

HYDROGEOLOGIC RECONNAISSANCE OF THE SAN MIGUEL RIVER BASIN,
SOUTHWESTERN COLORADO

By D. J. Ackerman and F. E. Rush

U.S. GEOLOGICAL SURVEY

Water-Resources Investigations Report 84-4133

Prepared in cooperation with the
U.S. DEPARTMENT OF ENERGY

Lakewood, Colorado

1984

UNITED STATES DEPARTMENT OF THE INTERIOR

WILLIAM P. CLARK, Secretary

GEOLOGICAL SURVEY

Dallas L. Peck, Director

For additional information
write to:

Colorado District Chief
U.S. Geological Survey, MS 415
Box 25046, Denver Federal Center
Lakewood, CO 80225
Phone: (303) 236-4882

For sale by:

Open-File Services Section
Western Distribution Branch
U.S. Geological Survey
Box 25425, Federal Center
Denver, CO 80225
Phone: (303) 236-7476

CONTENTS

	Page
Abstract-----	1
Introduction-----	1
Objective and scope-----	3
Description of study area-----	3
Previous studies-----	3
Physical setting-----	5
Physiography and drainage-----	5
Structure-----	6
Stratigraphy-----	6
Hydrogeology-----	8
Hydrogeologic units-----	9
Precipitation-----	10
Runoff-----	14
Inflow to the ground-water systems-----	17
Outflow from the ground-water systems-----	17
Evapotranspiration-----	17
Springflow-----	19
Discharge to streams-----	19
Subsurface outflow-----	19
Wells-----	20
Inflow-outflow balance-----	20
Chemical character of ground water-----	20
Relation between flow systems and salt beds-----	22
Need for additional studies-----	23
Summary and conclusions-----	23
References-----	23

ILLUSTRATIONS

	Page
Plate 1. Map showing generalized hydrogeology of the San Miguel River basin, southwestern Colorado-----	In pocket
2. Map showing generalized hydrology of the San Miguel River basin, southwestern Colorado-----	In pocket
Figure 1. Map showing location of the Paradox basin and other areas underlain by rock salt in the conterminous United States-----	2
2. Map showing the location of the San Miguel River basin with respect to the Paradox basin (area underlain by bedded salt) of Colorado and Utah-----	4
3. Graph showing relation of precipitation to altitude in and near the San Miguel River basin, 1951-70-----	11
4. Map showing the distribution of average annual precipitation-----	12
5. Graph of mean monthly precipitation at three stations-----	13
6. Graph of cumulative departure of average annual precipitation at three stations-----	15
7. Map showing distribution of average annual runoff in the San Miguel River basin and vicinity-----	16
8. Map showing potentiometric contours for the lower Paleozoic aquifer in the San Miguel River basin and vicinity-----	18

TABLES

	Page
Table 1. Climatological data for representative weather stations-----	5
2. Rock and hydrogeologic units-----	7
3. Estimated average annual precipitation-----	14
4. Water budget for the saturated part of the upper ground-water system-----	21

CONVERSION TABLE

The following factors may be used to convert the International System of Units (SI) published herein to inch-pound units.

<i>Multiply SI units</i>	<i>By</i>	<i>To obtain inch-pound units</i>
<u>Length</u>		
kilometer (km)	6.214×10^{-1}	miles
meter (m)	3.281	foot
millimeter (mm)	3.937×10^{-2}	inch
<u>Area</u>		
square kilometer (km ²)	3.861×10^{-1}	square mile
<u>Volume</u>		
cubic meter (m ³)	8.107×10^{-4}	acre-foot
cubic hectometer (hm ³)	8.107×10^2	acre-foot
<u>Flow</u>		
cubic meter per second (m ³ /s)	3.531×10^1	cubic foot per second
cubic meter per year (m ³ /yr)	3.531×10^1	cubic foot per year
liter per second (L/s)	3.531×10^{-2}	cubic foot per second
<u>Specific Conductance</u>		
microsiemens (μS)	1.0	micromho

To convert degrees Celsius (°C) to degrees Fahrenheit (°F), use the following formula: $9/5 (°C) + 32 = °F$.

National Geodetic Vertical Datum of 1929 (NGVD of 1929): A geodetic datum derived from a general adjustment of the first-order level nets of both the United States and Canada, formerly called mean sea level. NGVD of 1929 is referred to as sea level in this report.

HYDROGEOLOGIC RECONNAISSANCE OF THE SAN MIGUEL RIVER BASIN, SOUTHWESTERN COLORADO

By D. J. Ackerman and F. E. Rush

ABSTRACT

The San Miguel River basin is an area of 4,130 square kilometers, of which about two-thirds is in the southeastern part of the Paradox basin. The Paradox basin is a part of the Colorado Plateaus that is underlain by a thick sequence of evaporite beds of Pennsylvanian age. The rock units that underlie the area have been grouped into hydrogeologic units based on their water-transmitting ability. Evaporite beds consisting mostly of salt are both overlain and underlain by confining beds. Aquifers are present above and below the confining-bed sequence. The principal element of ground-water outflow from the upper aquifer is flow to the San Miguel River and its tributaries; this averages about 90 million cubic meters per year.

The aquifers generally are isolated from the evaporite beds by the bounding confining beds; as a result, most ground water has little if any contact with the evaporites. No natural brine flows have been identified in the basin. Salt water has been reported in petroleum-exploration wells, but no active salt solution has been located.

INTRODUCTION

The U.S. Geological Survey has been conducting investigations funded by the U.S. Department of Energy related to the underground isolation of high-level radioactive wastes. These investigations have included geologic, geophysical, and hydrologic studies to locate suitable underground environments for waste storage and to develop and improve techniques for site exploration and evaluation. As part of the investigations, this report presents information on the general hydrogeology of the San Miguel River basin in the eastern part of the Paradox basin. The Paradox basin (fig. 1) was chosen for exploration because the salt beds of the basin were believed to have favorable physical, chemical, and mechanical properties as a storage environment.

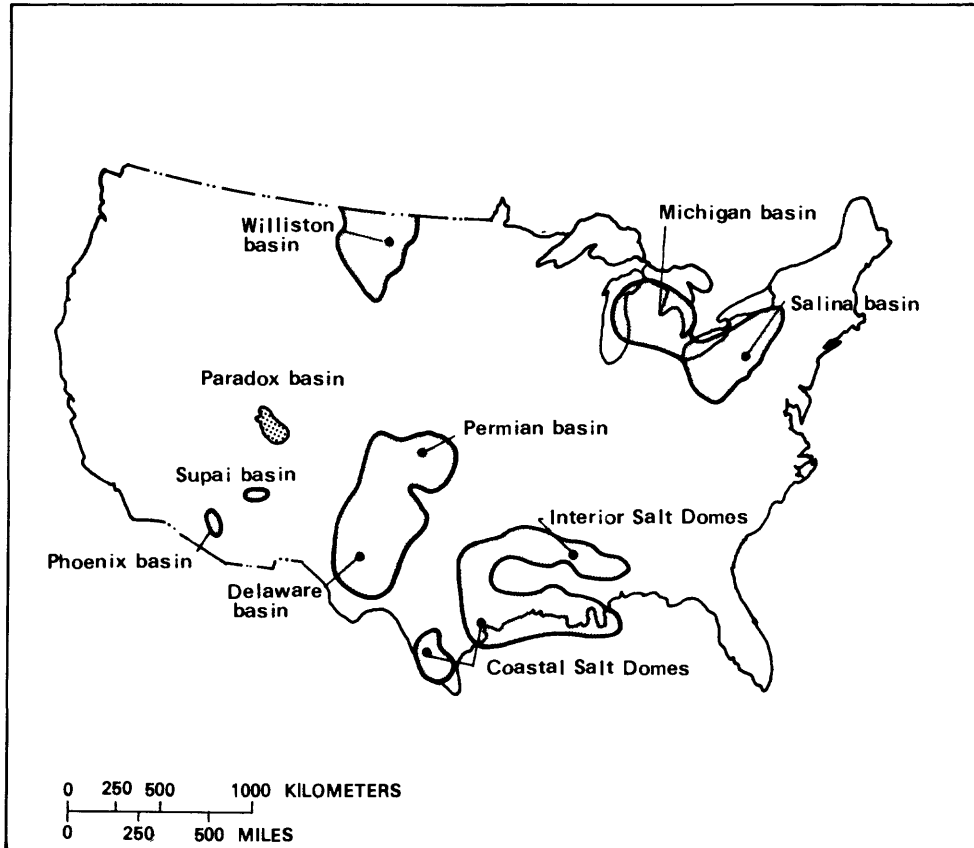


Figure 1.--Location of the Paradox basin and other areas underlain by rock salt in the conterminous United States.

Objective and Scope

The objective of this report is to present a brief interpretation of the hydrogeologic flow systems of the river basin including flow systems in deep zones and any systems which may impinge on salt deposits. The interpretations are based primarily on existing data; however, where additional information could be obtained readily, onsite inventories and measurements were made during 1978 and 1979.

