REGIONAL HYDROLOGY OF THE DOLORES RIVER BASIN, EASTERN PARADOX BASIN, COLORADO AND UTAH

By J. E. Weir, Jr., E. Blair Maxfield, and E. A. Zimmerman

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METRIC CONVERSION TABLE

For those readers who prefer to use inch-pound units rather than metric units, conversion factors for the terms used in this report are listed below:

Metric Unit	Multiply by	To obtain inch-pound unit
centimeter (cm)	3.937×10^{-1}	inch
millimeter (mm)	3.937×10^{-2}	inch
millimeter per annum (mm/a)	3.937×10^{-2}	inch per year
kilometer (km)	6.214×10^{-1}	mile
square kilometer (km^2)	3.861×10^{-1}	square mile
meter (m)	3.281	foot
cubic meter (m^3)	35.31	cubic foot
cubic meter per annum (m^3/a)	35.31	cubic foot per year
cubic meter per second (m^3/s)	35.31	cubic foot per second
degree Celsius (°C)	1.8°C + 32	degree Fahrenheit
milligram per liter (mg/L)	1/ 1.0	part per million
microsiemens (µS)	1.0	micromho per centimeter at 25° Celsius
liter per second (L/s)	1.585×10^{1}	gallon per minute
liter per minute (L/min)	9.516×10^{2}	gallon per minute

1/ Approximate

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.

CLASSIFICATION OF NATURAL WATER

(From Feltis, 1966, p. 8, and Robinove, Langford, and Brookhart, 1958, p. 3)

Class	Dissolved solids (mg/L)	Specific conductance (μS)
Fresh	0 to 1,000	0 to 1,400
Slightly saline	1,000 to 3,000	1,400 to 4,000
Moderately saline	3,000 to 10,000	4,000 to 14,000
Very saline	10,000 to 35,000	14,000 to 50,000
Briny	More than 35,000	More than 50,000

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ABSTRACT

Investigation of the geohydrology of the Dolores River basin is one of five reconnaissance studies of the Paradox basin conducted as part of a program designed to evaluate the potential for storage of nuclear waste in salt deposits. The work was done by the U.S. Geological Survey under the auspices of the U.S. Department of Energy (Interagency Agreement DE-AI97-79ET44611). The area, approximately 7,900 square kilometers, is in the eastern part of the Paradox basin and includes the eastern slope of the La Sal Mountains, the western slopes of the Rico and La Plata Mountains, and the southwest flank of the Uncompahgre Plateau.

The climate of the study area is more humid than most of the surrounding Colorado Plateau region. Precipitation ranges from slightly less than 200 millimeters per year to more than 1,000 millimeters per year; the estimated volume of water falling on the area is $4,000 \times 10^6$ cubic meters per year. Of this total, about 600×10^6 cubic meters per year is runoff; 190×10^6 cubic meters per year recharges the upper ground-water system; and an estimated 55×10^6 cubic meters returns to the atmosphere via evapotranspiration from stream valleys. The remainder evaporates.

Rocks ranging in age from Proterozoic to Holocene crop out in the area. Sedimentary strata of Paleozoic age comprise most of the geologic section.

Principal hydrogeologic units are permeable sandstone and limestone and nearly impermeable salt (halitic) deposits. In order of decreasing estimated hydraulic conductivity, the hydrogeologic units include: (1) The lower Paleozoic aquifer; (2) the alluvial aquifer; (3) the Mesozoic sandstone aquifer; (4) the Tertiary-Upper Cretaceous aquifer; (5) the Cretaceous confining beds; (6) the upper Paleozoic confining beds; (7) Mesozoic-upper Paleozoic confining beds; (8) lower Paleozoic-Proterozoic confining beds; and (9) the salt confining beds, consisting of the salt deposits of the Paradox Member of the Hermosa Formation. The salt confining beds separate the upper and lower ground-water systems.

Structurally, the area is dominated by northwest-trending salt anticlines and contiguous faults paralleled by synclinal structures. The Uncompahgre Plateau lies along the north and northeast sides of the area. The intrusive masses that form the La Sal Mountains are laccoliths with bysmaliths and other complex intrusive forms comprising, in gross form, moderately faulted domal structures. Intrusive rocks underlie the La Plata and Rico Mountains along

the southeastern edge of the area. These geologic structures significantly modify ground-water flow patterns in the upper ground-water system, but have no conspicuous effect on the flow regime in the lower ground-water system.

The water in the upper ground-water system generally is fresh except where it is affected by evaporite dissolution from salt anticlines. The water of the lower ground-water system is slightly saline to briny. Water quality of the Dolores River is slightly saline to fresh, based on dissolved chemical constituents; some of the smaller tributaries of the river have saline water.

The Dolores River, though slightly saline to fresh, contributes an estimated 494 metric tons of salt daily to the Colorado River system; this is almost five times the quantity of sodium chloride contributed to the Colorado River by all other streams draining the Paradox basin.

INTRODUCTION

The U.S. Geological Survey has investigated various hydrogeologic media to evaluate their suitability for storing radioactive wastes. Among the rock media potentially acceptable for a waste repository is salt (halite), largely because of its negligible permeability and its propensity for "healing" by plastic flowage the cracks that may have resulted from tectonic disturbances. Salt also has several unfavorable characteristics, including its solubility in freshwater. However, this solution can take place only where the salt is exposed at the land surface or is subjected to through-flowing ground water that has a small sodium chloride concentration. Therefore, the central zones of salt deposits that are both buried and distant from through-flowing ground water may be hydrologically acceptable for storing waste.

The Paradox basin is one of the areas under consideration for storage of wastes in salt deposits. This report is one of a series of reconnaissance geohydrologic studies of the Paradox basin begun in 1977. The purpose of the investigation was to compile and interpret available hydrologic data, with principal emphasis on the hydrologic relation of the water resources with respect to the salt deposits, in order to serve as a basis for more detailed evaluations of potential repository sites. Existing geohydrologic data and reports were the principal sources of information; some new data were collected to augment existing information.

Location and Extent of the Area

The part of the Paradox basin described in this report is shown in figure 1. The area is defined by the drainage area of the Dolores River. It drains an area approximately outlined by the Uncompahgre Plateau on the north and northeast, the La Sal Mountains on the west, and the La Plata and Rico Mountains on the south and east.

The study area is bounded on the north by the drainage divide between the Dolores and Uncompahgre-Colorado River. The western boundary follows the drainage divide between the Dolores and Colorado Rivers in a southerly direction for about 85 km, then follows the drainage divide between the Dolores and San Juan Rivers in a southeasterly direction for about 130 km. Near the town of La Plata, Colorado, the boundary trends northeast following the drainage divide between the Dolores and Animas Rivers for about 45 km. Where the boundary intercepts the San Miguel River drainage, it trends northwest following the Dolores and San Miguel Rivers' drainage to a point where the San Miguel and Dolores Rivers join; then, it trends north to the Uncompahgre Plateau.

The Dolores River basin is about 155 km long from northwest to southeast; it averages about 55 km in width. Its area is about 7,900 km^2. The Dolores River drainage basin includes two areas (about 1,500 km^2) near Gateway and Rico, Colorado, that are outside the Paradox basin, as defined by limits of salt deposition (pl. 1). The Paradox basin is nearly evenly divided into

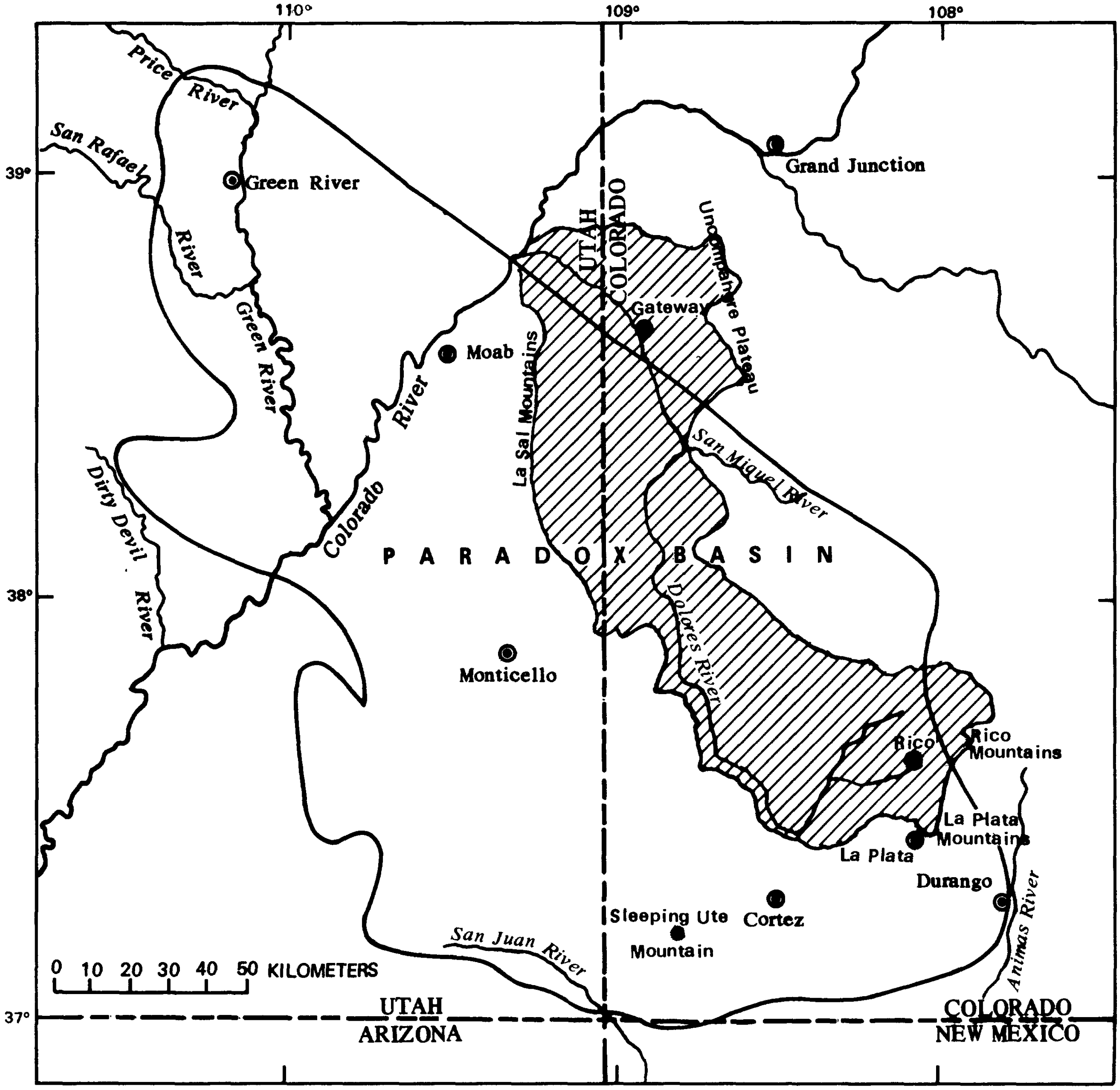

Figure 1.--Location of the Dolores River drainage basin in the Paradox basin of southeastern Utah and southwestern Colorado.

two parts by the common boundary between southeastern Utah and southwestern Colorado. The area described in this report is mostly in Colorado, with only a narrow strip in eastern Utah.

