New Mexico

[All values are in cubic feet per second]

Water year	Oct.	Nov.	Dec.	Jan.	Feb.	Mar.	Apr.	May	June	July	Aug.	Sept.	Annual
1976	-	-	-	-	-	-	1.21	1.05	0.48	0.38	4.18	0.79	-
1977	0.67	1.07	1.15	1.66	1.68	1.66	1.53	2.00	.54	.69	1.71	.340	1.48
1978	.47	.61	.95	1.55	2.09	1.34	.81	.98	.37	.28	3.33	.20	1.08
1979	.22	1.59	.80	1.99	2.66	3.57	1.36	1.13	.56	.16	1.26	.76	1.33
1980	.30	.69	.65	1.59	1.77	1.80	.82	.29	.12	.047	.095	2.28	.87

Table 23.--Classification of water based on dissolved-solids concentrations

The U.S. Geological Survey has assigned terms for freshwater and degrees of salinity based on concentrations of dissolved solids as follows:

Classification	Dissolved-solids concentration (milligrams per liter)
Fresh	Less than 1,000
Slightly saline	1,000 - 3,000
Moderately saline	3,000 - 10,000
Very saline	10,000 - 35,000
Briny	More than 35,000