Description of Study Area

The San Miguel River basin is in southwestern Colorado (fig. 2). The river basin is about 110 km long measured in a northwesterly direction and has an area of 4,130 km², of which about two-thirds is in the Paradox basin.

The San Miguel River basin is sparsely populated. Most of the population lives at relatively low altitudes in or near the small towns (pl. 1) of Telluride (T. 42 N., R. 9 W.), population 1,047; Nucla (T. 46 N., R. 15 W.), population 1,027; and Naturita (T. 46 N., R. 15 W.), population 819 (U.S. Bureau of the Census, 1981). The economy in the river basin is based mainly on agriculture and mining, with some lumbering and tourism.

The river basin is mostly mountainous; land-surface altitudes range from about 1,475 m at the mouth of the San Miguel River at the northwestern end of the river basin (T. 48 N., R. 17 W.) to about 4,275 m in the high mountains at the southeastern end of the basin.

The San Miguel River basin has a climate characterized by a seasonal range of weather conditions typical of continental-interior localities at this latitude. The climate of the basin is markedly affected by altitude. Average annual precipitation is about 300 mm in the lower part of the basin and is as much as 1,300 mm in the mountains in the southeastern part of the basin (Iorns and others, 1965, pl. 4). Temperature extremes typically range from less than -35°C in the mountains in January to +35°C in the lower parts of the basin in July. Climatological data for three stations in the basin are summarized in table 1. The towns where the stations are located are shown on plates 1 and 2.

According to Iorns and others (1965, pl. 5), the relative proportions of vegetative communities in the basin are: subalpine forest and meadow, 41 percent; montane brush, 24 percent; pinon-juniper, 18 percent; big sagebrush, 14 percent; and irrigated land, 3 percent.

Previous Studies

The general hydrology of the study area has been reported by Iorns and others (1965) and by Boettcher (1972). The hydrogeologic map in this report (pl. 1) is based partly on geologic maps by Williams (1964), Haynes and others (1972), Stevens and others (1974), and Tweto and others (1976). A report on the Paradox basin by Hanshaw and Hill (1969) includes information on the geochemistry and hydrodynamics of Mississippian to Permian rocks. As part of

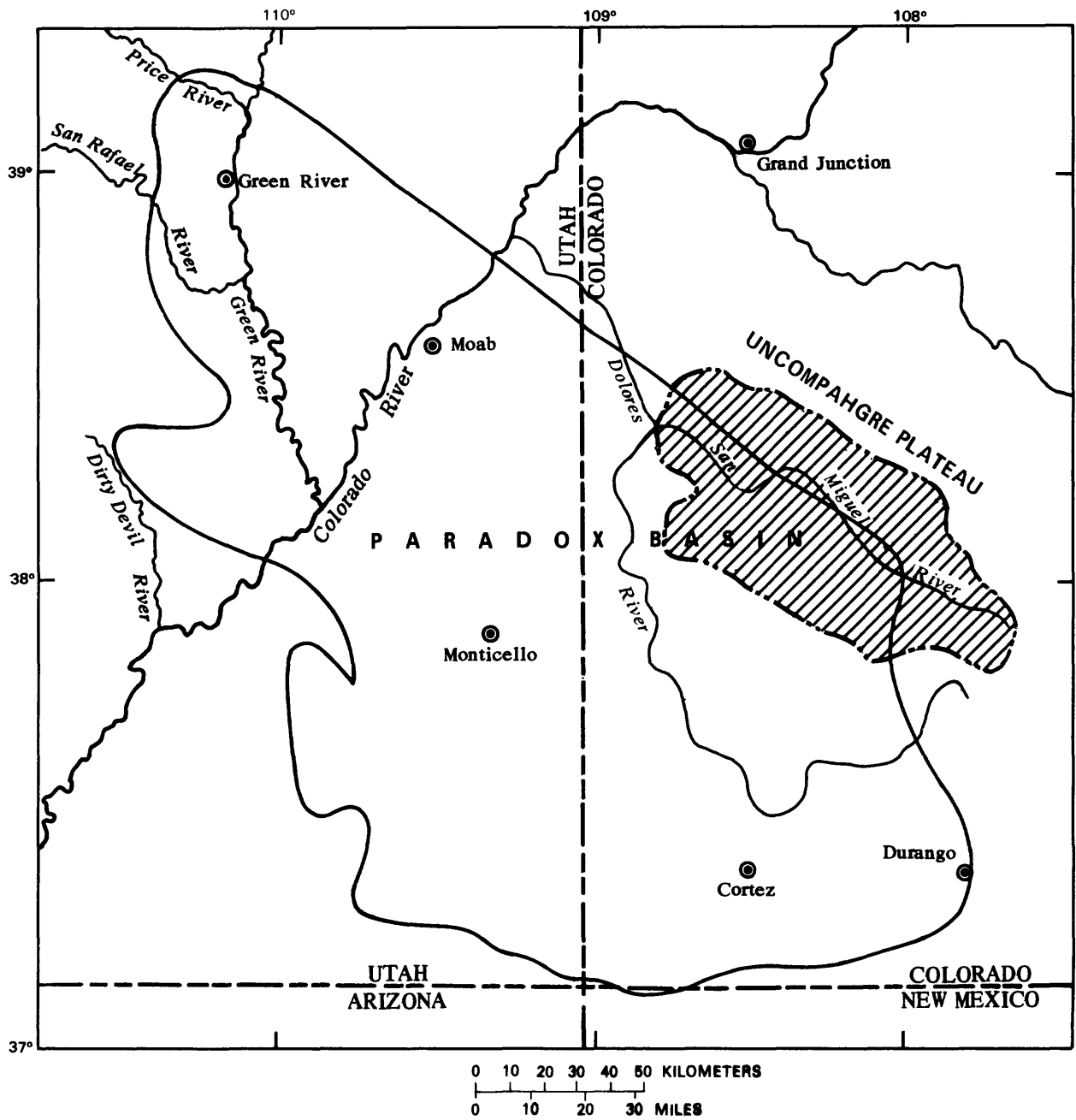


Figure 2.—Location of the San Miguel River basin with respect to the Paradox basin (area underlain by bedded salt) of Colorado and Utah.

Table 1.--*Climatological data for representative weather stations*

[Based on data from the National Weather Service (U.S. Weather Bureau);
°C, degree Celsius]

	Uravan (T. 48 N., R. 17 W.)	Norwood (T. 45 N., R. 13 W.)	Telluride (T. 42 N., R. 9 W.)
Altitude (meters above sea level)--	1,527	2,140	2,682
Climatological data:			
Mean annual precipitation (millimeters)-----	302	373	584
Mean annual air temperature (°C)	11.4	6.7	4.4
Mean annual daily maximum air temperature (°C)-----	20.3	¹ 15.1	¹ 13.4
Mean daily maximum air temperature for July (°C)-----	35.1	28.6	25.3
Mean daily minimum air temperature for January (°C)---	-10.1	¹ -12.8	¹ -14.3
Period of record-----	1961-79	1940-79	1940-79

¹Period of record, 1950-79.

the general program to provide geologic and hydrologic information for determining the suitability of salt deposits for waste storage, reports by Hite and Lohman (1973), Papadopulos and Winograd (1974), DeBuchananne and Twenhofel (1975), and Friedman and Simpson (1978) are noteworthy. These reports and reports by Cater (1970) and Shawe (1970) contain references to most of the geologic interpretations for the basin. Most geologic interpretations presented here are drawn from Shawe and others (1968), Cater (1970), and Shawe (1970). This report is one of a series of reports describing the hydrogeology of the Paradox basin. A report for the part of the Paradox basin northwest of the Colorado River has been published previously (Rush and others, 1982). More detailed information on wells and springs in the basin is on file in the Colorado District office of the U.S. Geological Survey, Lakewood, Colo. Most records are available as computer printouts. Information on the availability of unpublished data may be obtained from the District office.

PHYSICAL SETTING

Physiography and Drainage

The southeastern one-fourth of the San Miguel River basin is in the Southern Rocky Mountains physiographic province. The remainder of the basin is in the Canyonlands section of the Colorado Plateaus physiographic province (Fenneman, 1946).

The headwaters of the San Miguel River and its major tributaries are mostly in the southeastern part of the basin in the San Juan Mountains (pls. 1 and 2). The San Miguel River is a tributary to the Dolores River. The waters from both rivers enter the Colorado River northwest of the San Miguel River basin as shown in figure 2. The present course of the San Miguel River generally is near the axis of the Nucla syncline (pl. 1). In outcrop most of the flanks of the syncline are Dakota Sandstone. The San Miguel basin consists of the northwestern-flowing San Miguel River and its major tributaries; these are deeply incised in a syncline that plunges gently downstream.

The largest tributary to the San Miguel River is Tabeguache Creek, a perennial stream that drains a large area along the southwest flank of the Uncompahgre Plateau (pl. 2). Other major tributaries are Dry, Naturita, and Beaver Creeks.

The San Miguel River basin includes part of the Paradox basin (fig. 2) and part of the southwestern flank of the Uncompahgre Plateau. The Paradox basin is not a physiographic or topographic feature; it is defined by the extent of the thick sequence of Pennsylvanian evaporites (bedded salt), the Paradox Member of the Hermosa Formation for which the basin is named.