Previous Work

Hunt (1958) described the structural and igneous geology of the La Sal Mountains in detail and briefly noted some of the water resources. Hunt's report includes some of the northwestern part of the Dolores River basin. Richmond (1962) described the Quaternary stratigraphy and Pleistocene and Holocene physiographic development of the La Sal Mountains. Williams (1964) compiled much of the geology of the area in a geologic and structural map that includes the northern one-half of the Dolores River basin. Witkind (1964) described the geology of the Abajo Mountains area in southeastern Utah; Witkind's report described the stratigraphic characteristics of various units, and briefly noted some of the water resources. Ekren and Houser (1965) described the geology and petrology of the Ute Mountain area in southwestern Colorado; their report described the stratigraphic characteristics of various units, briefly noting some of the water resources.

Iorns, Hembree, and Oakland (1965), in a regional study of the Upper Colorado River Basin, presented basic data and summarized the hydrology of a region that included the Dolores River basin. Baars' (1966) analysis of the pre-Pennsylvanian paleotectonics included some of the hydrologic characteristics of the stratigraphic units involved. Feltis (1966), in a reconnaissance survey of regional ground-water sources, described the occurrence and quality of water in bedrock aquifers of eastern Utah. A report on the Paradox basin by Hanshaw and Hill (1969) included small-scale potentiometric maps and hydrologic interpretations for five aquifers ranging in age from Mississippian to Permian; chemical analyses of water from strata of Mississippian, Pennsylvanian, and Permian age also are included. A geologic and structural map by Haynes, Vogel, and Wyant (1972) included much of the southern part of the area. Hite and Lohman (1973) described general characteristics of the salt anticlines in the Paradox basin and their relationship to possible radioactive-waste disposal sites. Konikow and Bedinger (1978) described the hydrology of a part of Paradox Valley, emphasizing a saltwater problem. Most of the authors cited in this paragraph used some data from exploratory drilling done by oil and mining companies.

Other reports published as part of the general program to provide geologic and hydrologic information for determining the suitability of salt deposits for radioactive-waste storage include those by Gard (1976), Hite (1977), Rush and others (1982), Thackston and others (1981), and J. E. Weir, Jr. and others (U.S. Geological Survey, written commun., 1982). The first two reports describe geology of salt anticlinal areas and contain references to most of the geologic interpretations published for the Paradox basin.

Numbering System for Hydrologic Data Sites

Hydrologic data sites referred to in this report are numbered by location according to a system based on the rectangular subdivision of the public lands. Three surveys provide the basis for the numbering system. The location numbers for sites in Utah are based on the Salt Lake base line and meridian. The location number consists of three units: (1) The first unit is the township south of the base line; (2) the second unit, separated from the first by a slant, is the range east of the meridian; and (3) the third unit, separated from the second by a dash, designates the section number. The section number is followed by as many as three letters that indicate successive quadrant divisions of the section to quarter, sixteenth, and sixty-fourth parts of a section: the letter a designates the northeast quadrant; the letter b designates the northwest quadrant; the letter c designates the southwest quadrant; and the letter d designates the southeast quadrant; these letters may be followed by a sequence number to differentiate sites within the same one-sixty-fourth section tract.

Sites in Colorado are numbered according to their locations under either the Sixth Principal Meridian Survey or the New Mexico Survey. Sites in the Sixth Principal Meridian Survey are in only the northernmost part of the Dolores River basin in Colorado. The location number again consists of three units: (1) The township south of the base line (either 14 or 15); (2) the range west of the meridian (from 100 to 104) separated from the first by a slant; and (3) the section number, separated from the second by a dash. Further subdivisions, as above, are designated by the letters a, b, c, or d.

Sites in the New Mexico Survey are numbered from a base line and meridian in New Mexico. The numbering system is virtually the same, except that the township part of the number is north of the base line, and the ranges are numbered to the west. Sites in this part of the Dolores River basin have township numbers ranging from 37 to 51 and range numbers from 9 to 20.

As an example, a well with location number 44/19-25acc is in the SW¼ of the SW¼ of the NE¼ of section 25, T. 44 N., R. 19 W., and is in Colorado. Had the township been 15 or less, and the range more than 100, the site would be in the northern part of the drainage basin in Colorado. If the range were from 24 to 26, the site would be in Utah. If the location of a hydrologic site is not accurately known, only that part of the location number is given that represents the ability to determine the location of the site.

HYDROLOGIC ENVIRONMENT

Climate

The region around the Dolores River basin has a variable climate. Climate is affected more by differences in altitude and the effect of mountains on the movement of air masses and storms than by the small range of geographic latitude. Pacific air masses and storms dominate the regional weather during October through April; warm, moisture-laden air masses from the

Gulf of Mexico may traverse the region in summer. Summer weather produces less frequent but more intense storms. Higher parts of the mountains are comparatively wet and cool; their slopes and adjacent plateaus are drier and subject to large variations in temperature diurnally and seasonally. The semiarid and arid canyons and valleys at lower altitudes have hot, dry summers and cold, dry winters.

In the hydrologic regimen of the Dolores River basin, evaporation constitutes the principal consumptive use, or water loss. Consumptive use includes water loss through transpiration by all types of vegetation (not only phreatophytes, described separately in this report), and evaporation from land, vegetation, and water surfaces. Potential evapotranspiration is defined by Thornthwaite and Mather (1955) as the water loss that will occur if there is no deficiency of soil water. A weighted, mean annual, potential evapotranspiration for the area is about 900 mm. Potential evapotranspiration (total evaporational loss) ranges from about 1,370 mm in the lower altitudes (below 1,500 m) to about 600 mm near the summits of the mountains (about 3,300 m). These values for potential water loss are much greater than actual water loss, because there is a nearly continuous deficiency of soil moisture in this semiarid to arid environment.

Physiography and Drainage

The Dolores River basin includes most of the eastern and southern parts of the Paradox basin, except for the northeasternmost part, which is in the San Miguel River basin. The Paradox basin is a major subdivision of the Colorado Plateau province as defined by Fenneman (1946). Altitudes exceed 1,500 m throughout most of the Colorado Plateau province. Thornbury (1965) defined the Colorado Plateau province as an area encompassing approximately 242,000 km^2 in parts of Arizona, New Mexico, Utah, and Colorado; about 90 percent of the province is drained by the Colorado River and its tributaries.

Despite the local existence of a high degree of structural relief, structural features with gently dipping sedimentary rocks characterize much of the province. Deep canyons are more common here than in any other part of the United States. Except in areas of highest altitudes, the climate is semiarid to arid. Differential erosion on strong and weak rocks has produced innumerable escarpments and benches; these benches commonly may follow or parallel structural features. The extensive relief is largely the result of deeply incised canyons eroded into moderately flat terrain.

Altitude extremes in the Dolores River basin range from about 1,250 m at the northwestern corner of the basin, at the confluence of the Dolores and Colorado Rivers, to more than 4,300 m on El Diente Peak, in the Rico Mountains. Steplike structural benches called mesas, are common between the river and the mountain ranges that nearly surround the area. In the north, the benches nearest the river are most commonly of Navajo and Wingate Sandstones and Kayenta Formation. The next set of benches mountainward are of the Morrison Formation, and the higher benches are of the Dakota Sandstone. In the southern part of the area, the benches nearest the river are underlain by Morrison Formation; progressively higher benches are underlain by the Dakota Sandstone and the Mesaverde Formation.

Drainage of the Dolores River basin is by way of the Dolores River, thence to the Colorado River near Cisco, Utah. The largest and principal tributary to the Dolores River is the San Miguel River. Most of the flow of the Dolores and San Miguel Rivers originates on the western slopes of the La Plata and Rico Mountains, and flow is replenished by snowmelt and springs. Many smaller perennial and intermittent streams tributary to the Dolores River are sustained by snowmelt and springs of the higher mountains and mesas. A somewhat lesser flow is contributed to the Dolores River system from perennial and intermittent streams sustained by snowmelt and springs along the flanks of the La Sal Mountains and the Uncompahgre Plateau.

The San Miguel River follows a strike valley on the side of the Uncompahgre Plateau, but the course of the Dolores River is anomalous. It flows southwestward down the flank of the Rico Mountains, and then turns north. Perhaps the river originally continued southwestward through the area of Sleeping Ute Mountain, but became diverted when the La Plata Mountains and Sleeping Ute Mountain were domed by Tertiary intrusives (Hunt, 1956, p. 69). Deformation of the salt anticlines resumed in early Eocene and recurred in later Eocene and Oligocene time (Cater, 1955). If the diversion of the Dolores River by the Sleeping Ute Mountain intrusives was prior to or coincident with deformation of the salt anticlines, this could further account for the anomalous course of the Dolores River across Paradox Valley.

Hydrogeologic Units

Major hydrologic systems in the area consist of a lower and an upper ground-water system separated by salt confining beds. The lower ground-water system includes the granitic and metamorphic basement upward to the base of the salt-bearing beds of the Paradox Member of the Hermosa Formation. The salt confining unit is the salt-bearing beds. The upper ground-water system consists of all stratigraphic units from the top of the Paradox Member to the surface, and locally includes Quaternary alluvium.

The lower ground-water system, consisting of three hydrogeologic units (table 1, in pocket), contains saltwater, and, locally, some oil and gas. The Leadville Limestone in the lower Paleozoic aquifer is the most permeable unit in the lower ground-water system. The Ouray and Elbert Formations, also in the lower Paleozoic aquifer, locally yield saltwater, oil, and gas to some of the boreholes that have penetrated them. The remaining stratigraphic units in the lower ground-water system are of lithologies that have little permeability; these hydrogeologic units comprise the lower Paleozoic-Proterozoic and the upper Paleozoic confining beds.

The salt confining beds (table 1) consist of 70 to 80 percent halite (Hite and Lohman, 1973, p. 28) and some associated potash salts that virtually are impervious to fluid flow. Shale, dolomite, and anhydrite interbedded with the salt are fractured, and yield brine, gas, and oil to exploratory holes in greatly varying quantities, ranging from trace quantities to commercially productive accumulations. Hite and Lohman indicate (1973, p. 42): "Oil and petroleum gases, primarily methane, are found in the Paradox Member by almost every well drilled in the Paradox basin." Generally, pressure in these hydrocarbon deposits dissipates within a few hours or days, indicating that they are localized reservoirs sealed by salt layers. The salt deposits constitute a highly effective barrier to fluid flow.

The upper ground-water system consists of five hydrogeologic units: (1) Mesozoic-upper Paleozoic confining beds; (2) Mesozoic sandstone aquifer; (3) Cretaceous confining beds; (4) Tertiary-Upper Cretaceous aquifer, and (5) alluvium aquifer (table 1). The Mesozoic-upper Paleozoic confining beds are mainly mudstone, siltstone, shale, and other fine-grained rocks.

The Mesozoic sandstone aquifer consists predominantly of sandstone beds that yield varying quantities of water to wells and springs where saturated. Some of the sandstone yields a little water from interstices, but most units that yield moderate quantities of water do so from fractures. Not every bed in this thick section is sandstone; some are shale, mudstone, limestone or conglomerate, and they also transmit some water where they are intensely fractured. The Navajo Sandstone and the Wingate Sandstone of the Glen Canyon Group and the Entrada Sandstone of the San Rafael Group are the most important bedrock aquifers throughout much of the northern part of the Dolores River basin. This is partly because water in these sandstones is fresh and, in a few places adjacent to the Dolores River area, yields of water from wells completed in the Navajo Sandstone are sufficient for some uses. In the southern part of the Dolores River basin, the Dakota Sandstone and Burro Canyon Formation are important aquifers. Many stock-watering wells west of the Dolores River and south of the La Sal Mountains produce from these units. On the east side of the Dolores River, in the southern part of the Dolores River basin, springs yield small quantities of water (3 to 5 L/min) from the Dakota Sandstone and the Burro Canyon Formation, especially on the high structural benches east of the Dolores River. The yields are small, but the water is fresh. The Dakota Sandstone yields small quantities of water to a few flowing wells in Disappointment Valley. Some of the other units, such as the Junction Creek Sandstone and Dolores Formation yield water, but their yields generally are very small, and their areal extent is limited.

Cretaceous confining beds are mainly shale. These units confine water in the underlying Dakota Sandstone in Disappointment Valley, causing artesian flow from a few wells in this valley. The Tertiary-Upper Cretaceous aquifer (table 1), consisting of the Mesaverde Group and intrusive rocks in the high mountains, yields water to springs. The Mesaverde Group is present mainly in the southeastern part of the study area. The alluvial aquifer, consisting of alluvium, wind-blown deposits, and glacial till, is important in the larger valleys, where stream-deposited alluvium is thickest.

Structure

The Paradox basin is defined as that part of the Colorado Plateau physiographic province that is underlain by Pennsylvanian evaporites, stratigraphically designated as the Paradox Member of the Hermosa Formation. Thus, the basin is more depositional than structural or topographic, although some parts of the basin boundary are the edges of adjacent positive structural features, such as Uncompahgre Plateau, San Rafael Swell, and La Plata and Rico Mountains.

Within the Paradox basin, the principal structural features are the salt anticlines, most of which are elongated welts trending predominantly northwest. Synclines parallel the salt anticlines. Faulting and fracturing associated with and contiguous to folding is assumed to probably influence lateral and vertical migration of ground water.

The salt-anticlinal structures (fig. 2) resulted from both regional compressive stresses and plastic flowage (Hite and Lohman, 1973, p. 68) of the Paradox Member of the Hermosa Formation. The southeastern parts of Fisher Valley and Lisbon Valley and all of Sinbad Valley, Paradox Valley, Dry Creek, Big Gypsum Valley, Dolores, and Calico Peak anticlines are within the Dolores River basin (Williams, 1964; Haynes, Vogel, and Wyant, 1972).

Intrusive rocks of Tertiary age form the cores of the La Sal, La Plata, and Rico Mountains bordering the Dolores River basin. The intrusive are described as stocks, laccoliths, sills, dikes, and bysmaliths (Eckel, 1949; Hunt, 1958; Witkind, 1964; and Ekren and Houser, 1965). Where these rocks are unfractured, they are barriers to local ground-water flow; where they are fractured and crop out, they also may receive and transmit recharge (Sumsion, 1971, p. 12).

The northern and northeastern parts of the Dolores River basin are bounded by the Uncompahgre Plateau. This feature is a large monoclinal structure with a core of Proterozoic granitic intrusives, (chiefly granite with coarse microcline phenocrysts), some granite gneiss, pegmatite dikes, and a few lamprophyre dikes. The granitic complex intruded an older sequence of quartz-biotite and quartz-feldspar schists and gneisses (Williams, 1964). Where these rocks crop out and are intensely fractured, they also may be recharge areas; however, where unfractured, they are confining units.

Broad structural benches where sandstone of the upper aquifer system are exposed (pl. 1) constitute recharge areas. Where those benches occur high on the flanks of the mountain masses, greater recharge is likely, primarily because precipitation is greater.

Ground-Water Occurrence

The upper ground-water system, consisting of all the stratigraphic units above the Paradox Member of the Hermosa Formation (table 1), crops out in the study area. The upper ground-water system locally is confined by unfractured strata with relatively little permeability, but in most places it is unconfined (under water-table conditions), because erosion has exposed the fractured hydrogeologic units throughout extensive areas. An example of confined (artesian) conditions is in Disappointment Valley, where flowing wells produce from the Dakota Sandstone at the top of the Mesozoic sandstone

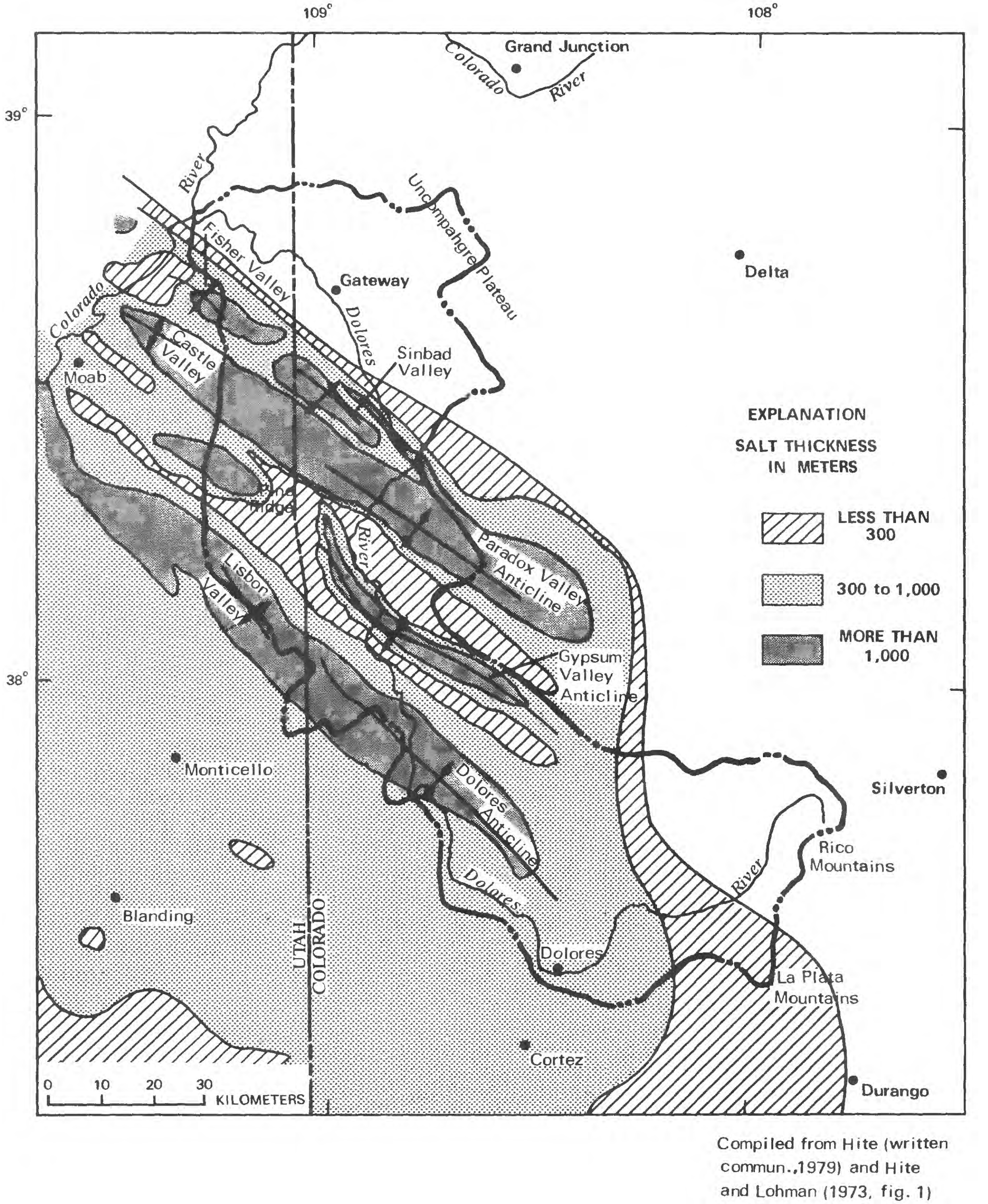

Figure 2.--Generalized salt thickness and major structural trends in the Dolores River basin and vicinity.

aquifer underlying Cretaceous confining beds. Where these aquifers crop out, they are recharged from local precipitation and runoff that percolates downward toward saturated zones.

Hydrogeologic units of the lower ground-water system do not crop out in the study area. This lower ground-water system receives its recharge in areas of outcrop outside the boundaries of the study area. The system is artesian, confined by overlying upper Paleozoic confining beds and salt confining beds, both of which are effective confining units. Based on information from drilled wells, the salt confining beds are probably thin in a few localities because of salt flowage (pl. 1 and fig. 2).

The principal direction of water flow in the zone of saturation is lateral. Where such stratigraphic units as the Brushy Basin Member of the Morrison Formation, Summerville, Chinle, and Moenkopi Formations, and most of the Dolores Formation are effective confining units that restrict vertical migration of fluids within the upper ground-water system. Where salt confining beds are present, they are a confining unit. Where salt beds are absent due to salt flowage, a small vertical interchange of water might occur between the two major ground-water systems.

Precipitation

The Dolores River basin, according to Pyke (1972, fig. 3b), is in a precipitation transition zone. It lies between areas to the south, east, and west that are characterized by maximum precipitation in August and secondary precipitation in February, May, and December. Precipitation for the Dolores River basin was first measured and recorded at Rico during 1906. Abundant precipitation data that have been collected in and near the basin are summarized in several tables and illustrations (figs. 3-6) in this section of the report.

A summary of average annual precipitation at weather stations in and near the study area is given in table 2. Location of the stations are shown in figure 3. Because some of the periods of record for precipitation are short in relation to records of La Sal and Durango, all other station averages were adjusted to the longer term means (table 2). These values then were plotted on a graph (fig. 4) to determine the general relation of precipitation to altitude in the area. As shown, average precipitation systematically increases with altitude from about 310 mm/a or less at an altitude of 1,390 m, to more than 600 mm/a at an altitude of 2,865 m.

Areal distribution of precipitation in the report area is shown in figure 3. Average annual precipitation on the mesas and lowlands ranges from about 300 to 400 mm. Average annual potential lake evaporation is estimated to be 1,050 to 1,200 mm (Kohler and others, 1959, pl. 2), or about 4 times greater than precipitation. Mesas and lowlands are, therefore, semiarid to arid. In the higher areas of the La Sal, La Plata, and Rico Mountains, precipitation equals or exceeds 750 mm/a; the climate is subhumid to humid, because the quantity of precipitation is closer to potential evaporation.