Structure

The thickness and orientation of individual rock units vary considerably throughout the San Miguel River basin. Three major structural features control the occurrences of most rock units--the Uncompahgre Plateau, the San Juan Mountains, and the Nucla syncline (pl. 1). All rock units abut against or dip away from the Uncompahgre Plateau; most units also dip away from a second high-altitude area, the San Juan Mountains. The Nucla syncline contains thick sequences of post-Mississippian strata. Basement faults controlled the location of salt anticlines (pl. 1) and may determine the continuity of rocks underlying the evaporites (Hite and Lohman, 1973, p. 26).

Stratigraphy

All ages from the Precambrian to the Quaternary are represented by the igneous, metamorphic, and sedimentary rocks in the river basin except for the Ordovician and Silurian (table 2). Cambrian through Mississippian time is represented by rocks of marine origin. Through most of Pennsylvanian time, thick salt beds and their interbeds were deposited. During Late Pennsylvanian and Permian times, shales and arkoses in excess of 3,000 m thick in the Nucla syncline and derived from the Uncompahgre highland were deposited throughout the river basin. Triassic shales and arkoses and pre-Morrison Formation Jurassic sandstones also derived from the Uncompahgre highland wedged out against diapiric salt anticlines of the Paradox basin as they were uplifted northwest of the river basin (Hite and Lohman, 1973, p. 21). Diapiric structure in the river basin probably is minor or nonexistent and is most likely limited to the northwestern end of the Dry Creek anticline (pl. 1).

Table 2.--Rock and hydrogeologic units

System or series	Rock unit		Maximum thickness (meters)	Predominant lithology	Hydrogeologic unit	
Quaternary	Alluvium, talus, colluvium, landslide glacial drift, terrace gravels, and eolian deposits.		60?	Silt, sand, and gravel.	Quaternary aquifer	
Tertiary	Volcanic rocks--intrusive and extrusive.		---	Light to dark tuffs, acidic andesites and rhyolites.	Tertiary and Upper Cretaceous confining beds	
Upper Cretaceous	Mesaverde Group		340?	Sandstone, shale, and coal.		
	Mancos Shale		900	Dark-gray carbonaceous marine shale.		
Lower Cretaceous	Dakota Sandstone and Burro Canyon Formations undifferentiated.		60	Interbedded sandstone conglomerate, shale, and coal.		
Upper Jurassic	Morrison Formation	Brushy Basin Member	150	Variegated bentonitic shale sandstone, conglomerate.	Mesozoic sandstone aquifer	
		Salt Wash Member	110	Lenticular sandstone and shales.		
Jurassic	San Rafael Group	Summerville Formation	46	Reddish-brown siltstone and sandstone.		
		Entrada Sandstone	79	Orange to buff massive sandstone and red silty sandstone.		
Lower Jurassic	Glen Canyon Group	Navajo Sandstone	24	Gray, massive, clean, eolian sandstone.		
		Kayenta Formation	70	Red and buff sandstone with some shale.		
		Wingate Sandstone	100	Red and brown massive fine-grained poorly cemented sandstone.		
Upper Triassic		Dolores Formation	120	Red shale, sandstone and limestone pebble conglomerate.	Mesozoic and Upper Paleozoic confining beds	
Lower Triassic		Chinle Formation	180	Reddish siltstone with some sandstone and shale.		
		Moenkopi Formation	90	Reddish-brown siltstone.		
Permian		Cutler Formation	3,149	Reddish-brown sandstone, siltstone, and shale.	Evaporite confining beds	
		Rico Formation	120	Similar to Cutler transitional to Hermosa.		
Pennsylvanian	Hermosa Formation	Upper Member	411	Gray limestone, shale, and sandstone.		
		Paradox Member	1,710	Dolomite, limestone, gypsum, and shale interbeds and thick beds of salt.		
		Lower Member	150	Gray limestone and shale.		
Mississippian		Molas Formation	30	Reddish-brown shale and limestone.	Upper Paleozoic confining beds	
		Leadville Limestone	120	Gray limestone and dolomite.		
Devonian		Ouray Limestone	49	Gray dolomitic limestone.		Lower Paleozoic aquifer
		Elbert Formation	55	Dolomite, limestone, and sandstone.		
Cambrian		Name not assigned	140	Gray to pink sandstone, siltstone, and dolomite.	Precambrian confining beds	
Precambrian			---	Granite, amphibolitic gneiss, schist and granite.		

The Cretaceous Period was a time of thick marine shale deposition with some nonmarine sandstone both at the beginning and at the close of the period. The Tertiary Period is represented in the San Miguel River basin by tuffs and laccolithic intrusions and the formation of the San Juan Mountains. It also is possible that sills of quartz monzonite related to the laccoliths of the San Juan Mountains may have intruded Pennsylvanian salt beds in the south-central part of the river basin. It is likely that thick beds of lower Tertiary sedimentary rocks once covered the area but were removed. During the Quaternary Period thin, discontinuous layers of silt, sand, and gravel of fluvial, eolian, and glacial, or landslide origin were deposited, principally along the bottoms of canyons and on valley floors.

HYDROGEOLOGY

The rock units that underlie the San Miguel River basin have been grouped into hydrogeologic units and ground-water systems according to their approximate relative water-transmitting ability and their general lithology. The grouping of rock units follows the plan presented by Rush and others (1982, table 2) for the northwestern part of the Paradox basin. Usually siltstone, shale, and the igneous and metamorphic rocks transmit little water. Sandstone, conglomerate, and carbonate rocks have a broad range in hydraulic conductivity; however, generally, they are more transmissive than the former group. Sandstone and conglomerate may have both primary and secondary permeability; carbonate rocks have mostly secondary permeability. Salt is plastic, flows (Hite and Lohman, 1973, p. 28-33), and presumably self-seals. Based on information from Cater (1970, p. 63 and 64), as little as 150 m of overburden is sufficient to start plastic deformation of salt. As a result, it likely transmits little, if any, ground water. If these salt deposits of the river basin are typical, then salt solution takes place only along the upper or lower surfaces (Hite and Lohman, 1973, p. 38). The best water-transmitting and water-yielding materials in the basin are the saturated alluvial deposits in the canyons and beneath river valleys.

Within the rock sequence (table 2), three aquifers have been defined, the lower Paleozoic, the Mesozoic sandstone, and the Quaternary aquifers. The lower Paleozoic aquifer includes Mississippian dolomites that generally are porous and permeable (Hanshaw and Hill, 1969, p. 271; and Hood and Danielson, 1979, p. 14). According to Neff and Brown (1958, p. 108), some of the Devonian rocks also are porous.

Hydrogeologic units immediately above and below the evaporites (salt) and the pre-Quaternary formations overlying the Dakota Sandstone generally transmit little water and are considered leaky confining beds. The evaporites and their interbeds (table 2) probably have only minor interconnected pores and fractures; therefore, they are nearly impermeable and thus constitute a boundary between the ground-water flow systems (Rush and others, 1982, p. 10). Throughout the river basin, the evaporites appear to have undergone only minor, if any, solution. This condition probably is due to the common presence of the almost impermeable units in the underlying and overlying confining beds. Exceptions occur along diapiric salt anticlines where the overlying confining beds were not deposited; as a result, salt solution has occurred

along the top surface of the salt (Hite and Lohman, 1973, p. 35). This condition probably exists northwest of the river basin, but not in it.

Outcrop distribution of the hydrogeologic units is shown on plate 1. Only five of the eight units described in table 2 crop out. The remaining units are present only in the subsurface, but they have been identified by deep-well drilling within the river basin and elsewhere in the Paradox basin.

In the part of the river basin where salt beds are present, the upper and lower ground-water systems are hydraulically isolated from each other by evaporite confining beds (table 2); as a result, the two systems generally function independently. Where the salt is absent, the Mesozoic and Paleozoic confining beds probably retard interaquifer flow.

The values of transmissivity and hydraulic conductivity of hydrogeologic units generally are not known; however, their probable permeability ranking follows, based mostly on lithologic interpretations and data from the north-western part of the Paradox basin (Rush and others, 1982, p.15):

Rank	Unit
Most permeable ↑ ↓ Least permeable	Quaternary aquifer. Mesozoic sandstone aquifer. Lower Paleozoic aquifer. <hr/> Tertiary and Upper Cretaceous confining beds. Mesozoic and Upper Paleozoic confining beds. Upper Paleozoic confining beds. Precambrian confining beds. <hr/> Evaporite confining beds.

Discontinuous conglomerates may be present within the confining-bed sequences immediately adjacent to the Uncompahgre Plateau, but they may grade into less permeable units vertically and horizontally.

Hydrogeologic Units

Water in the rocks of the river basin occurs in both the saturated and the unsaturated zones. Water percolates into the unsaturated zone from local precipitation and runoff and generally is moving downward toward the underlying zone of saturation. In some places, lenses of saturated rock may exist in the unsaturated zone as perched water bodies. The principal component of flow in the saturated zone usually is horizontal.