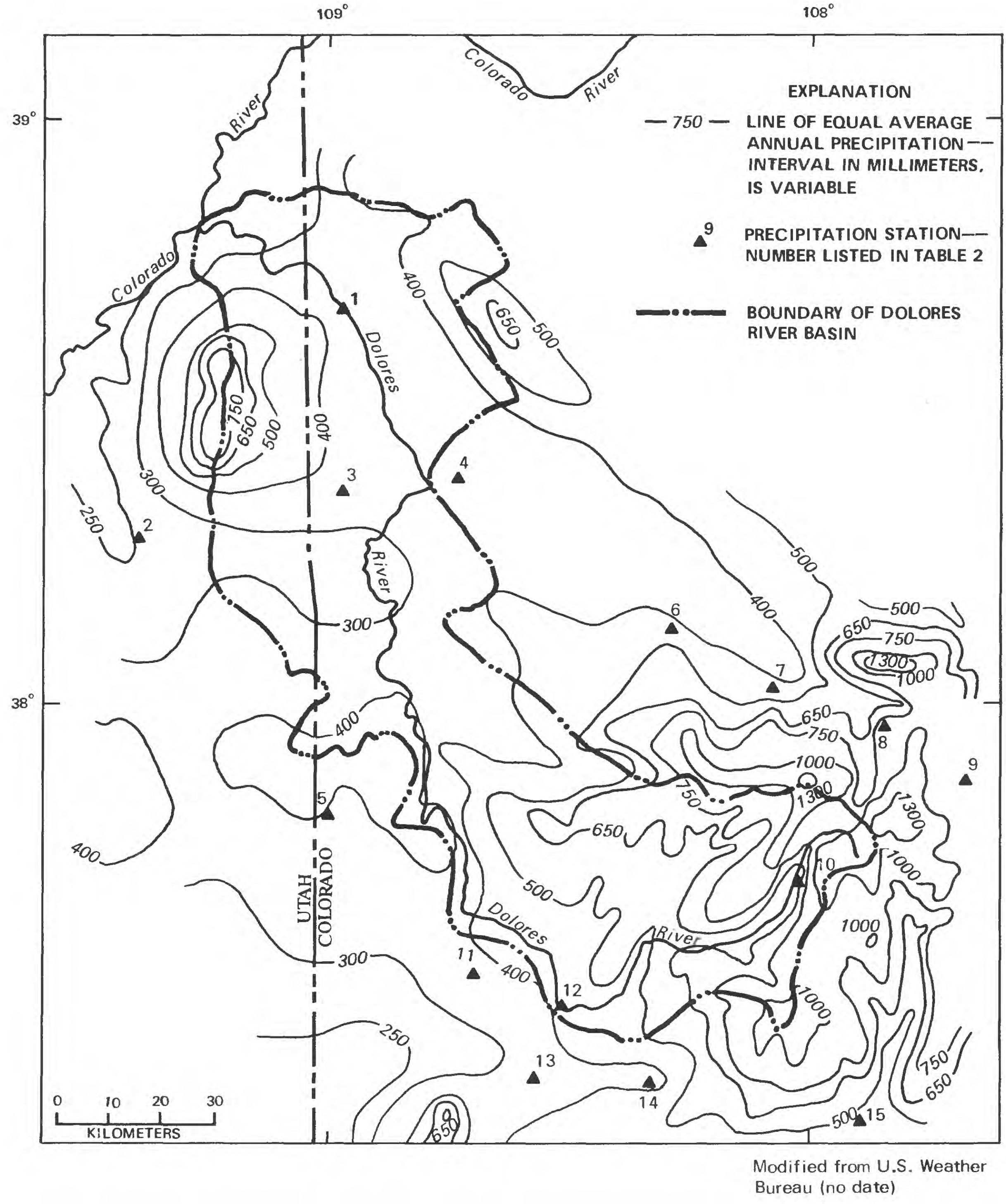

Figure 3.--Areal distribution of average annual precipitation and location of precipitation-recording stations in the Dolores River basin and vicinity.

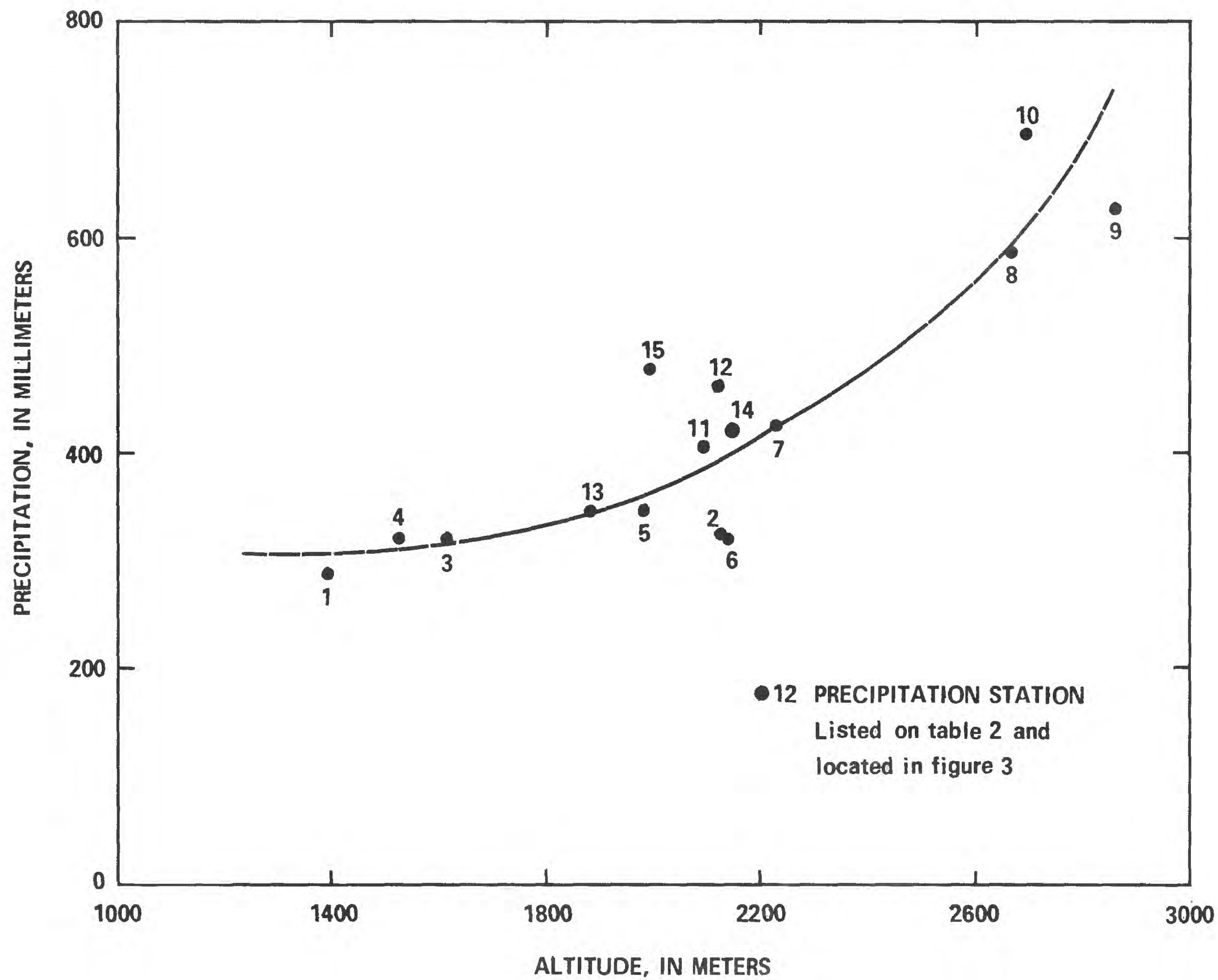

Figure 4.--General relation of precipitation to altitude in the Dolores River basin and vicinity.

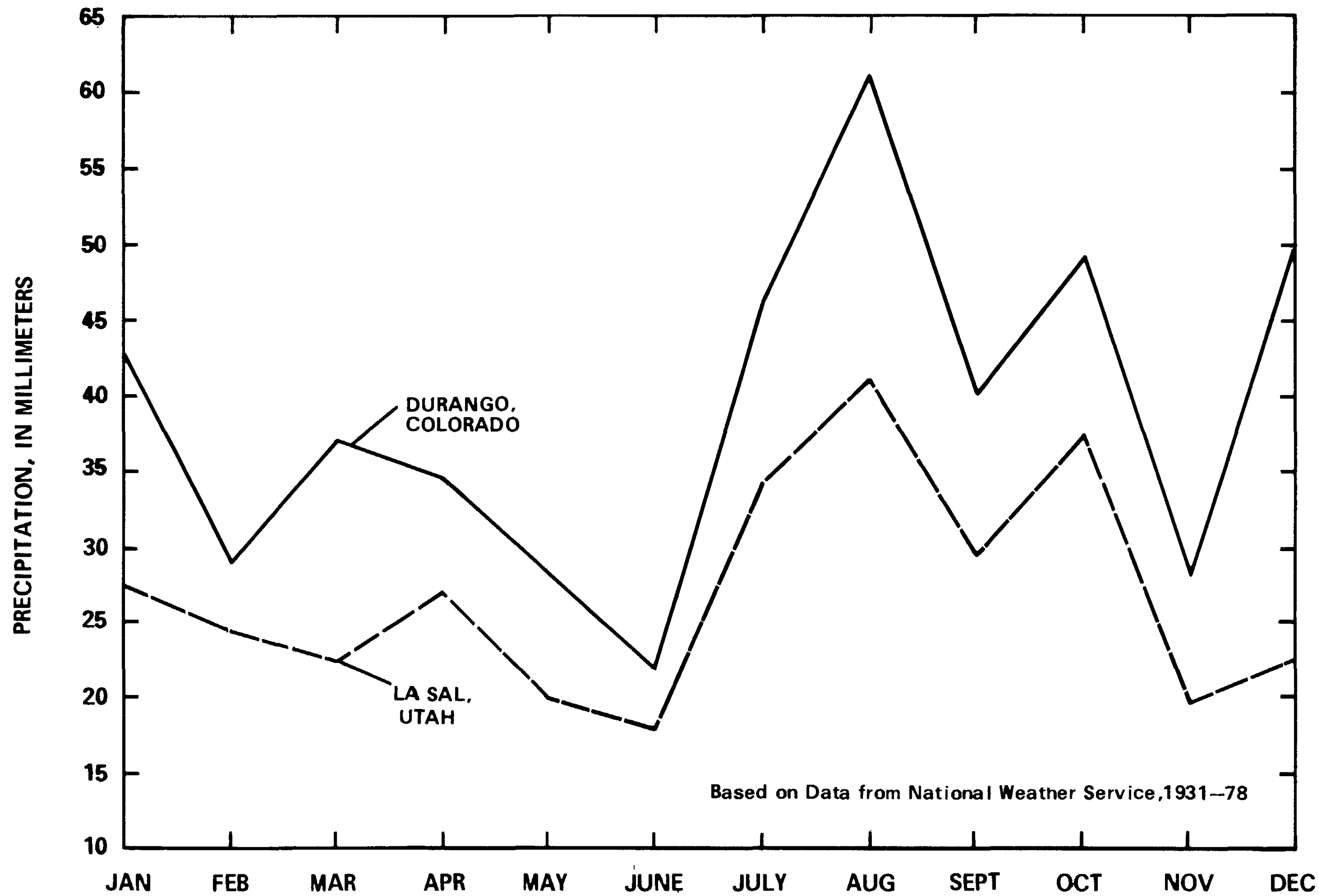

Figure 5.--Monthly distribution of average annual precipitation at Durango, Colorado, and La Sal, Utah.

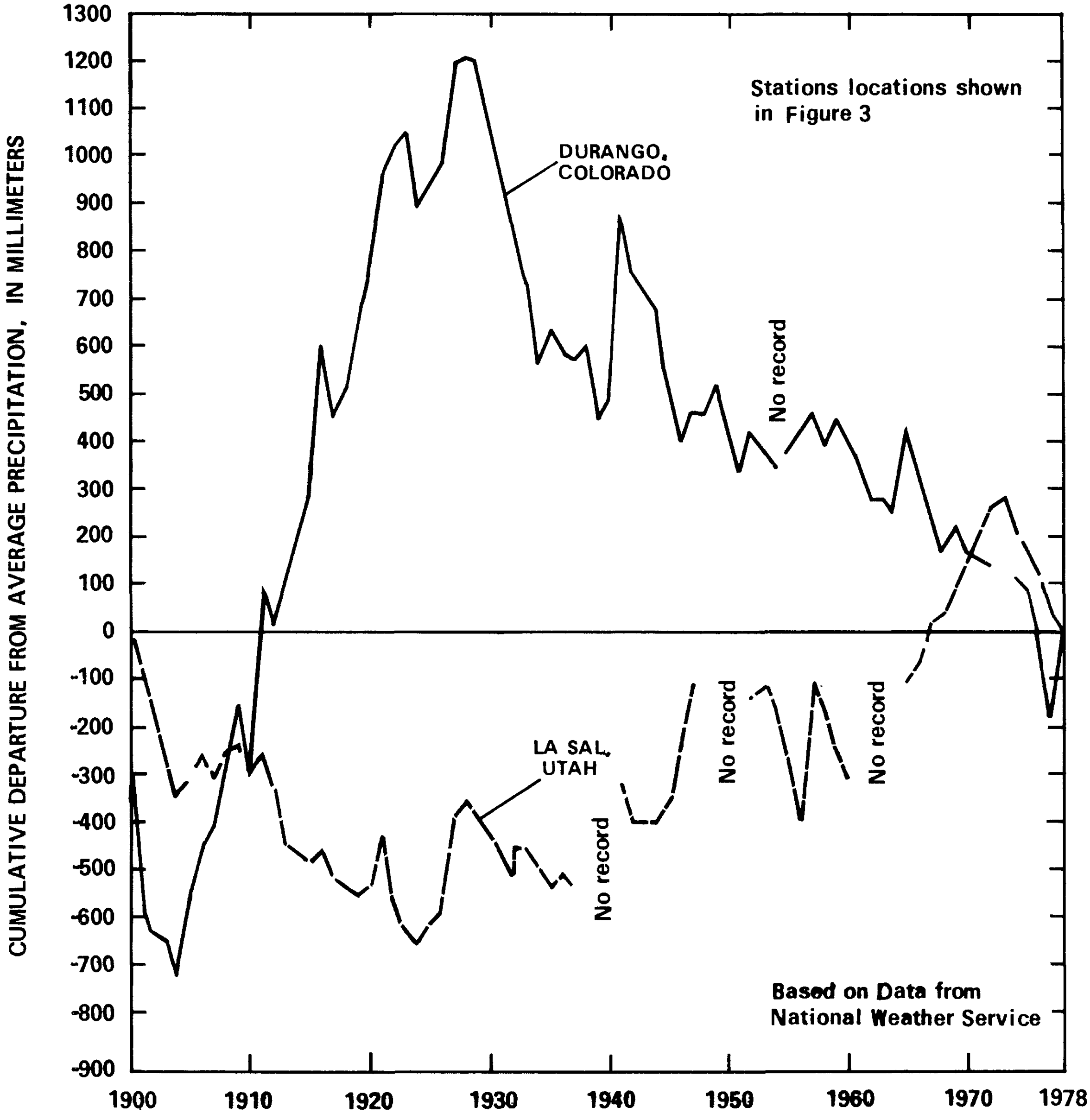

Figure 6.--Cumulative departure from average annual precipitation, based on measured precipitation at Durango, Colorado, and La Sal, Utah.

Table 2.--*Average annual precipitation at weather stations in the Dolores River basin and vicinity*

[Based on data from National Weather Service; precipitation data not continuous throughout period of record; adjustment to long term is based on cumulative departure at La Sal (a) and Durango (b)]

Station number (figs. 3, 4)	Station name	Altitude above sea level (meters)	Period of record	Average annual precipitation (millimeters)	
				Average	Adjusted
1	Gateway, Colo.	1,390	1947 through 1978	269.2	a272
2	La Sal, Utah	2,128	1901 through 1978	324.9	325
3	Paradox, Colo.	1,615	1943 through 1978	304.5	a318
4	Uravan, Colo.	1,528	1960 through 1978	311.2	a321
5	Northdale, Colo.	1,978	1930 through 1978	331.7	a345
6	Norwood, Colo.	2,139	1925 through 1978	369.6	b319
7	Placerville, Colo.	2,232	1947 through 1978	414.3	b429
8	Telluride, Colo.	2,669	1901 through 1978	577.6	b587
9	Silverton, Colo.	2,865	1905 through 1978	619.3	b634
10	Rico, Colo.	2,690	1906 through 1978	685.7	b698
11	Yellow Jacket, Colo.	2,089	1960 through 1978	385.3	b406
12	Dolores, Colo.	2,118	1916 through 1978	442.7	b461
13	Cortez, Colo.	1,883	1929 through 1978	331.5	b344
14	Mancos, Colo. Colo.	2,144	1898 through 1978	403.9	b421
15	Durango, Colo.	1,996	1900 through 1978	480.2	480

The estimated volume of average annual precipitation (table 3) is about 4,000 x 10^6 m^3. This estimate is based on the altitude-precipitation relations shown in figure 4.

Monthly distribution of precipitation for Durango and La Sal is shown in figure 5. Both stations have the same general distribution pattern: (1) A relatively dry period from February through June; and (2) a moist period from July through January.

To evaluate the long-term climatological character of the area, modern observations have to be put into a long-term prespective; information included in figures 6 and 7 show that relation. Dry conditions prevailed for 1942-77 at Durango and La Sal; a series of moist and dry periods occurred prior to 1942. Long-term climatic trends, shown in figure 7, can be identified from interpretations of tree-ring chronologies (Fritts, 1965). Since approximately 1130, no long-term systematic change in precipitation has been identified in the study area. Modern short-term variations in precipitation shown in figure 6 are typical of the short-term cycles occurring since 1130.

In conclusion: (1) Modern cycles are probably a continuation of the general trend, with no long-term increases or decreases in overall precipitation and (2) additional moist and dry periods, similar to those recorded in the past, probably will occur in the future.

Runoff

Runoff in the drainage network of the Dolores River occurs principally in response to snowmelt at higher altitudes in the spring and early summer. Runoff also occurs as a result of summer and autumn rainstorms, sometimes intense and usually limited in areal extent.

Average annual runoff for the upper Colorado River region is 63.5 mm (fig. 8), (Price and Arnow, 1974, p. 1); the distribution of annual runoff was estimated in that study. About 70 percent (5,530 km^2) of the Dolores River basin has less than the regional average, or about 170 x 10^6 m^3/a, using an estimated mean value of 30 mm/a for that part of the area. Using an estimated mean value of 200 mm/a for runoff from the Rico and La Plata Mountains, about 320 x 10^6 m^3/a is obtained for the higher elevations within the study area. Using 150 mm/a as estimated runoff from the La Sal Mountains and the Uncompahgre Plateau about 115 x 10^6 m^3/a is obtained. Thus, the total estimated runoff is approximately 600 x 10^6 m^3/a (rounded)--about 15 percent of the total precipitation.

A gage on the Dolores River near its mouth measures streamflow from the basin (fig. 9) and also was used to estimate runoff. Direct runoff is augmented by the base flow resulting from the steady influx of ground water (approximately 2,400 L/s) for the basin, as estimated from measurements near the mouth of the river; all measured flow in excess of the base flow is direct runoff. Average annual direct runoff as determined in this way is about 270 x 10^6 m^3; this value does not account for diversions of runoff for

Table 3.--*Estimated long-term average annual precipitation*
[ft, feet; m, meters; km^2, square kilometers; mm, millimeters; m^3, cubic meters]

Precipitation zone (from topographic maps) (ft)	(m)	Area (km^2)	Estimated precipitation (from fig. 4) Range (mm)	Average (m)	Average (rounded) ($x10^6$ m^3)
UPPER PART (Upstream from mouth of San Miguel River)					
>9,000	>2,743	1,050	>600	1.00	1,000
8,000-9,000	2,438-2,743	1,070	500-600	.55	590
7,000-8,000	2,134-2,438	1,200	400-500	.45	540
6,000-7,000	1,829-2,134	1,400	350-400	.37	520
5,000-6,000	1,524-1,829	790	300-350	.32	250
<5,000	<1,524	18	<300	.28	5
Subtotal	(rounded)------	5,530		.50	2,900
LOWER PART (Downstream from mouth of San Miguel River)					
>9,000	>2,743	223	>700	1.00	220
8,000-9,000	2,438-2,743	412	600-700	.65	270
7,000-8,000	2,134-2,438	438	400-500	.45	200
6,000-7,000	1,829-2,134	572	400	.40	230
5,000-6,000	1,524-1,829	518	<300	.28	150
<5,000	<1,524	236	<300	.28	70
Subtotal	(rounded)------	2,400		.50	1,150
TOTAL	(rounded)---------	7,900		.50	4,000

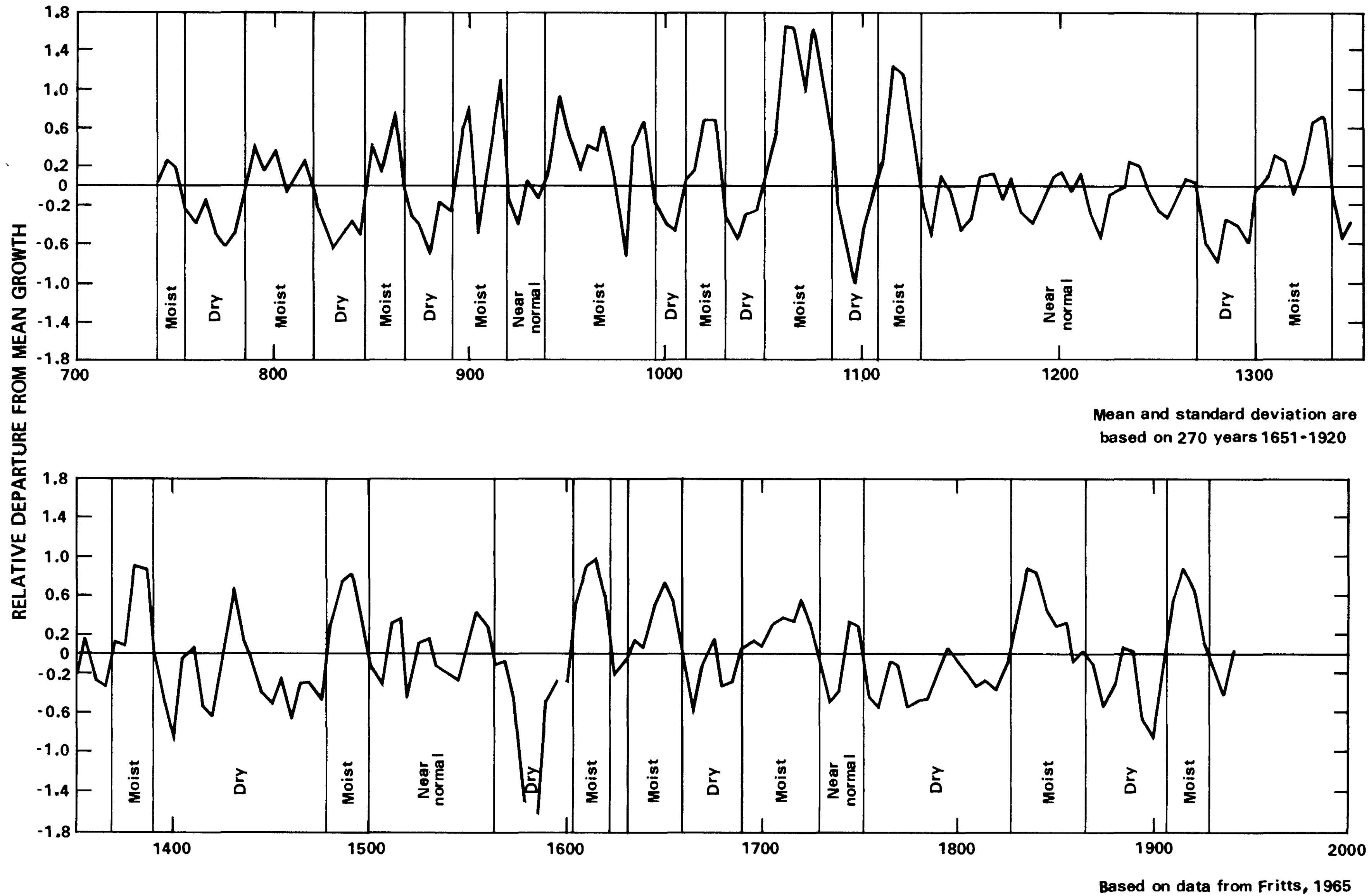

Figure 7.--Long-term precipitation at Mesa Verde National Park, Colorado, based on tree-ring chronologies.