Depth to the saturated zone probably is greatest beneath mesas in the northwestern part of the area where the local potentiometric surface can be greater than 200 m below land surface. Farther southeast and away from the deep canyons, depths to the potentiometric surface commonly are a few tens of meters or less.

The saturated part of the upper ground-water system is unconfined in places and may be confined in other places, whereas the lower Paleozoic aquifer probably is confined wherever it is overlain by the relatively impermeable confining beds. Variations in confinement of the upper system are related to facies changes of lithologies and in distribution of rock fractures. Where intensively fractured, relatively impermeable rock probably is less effective as a confining bed than similar rock that is less fractured.

The average specific yield (that is, the approximate quantity of water that a rock will yield by gravity) of sedimentary rocks and alluvium in the area has been estimated by Price and Arnow (1974, p. C10) to be about 0.2 to 0.7 percent. The evaporite confining beds, with almost no permeability and porosity, virtually have no specific yield. In general, the hydrogeologic units probably have the same relative ranking for specific yield as permeability (described in the preceding section).

Hanshaw and Hill (1969, p. 267, 280) did not include the Mesozoic sandstone aquifer in their study of regional aquifers in the Paradox basin because they believed that the Mesozoic sandstone aquifer commonly is devoid of water, is affected primarily by local recharge-discharge conditions because of its high altitude, and is above the regional water table. In addition, Hanshaw and Hill (1969, p. 267) found little data for the Mesozoic sandstone aquifer of the type they wished to use in their study. Although local hydrologic conditions may be complex in areas of high relief, the Mesozoic sandstone aquifer is continuous throughout large areas and generally yields water to wells that penetrate sandstone at depths of more than 100 m. Also, much of the San Miguel River basin has a more humid climate, resulting in a water table relatively close to the land surface.

Precipitation

In and near the San Miguel River basin the quantity of precipitation is markedly affected by land-surface altitude, as shown in figure 3. As stated previously, precipitation averages about 300 mm per year in the lowest part of the basin, whereas precipitation may exceed 1,300 mm per year on the mountains in the southeastern part of the basin. The areal distribution of annual precipitation throughout the basin is shown in figure 4. About one-half of the average total basin precipitation of 2.1×10^9 m³ (table 3) falls on the part of the basin above an altitude of 2,300 m. This approximately corresponds to that part of the basin that receives more than 500 mm of precipitation per year (fig. 4) and represents about 37 percent of the basin area.

The seasonal distribution of precipitation is similar for stations located at various points in the basin (fig. 5). Two dry periods, one in late fall and early winter and the second in late spring, are separated by wetter periods.

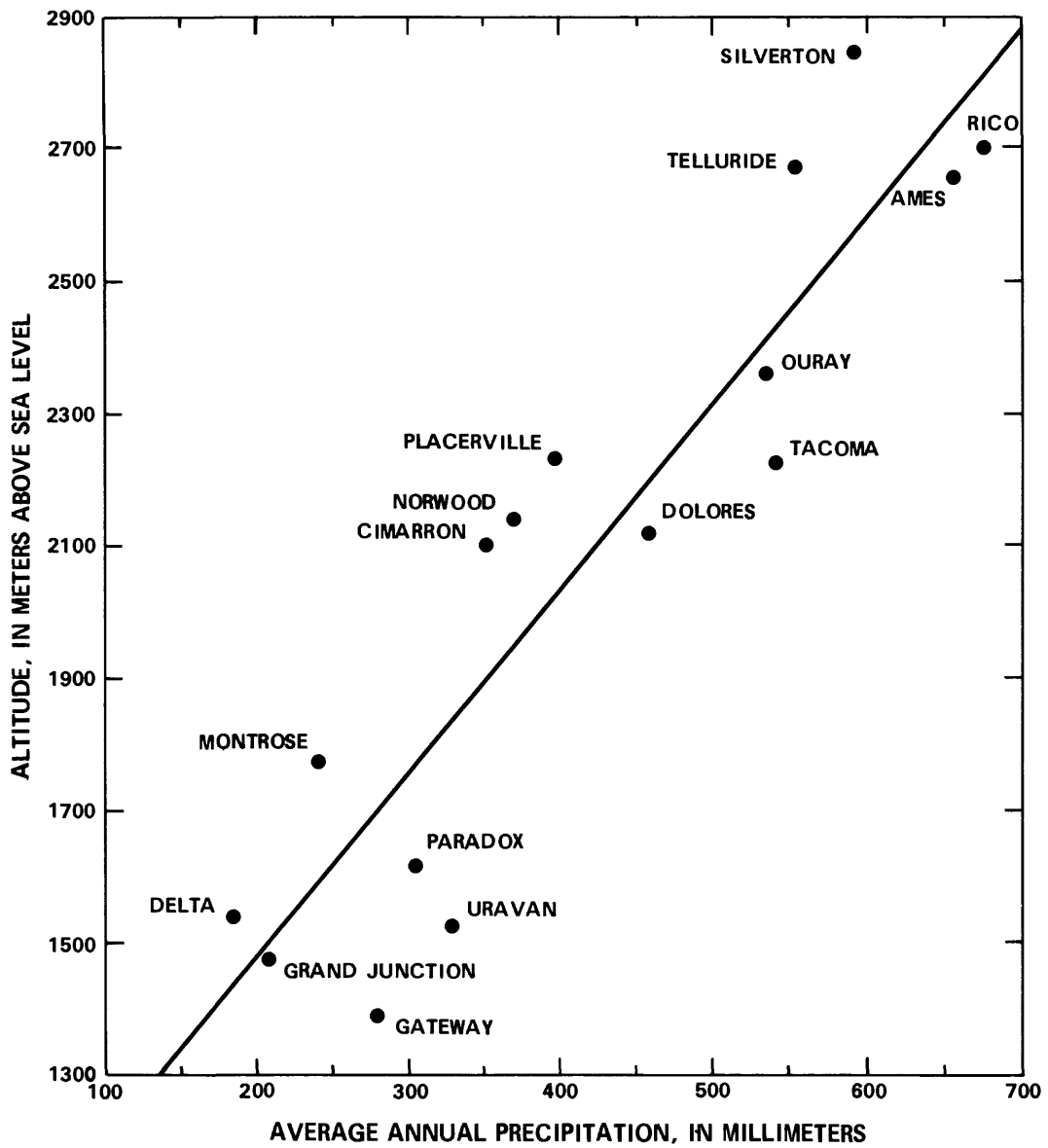
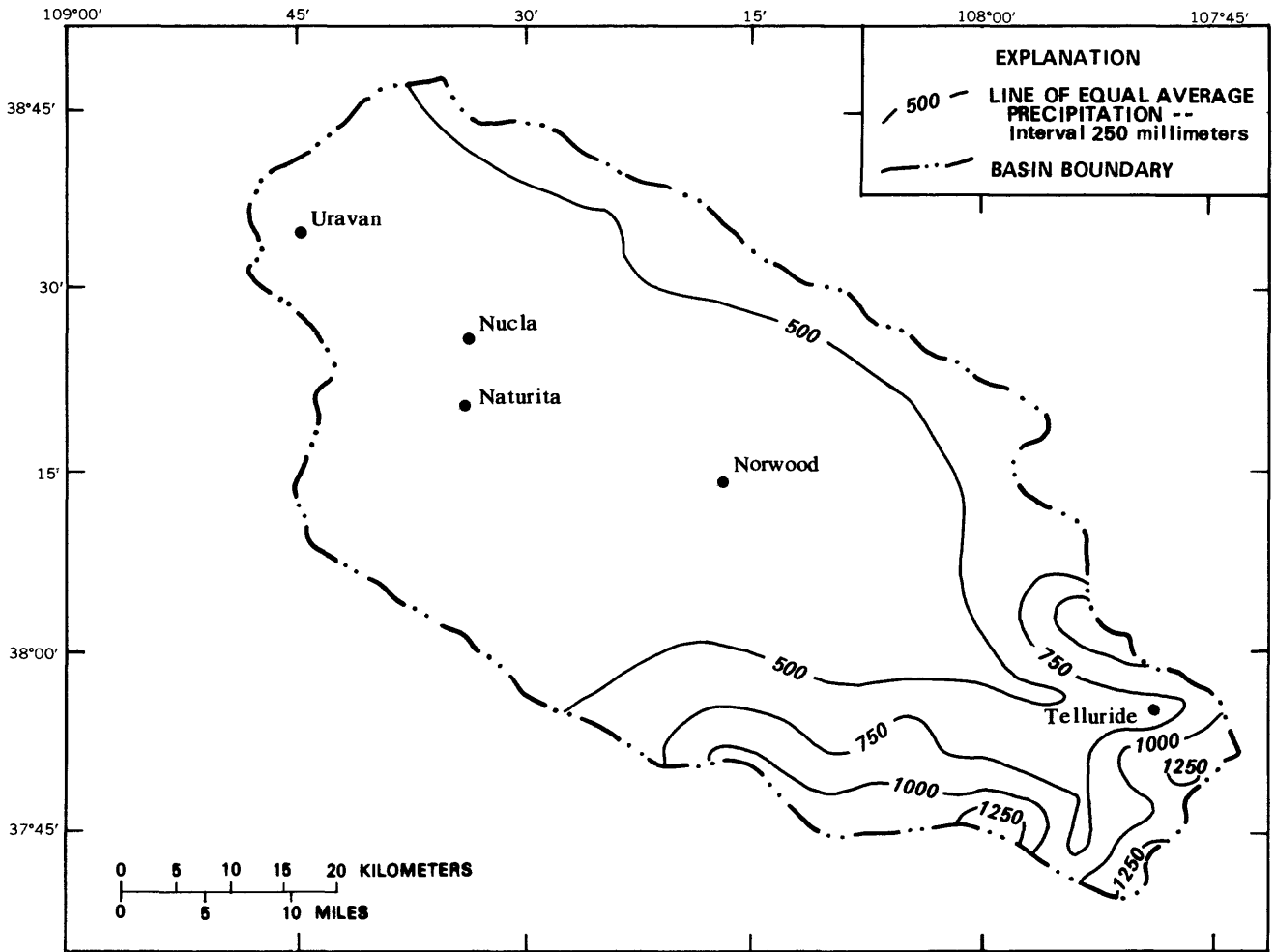


Figure 3.--Relation of precipitation to altitude in and near the San Miguel River basin, 1951-70.



Modified from Iorns and others (1965, Plate 4)

Figure 4.--Distribution of average annual precipitation.

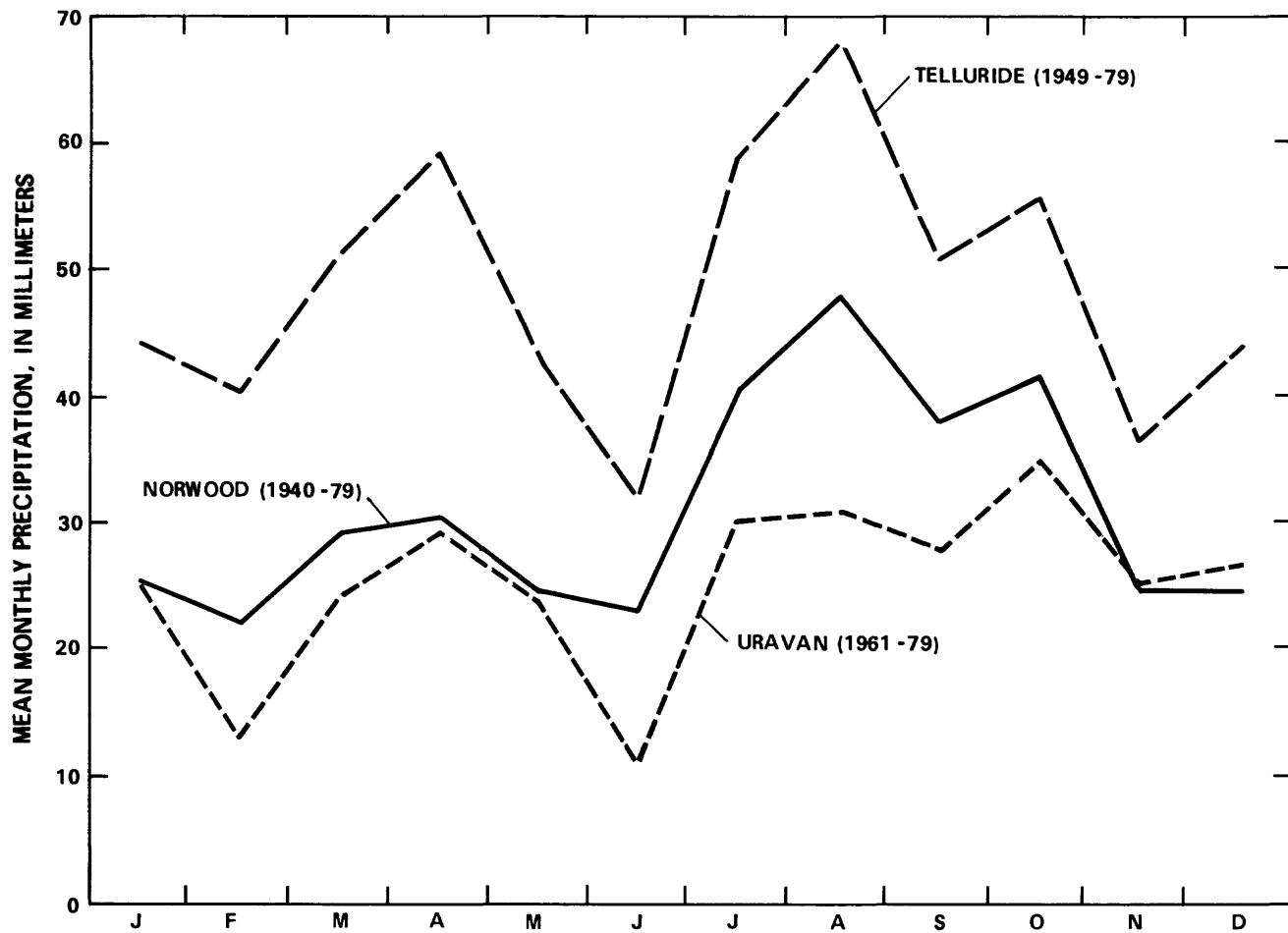


Figure 5.--Mean monthly precipitation at three stations.

Table 3.--*Estimated average annual precipitation*

Precipitation range (millimeters)	Average precipi- tation (millimeters)	Area		Precipitation	
		Square kilo- meters	Percent	Cubic meters x10 ⁶	Percent
<300	280	180	4.4	50	2.3
300 - 400	350	1,420	34.3	500	23.2
400 - 500	450	1,000	24.2	450	21.0
500 - 640	570	680	16.5	390	18.2
640 - 760	700	300	7.3	210	9.8
760 - 1,000	880	330	8.0	290	13.5
1,000 - 1,300	1,150	200	4.8	230	10.7
>1,300	1,330	20	.5	27	1.3
Totals (rounded)	--	4,100	100	2,100	100

During the study period (1978 and 1979), precipitation generally was less than long-term average, as shown in figure 6. The cumulative-departure data for the three stations show drier conditions from 1970 to 1979. Previous dry periods were 1916-34 and 1950-60. As a result of the drier conditions during the study, hydrologic conditions deviated from average conditions as follows:

1. Average depths to the water table were slightly greater for the upper ground-water system because of less ground-water recharge from below-average precipitation.

2. Springflow was less.

3. Flow of ground water to perennial streams was less.

4. Runoff resulting from snowmelt and summer thundershowers was less.

The extent to which these conditions were less than average is not known because of insufficient long-term data.

Runoff

Runoff in the basin, as defined by Langbein and Iseri (1960, p. 17), is caused principally by: (1) Melting of snow in the spring and (2) infrequent summer and fall showers. The showers may be intense, but they usually are restricted to small areas and do not last long.

Runoff varies significantly throughout the basin. According to Langbein and others (1949, pl. 1), runoff ranges from about 20 mm in the extreme western part of the basin to more than 250 mm in the mountains, as shown in figure 7.