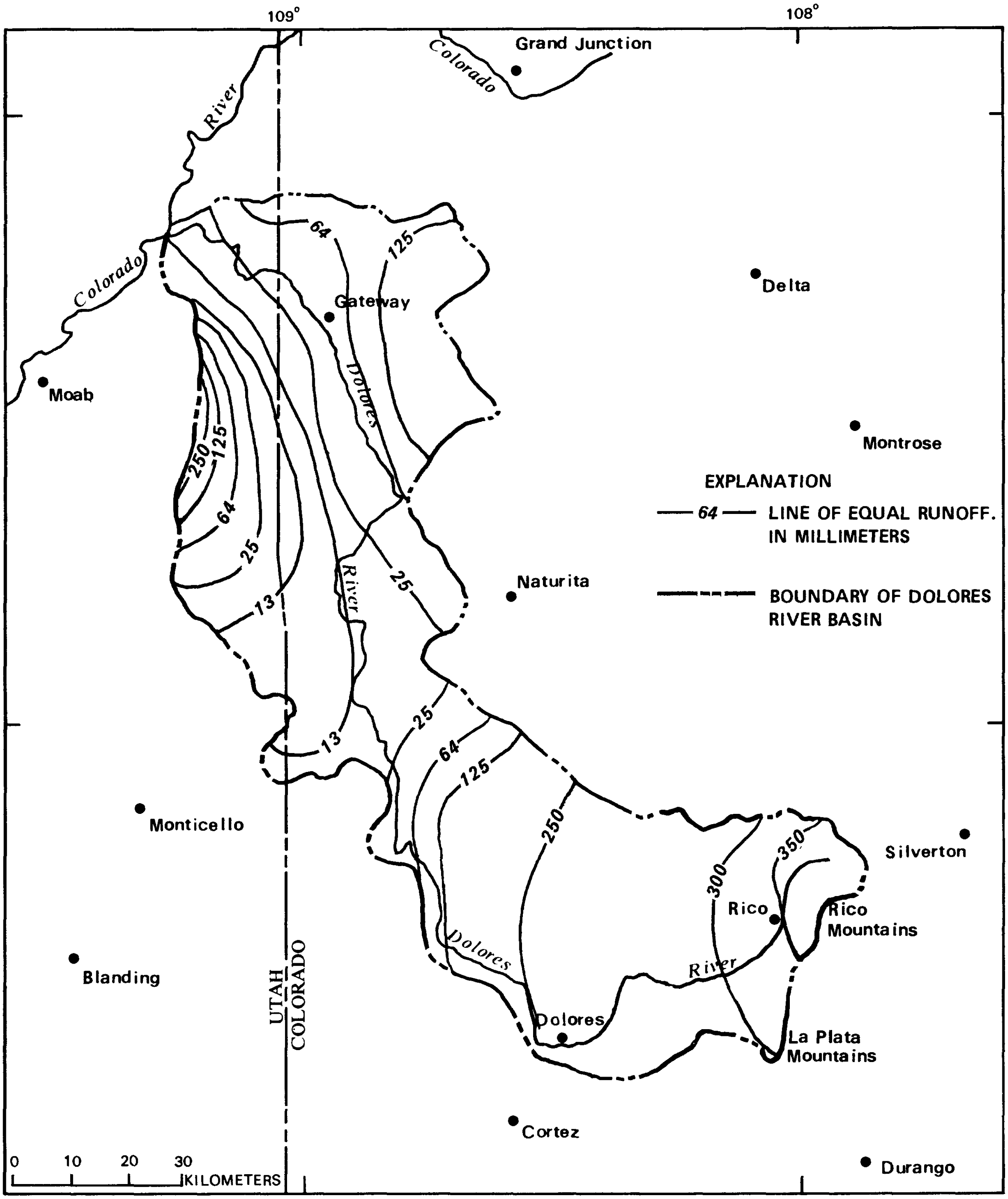

Figure 8.--Average annual runoff.

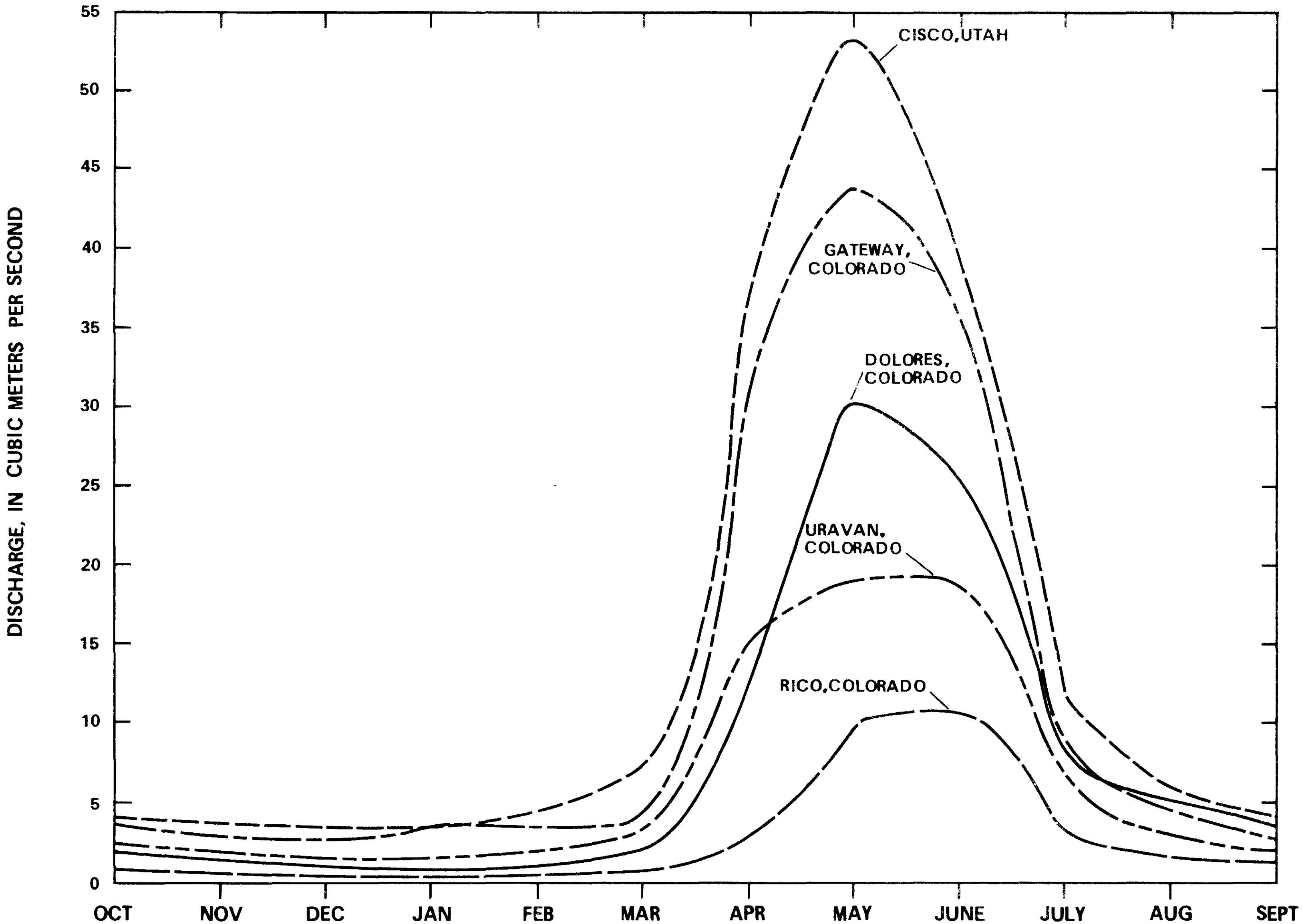

Figure 9.--Mean monthly flow of the Dolores River, 1951-77, and San Miguel River upstream from its confluence with the Dolores River.

irrigation and water supply, nor evapotranspiration losses within the drainage basin. Inflow from the San Miguel River was subtracted from flow measured at the Cisco gage, near the mouth of the Dolores River (fig. 10), so that data from the Cisco gage would represent water derived only from the Dolores River basin.

The two methods of estimating average annual runoff discussed above probably do not give exact values for runoff. Using runoff data in figure 8 may give values that are somewhat high. The true runoff probably is between the two estimates.

GROUND-WATER FLOW

Potential sources of inflow to the ground-water flow systems include recharge from precipitation, infiltration locally from the Dolores River, and subsurface inflow across the area boundary from adjoining areas. Evaporites generally prevent vertical flow between the upper ground-water system and the lower ground-water system. Probably most of the inflow to the lower system is by lateral ground-water flow from beyond the study-area boundary (fig. 11). A small quantity of recharge from precipitation to the lower ground-water system probably occurs in the La Plata and Rico Mountains and along the southwestern edge of the Uncompahgre Plateau.

Outflow from the lower ground-water system moves in a generally southwestward direction into adjacent areas of the Paradox basin. Outflow from the upper ground-water system moves toward the Dolores River and its major tributaries, where its discharge constitutes the base flow of these streams.

Inflow to the Ground-Water Systems

Recharge from Precipitation

Recharge from precipitation is probably a large part of the total ground-water inflow, but cannot be directly estimated. Recharge will be discussed further in the Inflow-Outflow Balance section later in this report.

Recharge from precipitation is probably greatest near the La Sal, Rico, and La Plata Mountains, and near the Uncompahgre Plateau, where precipitation and runoff are greatest. Also, the greatest recharge probably occurs along ephemeral channels, where deep infiltration is most likely. Recharge from precipitation to the lower ground-water system is unlikely.