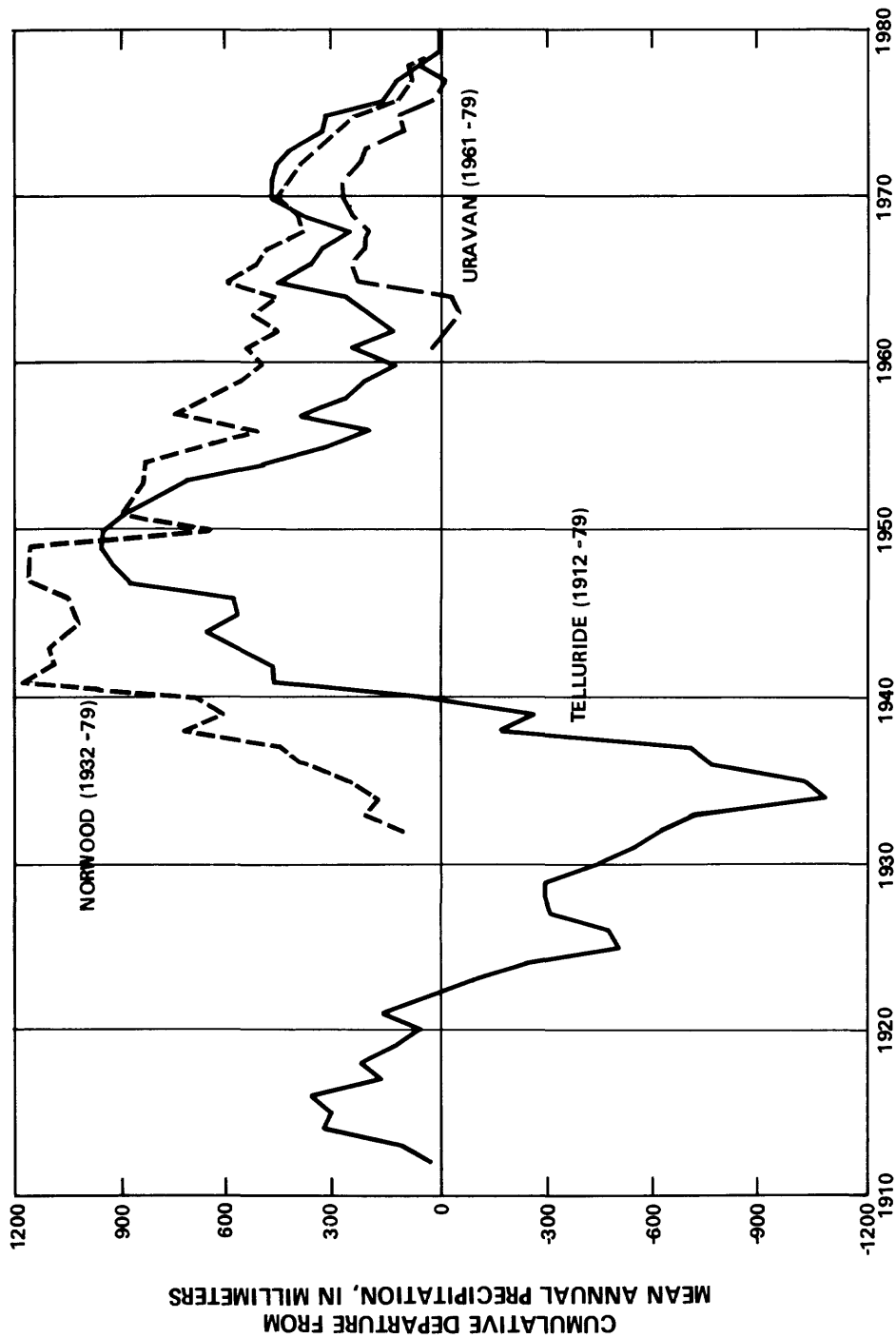


Figure 6.--Cumulative departure of average annual precipitation at three stations.

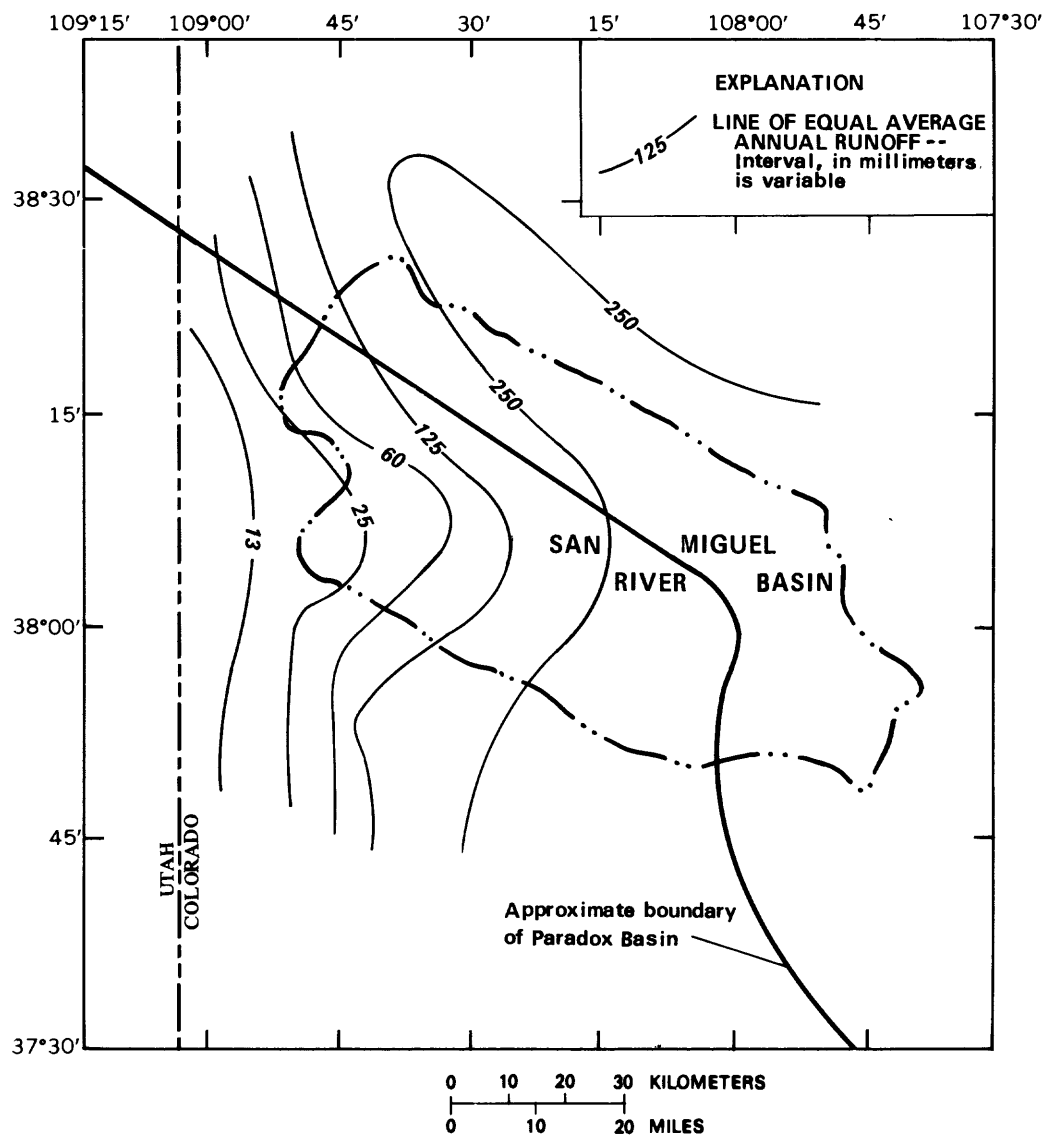


Figure 7.--Distribution of average annual runoff in the San Miguel River basin and vicinity. From Langbein and others (1949, pl. 1).

Records are sufficient to allow only an approximate computation of streamflow from the river basin. The average annual discharge of the San Miguel River at Uravan (about 7 km upstream from the river mouth), for 1954-62 and 1973-79 is $2.95 \times 10^8 \text{ m}^3/\text{yr}$ (U.S. Geological Survey, 1980, p. 70). Average yearly runoff from the whole basin, if computed from the average discharge at Uravan, would be 70 mm or about 14 percent of the computed precipitation. These values do not represent total surface-water outflow under natural conditions because of the following:

1. Evapotranspiration and seepage losses from about 110 km² of irrigated land.
2. Evaporation and seepage losses from storage reservoirs.
3. Ungaged streamflow from 250 km² downstream from the gage.

Inflow to the Ground-Water Systems

The source of all inflow to the upper ground-water system is, directly or indirectly, precipitation that falls within the river basin. The empirical method used to compute average annual recharge from precipitation in the northwestern part of the Paradox basin (Rush and others, 1982, p. 27) was not used for this basin because the method was developed for use in desert regions where no appreciable surface water flows from areas. This river basin does not meet this requirement.

For the lower ground-water system beyond the bedded-salt area (fig. 2), recharge occurs from downward percolation of precipitation and runoff. Where the system is beneath the evaporite confining beds, this type of recharge is unlikely and only lateral subsurface flow occurs. However, this lateral flow originates from precipitation that falls within the river basin.

Potentiometric contours for the upper ground-water systems are shown in plate 2. Potentiometric contours for the lower ground-water systems are shown in figure 8.

Outflow from the Ground-Water Systems

Ground-water outflow from the upper ground-water system occurs as evapotranspiration, springflow, discharge to gaining streams, discharge to wells, and subsurface outflow. Ground-water outflow from the lower system occurs only as subsurface outflow.

Evapotranspiration

Water is discharged from the saturated zone by evaporation from the land surface and transpiration by phreatophytes, plants with roots that extend to the water table. Evapotranspiration of water from the saturated zone occurs only where the water table is within about 15 m of the land surface. This probably is limited to the flood plains of perennial streams and grass and brush areas of high mesas; therefore, it is likely to be a small but significant component of outflow. No estimates of evapotranspiration for the basin

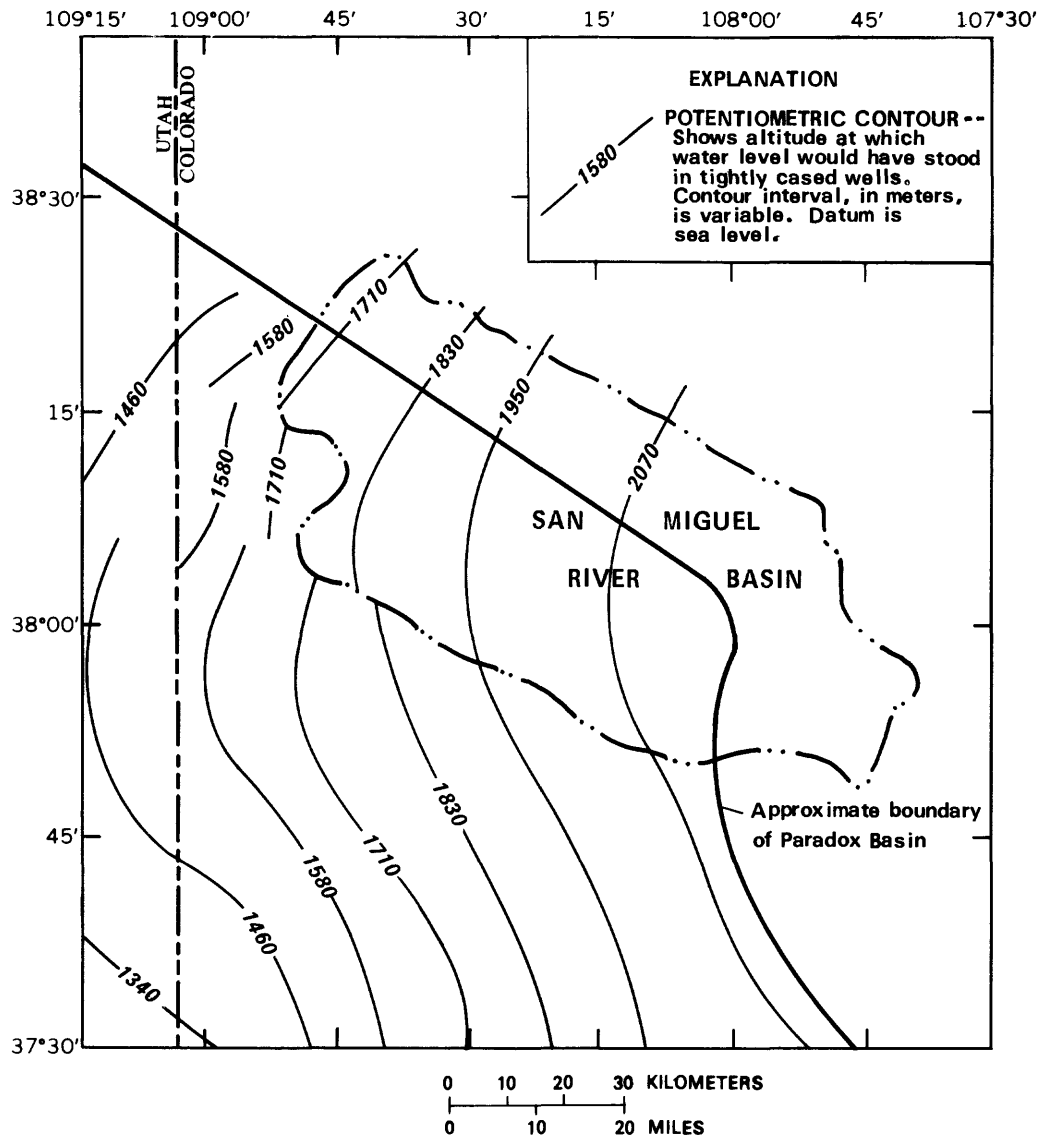


Figure 8.--Potentiometric contours for the lower Paleozoic aquifer in the San Miguel River basin and vicinity. Modified from Hanshaw and Hill (1969, fig. 2).

were made as part of this study, but it is assumed to be a small, but significant part of the total outflow.

Springflow

About 100 to 200 springs are in the San Miguel River basin. About 90 springs and seeps were inventoried and are shown on plate 2. The discharge of 53 springs was measured or estimated. Discharges ranged from 0.02 to 3 L/s and had a mean of 0.5 L/s. Many springs that flow in the spring and early summer are dry the remainder of the year. Most springs occur at the contact of rock units and discharge from the upper ground-water system. The estimated average annual spring discharge is 1×10^6 m³.

Discharge to Streams

Perennial streams of the basin are observed to alternately lose and gain water throughout their lengths; but, in general, they are net-gaining streams. For the San Miguel River near Placerville (T. 44 N., R. 11 W. on pl. 2), Iorns and others (1965, p. 53) estimated that 31 percent of the average annual streamflow was contributed by ground water. This estimate was for water years 1914-57 adjusted to 1957 conditions, a wetter-than-average year (fig. 6). Using the same method, a similar estimate was made for the San Miguel River at Uravan for water years 1955-62 and 1974-79, drier-than-average years (fig. 6). This second estimate indicates that approximately 28 percent of the average annual streamflow was contributed by ground water. Based on an average of these percentages and the streamflow at Uravan (p. 35), estimated net ground-water discharge to streams leaving the river basin as streamflow is approximately 9×10^7 m³/yr.

Subsurface Outflow

Only a small quantity of ground water flows from the river basin in the upper ground-water system, based on the distribution of potentiometric contours on plate 2. Most of the quantity would be transmitted through the Quaternary aquifer that underlies the San Miguel River flood plain at its mouth. Because the cross-sectional area of the aquifer is very small and the gradients slight, this very transmissive material would transmit only a relatively small quantity of underflow compared to the flow in the overlying river.

For the lower ground-water system, the entire ground-water outflow is in the subsurface. The transmissivity of the system is not known, but potentiometric contours (fig. 8) from Hanshaw and Hill (1969, fig. 2) indicate a generally westward flow of ground water from the San Juan Mountains in the southeastern part of the river basin, toward adjoining parts of the Paradox basin. Insufficient data are available to estimate the average annual rate of ground-water outflow in this system.

Wells

According to the records of the Colorado State Engineer's Office, about 350 permits have been issued to drill wells in the basin. Thirty-six wells were inventoried. Many of the wells for which permits were issued were not drilled, were dry, or were abandoned. Most wells in the San Miguel River basin are used only for domestic water supply.

Ground-water discharge by wells probably is an insignificant part of the outflow from the river basin. Maximum probable annual ground-water discharge from wells is about 1×10^6 m³/yr.

Inflow-Outflow Balance

Most unstressed ground-water systems like the ground-water systems of the San Miguel River basin can be assumed to be in dynamic equilibrium; that is, inflow equals outflow and storage is constant. A ground-water budget for the upper ground-water system of the San Miguel River basin is shown in table 4. Although the budget is incomplete and is based on several assumptions, the following conclusions may be made:

1. Discharge to streams is the largest item of outflow.
2. Recharge from precipitation probably is the only element of inflow and is equal to total outflow or greater than 9×10^7 m³/yr.

A budget for the lower ground-water system would have only two nearly equal elements--subsurface outflow and recharge from precipitation.

CHEMICAL CHARACTER OF GROUND WATER

Concentration and kind of dissolved mineral matter in the ground water depend upon the solubility and types of rocks encountered, the length of time the water is in contact with the rocks, and the quantity of carbon dioxide and soil acids in the water. Water that has been underground a long time or has traveled a long distance from the recharge area generally is more mineralized than water that has been in transit for only a short time or distance.

Water-chemistry data for ground water from the San Miguel River basin were compiled from data in the files of the Colorado District, Lakewood, Colo. Quantitative information is available mostly for the Cutler Formation and younger rock units of the upper ground-water system. The maximum measured concentration of dissolved solids for ground waters in the river basin was 5,550 mg/L.

The only clue to the chemical character of deeper ground water is from records of drill-stem tests of petroleum-exploration wells in the northwest one-half of the basin. Water recovered from evaporite confining beds and underlying hydrogeologic units during drill-stem tests, when described, was reported to be saltwater. In some, but not all instances, the saltiness may represent contamination by salt-base drilling fluid.

Table 4.--Water budget for the saturated part of the upper ground-water system

Budget element	Estimated average annual volume (x 10 ⁷ cubic meters per year)
Inflow:	
Recharge from precipitation-----	¹ >9
Subsurface inflow-----	Unknown, probably none.
Total inflow (rounded)-----	¹ >9
Outflow:	
Evapotranspiration-----	Small, but significant.
Springflow-----	0.1
Discharge to streams-----	9
Subsurface outflow-----	Small
Wells-----	0.1
Total outflow (rounded)-----	¹ >9

¹Taken to be equal to total outflow.

Many springs in the basin discharge water perched in the unsaturated zone or discharge ground water that has been in underground transit for a relatively short time. As a result, these springs discharge water that generally is less mineralized than water from deeper parts of the saturated zone that is discharged from springs and wells.

Specific-conductance values for six of seven springs discharging from the Mesozoic and upper Paleozoic confining beds averaged about 350 μ S. The remaining spring (sec. 34, T. 44 N., R. 11 W., at Placerville on pl. 2) is a warm spring, 33°C, with a specific conductance of 3,550 μ S. The water of the warm spring is a sodium bicarbonate sulfate type, whereas all the other springs, which are in the southeastern part of the basin, yield bicarbonate water.

Samples were collected from 44 springs issuing from and 28 wells completed in the Mesozoic sandstone aquifer; specific-conductance values averaged about 400 μ S for the springs and 1,400 μ S for the wells. Chemical analyses of water samples from 11 springs showed all but 1 spring sample to be calcium bicarbonate water. Chemical analyses of water samples from 15 wells showed that most waters were dominated by calcium or sodium cations and by the bicarbonate or sulfate anions. Those waters dominated by sodium or sulfate

ions had specific-conductance values greater than 1,000 μS , whereas those waters dominated by bicarbonate, calcium, and magnesium had specific-conductance values of less than 1,000 μS . As ground water in this hydrogeologic unit increases in salinity, its character apparently changes toward a sodium sulfate water. It is apparent from the differences in chemistry that water from wells completed in this hydrogeologic unit had traversed longer flow paths or had longer contact times than water from the springs.