Possible Recharge from the Dolores River

Water-level contours (pl. 2) show that water moves in the upper ground-water system toward the river. Thus, little if any recharge occurs from the Dolores River to the shallower, upper ground-water system in the area. The

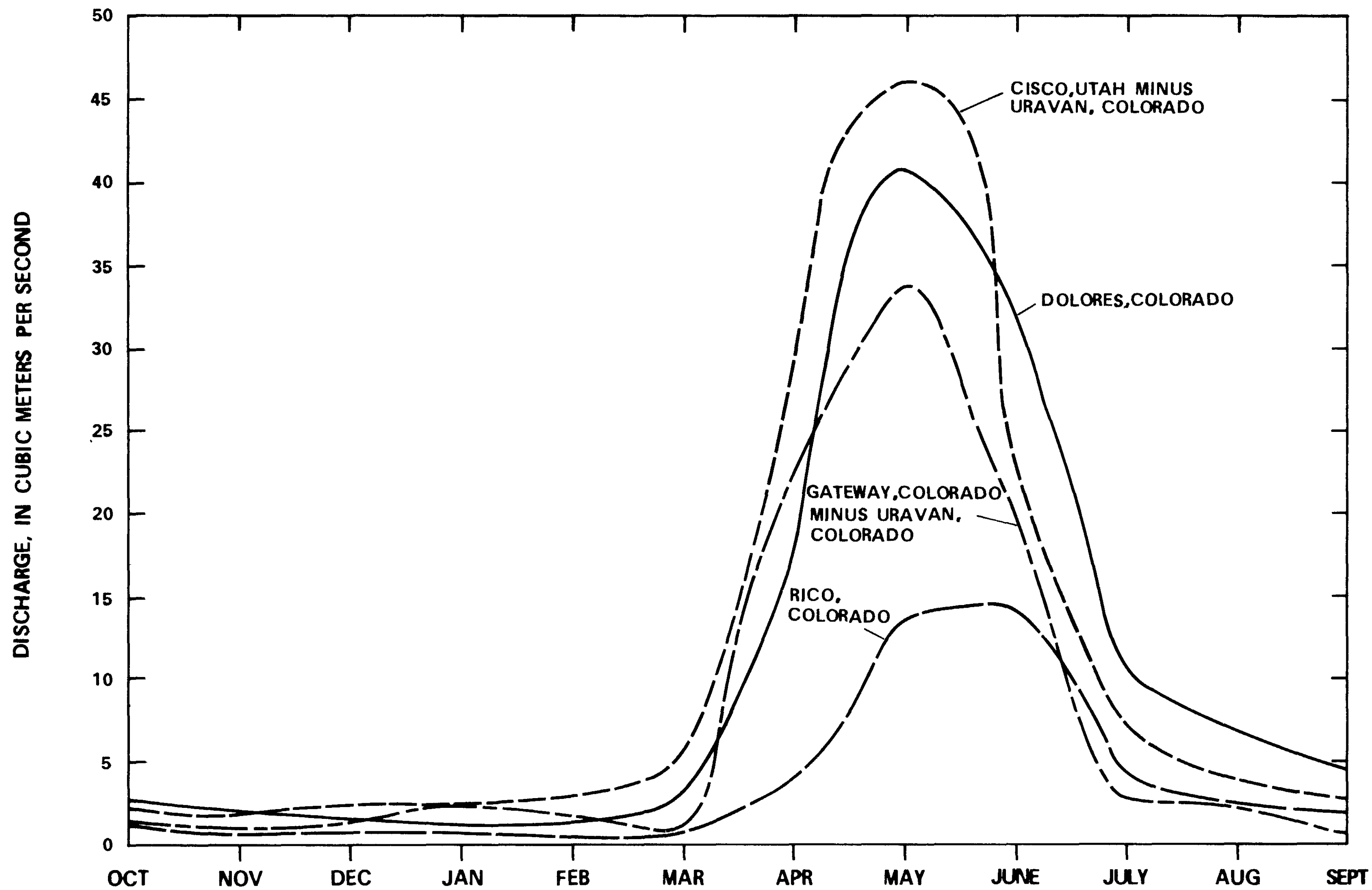

Figure 10.--Mean monthly flow of the Dolores River with inflow from the San Miguel River subtracted from flow measured at gaging stations downstream from the confluence (thus eliminating water derived outside the Dolores River basin).

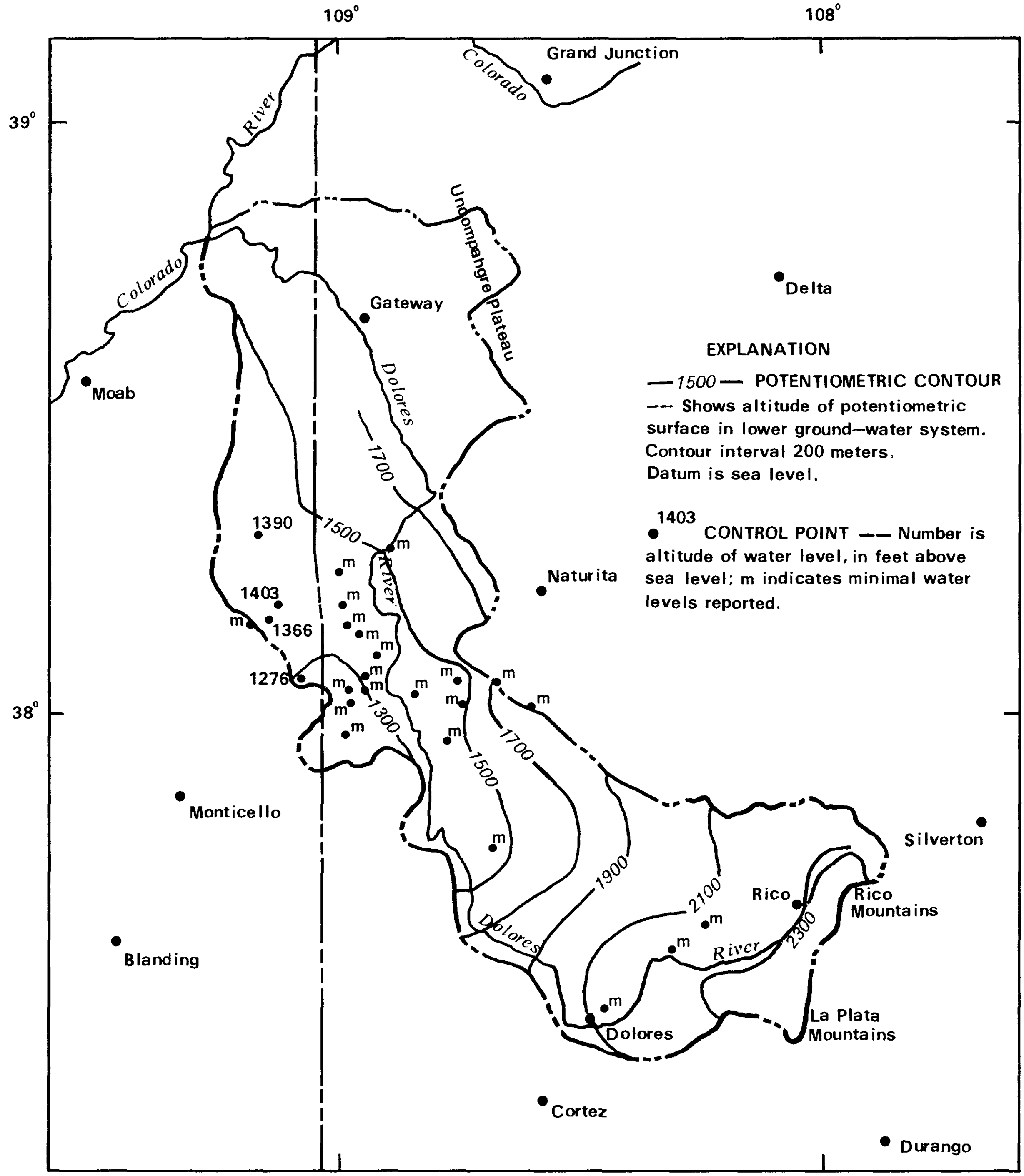

Figure 11.--Generalized potentiometric surface of the lower ground-water system. (Adapted largely from Hanshaw and Hill, 1969.)

river is a gaining stream throughout its length; however, ground-water inflow is small in its midreach. The river also does not recharge the lower ground-water system.

Subsurface Inflow

Based on potentiometric contours, ground water flows into the lower ground-water system from adjacent areas, from the north and southeast. The principal water-bearing unit in this system is the lower Paleozoic aquifer, which is an aquifer of regional extent underlying the Colorado Plateau physiographic province.

Hydrologic data for the Leadville Limestone, the most permeable part of the lower Paleozoic aquifer, has been obtained in the Paradox basin from borehole and testing records (table 4). The Leadville Limestone crops out a short distance north of Durango, just beyond the eastern limit of the Paradox basin. The Madison Limestone, approximately equivalent stratigraphically to the Leadville Limestone, is exposed along the southern flank of the Uinta Mountains about 150 km north of the study area in Utah. Both of these outcrop areas of Mississippian rocks receive recharge from precipitation and from runoff. Other areas of recharge to the Leadville Limestone northeast of the Paradox basin include scattered outcrops around the White River Plateau in central-western Colorado.

Movement of water through the lower Paleozoic aquifer is mainly lateral in and adjacent to the Paradox basin. Minor vertical movement of ground water may occur in the areas where the salt confining bed is thin or missing, because it was squeezed out of synclinal areas into adjacent salt anticlines. One such area is between Sinbad Valley and Paradox Valley anticlines (pl. 2). The synclinal area here probably has a thin or missing salt bed. Even in such areas, however, confining layers consisting of the Molas Formation, the upper member of the Hermosa Formation, and the Rico Formation (upper Paleozoic and Mesozoic-upper Paleozoic confining beds) retard fluid flow.

Inflow to the upper ground-water system is primarily recharge from precipitation within the basin. Based on potentiometric data, the La Sal, La Plata, and Rico Mountains, and the Uncompahgre Plateau form ground-water divides that coincide approximately with drainage divides. Thus, no ground water flows into the upper system from outside the basin in the mountainous parts of the study area. Additional data are needed to show whether the southwestern basin boundary also is a ground-water divide.

Outflow from the Ground-Water Systems

Ground-water outflow includes evapotranspiration, springflow, discharge to the Dolores River, subsurface outflow, and discharge by wells. Significant subsurface outflow is likely only for the lower ground-water system.

Table 4.--*Results of selected drill-stem tests*

[Altitude, approximate altitude of land surface above sea level; Depth, total drilled depth of well; Head, above sea level unless number is preceded by minus sign (some listed values may be too small because equilibrium was not reached during test); Fluid-recovery rate, in meters per hour per meter, meters of formation fluid recovery in drill stem per hour per meter of test-interval thickness; dashes, no data; m, meters; °C, degrees Celsius]

Petroleum exploration hole number	Location Utah	Altitude (m)	Depth (m)	Hydrogeologic units (table 1)	Test interval (m)	Head (m)	Fluid recovery			Remarks
							Fluid	Quantity (m)	Rate [(m/hr)/m]	
1	28/25-32dc	2,330	3,800	Lower Paleozoic aquifer.	3,784-3,800	1,390	Water cushion	803	--	Fluid temperature is 75°C.
							Drilling mud	226	--	
							Saltwater	192	--	
2	30/25-10ca	2,055	1,797	Salt confining beds.	1,287-1,306	1,403	Gas and oil	166	--	Fluid temperature is 41°C.
							Cut drilling Mud			
							Gas		--	
3	30/25-10ca	2,055	1,797	Mesozoic-upper Paleozoic confining beds.	980-987	1,656	Drilling mud	27	--	
							Saltwater	312	51	
4	30/25-14ca	2,036	1,634	Salt confining beds.	1,053-1,069	1,769	Gas and condensate-cut drilling Mud	27	--	Fluid temperature is 37°C.
							Gas		--	
5	30/25-16cc	2,091	2,945	Lower Paleozoic aquifer	2,865-2,880	1,366	Slightly saltwater	290	18	Fluid temperature is 68°C.

Table 4.--*Results of selected drill-stem tests*--Continued

Petroleum exploration hole number	Location Utah	Altitude (m)	Depth (m)	Hydrogeologic units (table 1)	Test interval (m)	Head (m)	Fluid recovery: Fluid	Fluid recovery: Quantity (m)	Fluid recovery: Rate [(m/hr)/m]	Remarks
6	30/25-16cc	2,091	2,945	do.	2,823-2,865	712	Gas-cut mud	82	--	Fluid temperature is 68°C.
7	30/25-18dc	1,926	2,774	do.	2,746-2,774	1,228	Saltwater with H_2S odor.	1,240	30	
8	31/26-18ab	2,035	3,148	do.	3,035-3,075	1,276	Water cushion	305	--	
							Saltwater	468	12	
9	31/26-18ab	2,035	3,148	do.	2,995-3,003	1,225	Water cushion	305	--	
							Drilling mud	64	--	

Evapotranspiration

Shallow ground water is discharged by transpiration of phreatophytes and evaporation from the soil. Shallow ground water occurs beneath the flood plain of the Dolores River and beneath the principal perennial and ephemeral stream channels (pl. 1). On the flood plain, infiltrated river water or ground water moving toward stream channels evapotranspires; along tributary channels, water in relatively shallow perched zones of saturation, derived from infiltrating runoff, evapotranspires.