All water-quality samples from the Tertiary and upper Cretaceous confining beds were collected from springs. Specific-conductance values for 27 samples averaged about 500 μS . This is approximately 100 μS more than the average for springs issuing from the Mesozoic sandstone aquifer. The greater salinity results from the contact with the fine-grained shales of the Tertiary and Upper Cretaceous confining beds that contain soluble minerals. Chemical analyses of four samples from springs in this hydrogeologic unit show most water to be of a calcium bicarbonate type. One analysis shows the water to be of a sodium sulfate chloride type.

No data on water chemistry were available for the Quaternary aquifer. In most areas near perennial streams, however, the dissolved-solids concentrations are expected to be less than 1,000 mg/L and the water chemistry to be similar to the stream.

RELATION BETWEEN FLOW SYSTEMS AND SALT BEDS

In San Miguel River basin, as in the northwestern part of the Paradox basin (Rush and others, 1982, p. 47), ground-water circulation principally is through the Mesozoic sandstone aquifer and the lower Paleozoic aquifer. These aquifers generally are isolated from the evaporite beds by the bounding confining beds. As a result, ground water in the confining beds has little contact with the Paradox Member salt beds and has very slow rates of circulation. Salt solution and removal probably are very slow in most parts of the river basin.

Salt solution, if it occurs, probably could involve circulation of water mostly along the contact zones of the salt section rather than through the section, because the plastic character of the salt beds probably precludes significant permeability. Fracture zones, perhaps associated with faulting and folding, would be the most favorable avenues of circulation in the ground-water systems, but not in the salt.

Saltwater has been reported for petroleum-exploration wells but has not been identified as ground-water outflow. No saltwater springs are known in the area.

NEED FOR ADDITIONAL STUDIES

Four types of detailed hydrologic studies would increase knowledge of the ground-water flow systems of the basin: (1) Investigations of the various elements of inflow to and outflow from the systems, (2) a more detailed description of the geologic framework of the flow systems, (3) a quantitative description of the flow systems in small subareas, and (4) digital modeling of the flow systems as an adequate data base becomes available. Most of these studies would have to be based to a large extent on data not available at this time.

SUMMARY AND CONCLUSIONS

1. The reconnaissance of the general hydrology of the San Miguel River basin was made as a part of a program to investigate potential areas for underground storage of high-level radioactive wastes in the Paradox basin.

2. The 26 rock units that underlie the area have been grouped into eight hydrogeologic units and two ground-water systems. Three aquifers have been identified, two above and one below a thick sequence of confining beds. Within the confining-bed sequence are the salt beds and salt interbeds of the Paradox Member of the Hermosa Formation.

3. Average annual precipitation falling on the river basin ranges between 300 mm and 1,300 mm, and the quantity is related to land-surface altitude. The average annual precipitation for the basin is 2.1×10^9 m³.

4. The source of probably all inflow to the upper and lower ground-water systems is precipitation that falls within the river basin.

5. The flow in the upper ground-water system is mostly from high-altitude areas to nearby perennial-flow reaches of the San Miguel River and its tributaries. In the lower ground-water system, the flow is mostly from the recharge area in the southeastern part of the basin westward in the subsurface out of the basin.

6. The principal element of outflow from the upper ground-water system is discharge to streams, an estimated 9×10^7 m³/yr. All other elements of outflow are relatively small.

7. Saltwater has been reported only in petroleum-exploration wells. Active salt solution in the basin, where it occurs, has not been identified.

8. Additional studies of the ground-water flow systems are needed, including further definition of inflow and outflow elements of the systems, more detailed description of the geologic framework, quantitative description of the flow systems in small subareas, and digital modeling.

REFERENCES

- Boettcher, A. J., 1972, Ground-water occurrence in northern and central parts of western Colorado: Denver, Colorado Water Conservation Board, Water Resources Circular 15, 25 p.
- Cater, F. W., 1970, Geology of the salt anticline region in southwestern Colorado: U.S. Geological Survey Professional Paper 637, 80 p.

- DeBuchanne, G. D., and Twenhofel, W. S., 1975, United States Geological Survey's hydrological research program and plans related to disposal of radioactive waste into geologic formations: U.S. Geological Survey Open-File Report 75-626, 23 p.
- Fenneman, N. M., 1946, Physical divisions of the United States: U.S. Geological Survey map, scale 1:7,000,000 (Reprinted, 1964).
- Friedman, J. D., and Simpson, S. L., 1978, Landsat investigations of the northern Paradox basin, Utah and Colorado; implications for radioactive waste emplacement, Part 1, Lineaments and alignments: U.S. Geological Survey Open-File Report 78-900, 49 p.
- Hanshaw, B. B., and Hill, G. A., 1969, Geochemistry and hydrodynamics of the Paradox Basin region, Utah, Colorado, and New Mexico: *Chemical Geology*, v. 4, no. 1-2, 263-294 p.
- Haynes, D. D., Vogel, J. D., and Wyant, D. G., 1972, Geology, structure and uranium deposits of the Cortez quadrangle, Colorado and Utah: U.S. Geological Survey Miscellaneous Geologic Investigations Map I-629, scale 1:250,000, 2 sheets.
- Hite, R. J., and Lohman, S. W., 1973, Geologic appraisal of Paradox Basin salt deposits for waste emplacement: U.S. Geological Survey Open-File Report 73-114, 75 p.
- Hood, J. W., and Danielson, T. W., 1979, Bedrock aquifers in the lower Dirty Devil River basin area, Utah, with special emphasis on the Navajo Sandstone: U.S. Geological Survey Open-File Report 79-1163, 85 p.
- Iorns, W. V., Hembree, C. H., and Oakland, G. L., 1965, Water resources of the Upper Colorado River Basin--Technical Report: U.S. Geological Survey Professional Paper 441, 370 p.
- Langbein, W. B., and others, 1949, Annual runoff in the United States: U.S. Geological Survey Circular 52, 14 p.
- Langbein, W. B., and Iseri, K. T., 1960, General introduction and hydrologic definitions: U.S. Geological Survey Water-Supply Paper 1541-A, 29 p.
- Neff, A. W., and Brown, S. C., 1958, Ordovician-Mississippian rocks of the Paradox basin, in Sanburn, A. F., ed., Intermountain Association of Petroleum Geologists Annual Field Conference, 9th, 1958, Guidebook: Salt Lake City, Intermountain Association of Petroleum Geologists, p. 102-108.
- Papadopoulos, S. S., and Winograd, I. J., 1974, Storage of low-level radioactive wastes in the ground--Hydrogeologic and hydrochemical factors, with an appendix on the Maxey Flats, Kentucky, radioactive waste storage site--Current knowledge and data needs for a quantitative hydrogeologic evaluation: U.S. Geological Survey Open-File Report 74-344, 49 p.
- Price, Don, and Arnow, Ted, 1974, Summary appraisals of the Nation's groundwater resources--Upper Colorado region: U.S. Geological Survey Professional Paper 813-C, 40 p.
- Rush, F. E., Whitfield, M. S., and Hart, I. M., 1982, Regional hydrology of the Green River-Moab area, northwestern Paradox basin, Utah: U.S. Geological Survey Open-File Report 82-107, 86 p.
- Shawe, D. R., 1970, Structure of the Slick Rock district and vicinity, San Miguel and Dolores Counties, Colorado: U.S. Geological Survey Professional Paper 576-C, 18 p.

- Shawe, D. R., Simmons, G. C., and Archbold, N. L., 1968 [1969], Stratigraphy of Slick Rock district and vicinity, San Miguel and Dolores Counties, Colorado: U.S. Geological Survey Professional Paper 576-A, 108 p.
- Stevens, T. A., Lipman, P. W., Hail, W. J., Jr., Barker, Fred and Luedke, R. G., 1974, Geologic map of the Durango quadrangle, southwestern Colorado: U.S. Geological Survey Miscellaneous Investigations Series Map I-764, scale 1:250,000.
- Tweto, Ogden, Stevens, T. A., Hail, W. J., Jr., and Moench, R. H., 1976, Preliminary geologic map of the Montrose 1°x2° quadrangle, southwestern Colorado: U.S. Geological Survey Miscellaneous Field Studies Map MF-761, scale 1:250,000.
- U.S. Bureau of the Census, 1981, General population census of Colorado: U.S. Bureau of the Census Report PC80-1B, Part 7, 856 p.
- U.S. Geological Survey, 1980, Water resources data for Colorado, Volume 3, Dolores River basin, Green River basin, and San Juan River basin: U.S. Geological Survey Water-Data Report CO-79-3, 438 p.
- Williams, P. L., 1964, Geology, structure, and uranium deposits of the Moab quadrangle, Colorado and Utah: U.S. Geological Survey Miscellaneous Geological Investigations Map I-360, scale 1:250,000.