The area covered by phreatophytes is estimated to be about 147 km^2. In general, the areas where the water table is near the land surface, about one-third of the total phreatophyte area and mainly along the Dolores River, have stands of salt cedar, cottonwood, willow, and salt grass. Areas with a greater depth-to-water (as much as 15 m), about two-thirds of the total area, support greasewood and rabbit brush.

Total discharge by phreatophytes is about 55×10^6 m^3/a. This total is based on an estimated average annual rate of about 1 m^3/a for salt cedar, cottonwood, and willow, and about 0.1 m^3/a for greasewood, rabbit brush, and salt grass. These unit quantities of evapotranspirative losses were based on research done by Lee (1912), White (1932), Young and Blaney (1942), Houston (1950), and Harr and Price (1972) in other areas.

Springflow

Known springs in the Dolores River basin number 202, as determined from a count of those springs shown on the 7½-minute topographic quadrangles. The actual number of perennial and ephemeral springs is probably much greater, because many are small, intermittent springs in remote areas that may not have been detected during topographic mapping or were unreported. About 150 of the springs are perennial. Data were obtained from 39 springs within the study area (table 5). Most springs have small discharges and occur high on the flanks of surrounding mountains. The estimated total spring discharge for the area, other than inflow to the channel of the Dolores River, is about 8,000 L/min, or 4.2×10^6 m^3/a.

Many of the springs occur along canyon walls at formation contacts, usually where permeable rocks overlie beds with little permeability. Fractures in the competent sandstone units commonly control the point of discharge. Discharge ranges from zero to 1,200 L/min; the mean is 54 L/min. Many springs that flow during the spring and early summer seasons are dry by late July or August, especially springs at lower altitudes.

Many springs discharge from the Dakota Sandstone and the Burro Canyon Formation (Mesozoic sandstone aquifer). These springs are at higher altitudes along the flanks of the surrounding mountains; they are mostly perennial springs with an average discharge of 55 L/min, and a probable wide seasonal range in discharge. The water usually is fresh, with an average specific conductance of 375 µS. These high-altitude springs discharge from perched aquifers. The underlying formations are the Brushy Basin Member of

Table 5.--*Hydrologic data from selected springs*

[m, meters; L/min, liters per minute; °C, degrees Celsius, µS, microsiemens per centimeter at 25° Celsius]

Identifying number on plate 2	Location	Name	Altitude (m)	Stratigraphic unit (table 1)	pH	Discharge (L/min)	Temperature (°C)	Specific conductance (µS)	Date observed
	Utah								
1.	23S/24E-16cbc	Waring Canyon Seep	1,289	Navajo	--	Dry	--	--	9-14-78
2.	23S/24E-27cda	Cowskin Spring	1,535	do.	--	Dry	--	--	9-14-78
3.	24S/25E-20cac	Lower Hideout Canyon	1,652	do.	--	--	--	--	9-14-78
4.	24S/25E-32adb	Upper Hideout Canyon	1,850	do.	--	2.0	14.0	810	9-14-78
5.	25S/25E-34ddd	Sids Draw Spring	2,493	Dakota	--	Dry	--	--	7-15-80
6.	27S/24E-1bdb	Geyser Pass Spring	3,188	Alluvium	--	1.9	--	--	7-21-78
7.	27S/25E-26cab	Canopy Spring	2,606	Burro Canyon	--	Dry	--	--	7-21-78
8.	27S/25E-36ccc	-------	2,487	Morrison	--	7.6	--	--	7-21-78
9.	28S/25E-4dac	Chicken Creek Spring	2,506	Dakota	--	3.8	--	--	7-21-78
10.	28S/25E-24cdd	Pole Spring	2,158	do.	--	1,200	--	--	7-21-78
11.	28S/25E-32caa	East Coyote Wash Spring	1,963	do.	--	3.8	--	--	7-22-78
12.	28S/25E-36bcd	Pine Ranch Spring	2,159	Burro Canyon	--	7.6	--	--	7-22-78
13.	29S/25E-12dbd	Spring Canyon Spring	2,158	do.	--	17.0	--	--	7-22-78
14.	29S/25E-32caa	-------	1,963	Dakota	--	Dry	--	--	7-16-80
15.	30S/25E-24bdc	Lisbon Spring	1,929	do.	7.0	3.8	16.5	320	7-16-80
16.	31S/25E-1bbb	Patterson Ranch	2,018	Wingate	--	Dry	--	--	7-16-80
	Colorado								
17.	39N/14W-4adc	Willow Spring	2,441	Morrison	7.6	--	--	--	7-18-78
18.	40N/16W-14ada	Narraquinnep Spring	2,446	Dakota	7.3	1.1	11.0	380	7-17-80
19.	41N/16W-30bbb	Garbareno Spring	2,493	do.	7.4	3.8	11.5	440	7-17-80
20.	41N/16W-7bdb	Cottonwood Spring	2,463	do.	--	18.9	--	--	9-18-78
21.	41N/16W-7dba	White Sands Spring	2,46	do.	7.4	1.9	18.5	220	7-17-80
22.	41N/16W-16dda	Black Snag Spring	2,408	do.	7.3	1.9	11.0	380	7-17-80
23.	41N/16W-17aaa	Evans Spring	2,437	do.	7.4	0.4	14.0	340	7-17-80
24.	41N/17W-1dcc	Pot Spring	2,470	do.	--	3.8	--	--	7-17-80
25.	41N/17W-5dda	Big Water Spring	2,512	Dakota/Burro Canyon	7.4	37.9	11.5	520	7-17-80
26.	41N/17W-12bcb	Wolf Den Spring	2,474	Dakota	7.4	1.9	13.0	190	7-17-80
27.	42N/17W-32cbb	Bankston Spring	2,489	Dakota/Burro Canyon	7.4	3.8	11.5	280	7-17-80
28.	43N/17W-2acb	Gypsum Gap Spring	1,829	Burro Canyon	--	0.5	--	--	9-18-78
29.	43N/17W-27cca	-------	1,765	Alluvium	--	Dry	--	--	9-18-78
30.	44N/18W-34daa	Nicholas Wash Spring	1,710	Dakota	--	Dry	--	--	9-18-78
31.	44N/19W-20dcd	Horse Range Spring	2,100	Burro Canyon	--	0.9	--	--	9-14-78
32.	44N/20W-36bbb	-------	2,045	do.	--	Dry	--	--	9-14-78
33.	47N/17W-26add	Horsethief Spring	1,887	Dakota	7.2	3.8	27.0	160	7-16-80
34.	48N/18W-11bcd	-------	1,463	Entrada	7.1	0.9	15.5	1,160	7-16-80
35.	49N/18W-33dad	Sewemup Stock	1,506	Wingate	--	1.9	18.5	485	7-16-80
36.	49N/19W-9ada	-------	1,640	Granite	--	--	--	--	7-15-80
37.	49N/19W-9adc	-------	1,637	do.	--	11.4	15.0	12,000	7-17-80
38.	49N/19W-9cdd	Salt Creek Spring	1,654	Alluvium	--	--	--	--	7-15-80
39.	50N/20W-20adb	Willow Spring	2,185	Dakota	6.8	56.8	8.0	900	7-15-80

the Morrison Formation, composed mostly of bentonitic mudstone and siltstone, and the Summerville Formation, composed of sandstone, shale, and mudstone. These mudstones, shales, and siltstones are relatively impervious and plastic; they probably form effective confining units, even where they have been extensively fractured, as these fractures are assumed to have been resealed by plastic flowage (Hite and Lohman, 1973, p. 28-33).

Springs also discharge from the Point Lookout Sandstone of the Mesaverde Group (Tertiary-Upper Cretaceous aquifer); Juana Lopez Member of the Mancos Shale (Cretaceous confining beds); Saltwash Member of the Morrison Formation, Junction Creek Sandstone, Entrada Sandstone, Navajo Sandstone, and Wingate Sandstone (all five are parts of Mesozoic sandstone aquifer); and the Cutler Formation (Mesozoic-upper Paleozoic confining beds). Springs discharging from the Point Lookout Sandstone and Juana Lopez Member are in the southern part of the area, high on the flanks of the La Plata and Rico Mountains. These are perched aquifers, because of the negligible permeability of the underlying Mancos Shale below the Point Lookout Sandstone. The Juana Lopez Member is a thin sandy unit within the Mancos Shale.

In much of the area, springs from the Saltwash Member also discharge from a perched aquifer. The Saltwash Member is confined between the overlying bentonitic mudstone of the Brushy Basin Member and the underlying mudstone and siltstone of the Summerville Formation, all of which have little permeability. In the southern part of the area, the eastern equivalent of the Summerville Formation is the Wanakah Formation, parts of which are composed of marlstone having little permeability. In the northern part of the area, the Summerville Formation pinches out to the east, leaving the Saltwash Member in contact with the more permeable Entrada Sandstone. The Saltwash Member and Entrada Sandstone form a single aquifer, where the Summerville Formation is missing.

The Dewey Bridge Member of the Entrada Sandstone (grades into Carmel Formation of some reports) is a very fined-grained sandstone and siltstone. This unit has little permeability, causing perched conditions in the upper units of Entrada Sandstone.

The Kayenta Formation, a part of Mesozoic Sandstone aquifer, consists of lenticular channel sandstone, siltstone, and mudstone. No springs are reported from the Kayenta Formation within the area; however, springs issue from the Kayenta Formation as reported in the Moab-Monticello area (J. E. Weir, Jr. and others, U.S. Geological Survey, written commun., 1982) and in the Green River-Moab area (Rush and others, 1982). Because the Kayenta Formation in places is fractured, it probably is connected hydraulically with the Navajo Sandstone above and the Wingate Sandstone below. The Chinle Formation and its lateral equivalent, the Dolores Formation, both parts of the Mesozoic-upper Paleozoic confining beds, in the southeast part of the area, are composed of siltstone and mudstone; therefore, they are assumed to be effective confining units.

Generally, springs discharging from younger rocks occur along the flanks of the La Sal, La Plata, and Rico Mountains; those springs issuing from older rocks are nearer the Dolores River, reflecting the distribution of the formations exposed (pl. 1).

Discharge to the Dolores River

Streamflow records for four gages on the Dolores River (fig. 9) were analyzed to obtain an estimate for ground-water discharge to the river. Records for two stations in the lower reach of the San Miguel River also were analyzed to adjust for the inflow to the Dolores River from the San Miguel River (table 6). Adjustments also were made for other tributary inflow, based mainly on reconnaissance estimates. Baseflow periods were averaged (table 6) to obtain the best estimates for rates of ground-water contributions to the stream. The length of the historical records for the gages range from 20 to 27 years, except at the Gateway station, where records extend 5 years, and the Uravan station, where records extend 11 years. The record for the Uravan gage was extended to 20 years, based on data for the Naturita gage, about 25 km upstream.

The Dolores River is 295 km long. The reach from the gage near Rico, Colorado (fig. 12), to the gage near Cisco, Utah, is 271 km, and the estimated ground-water inflow to this reach averages 6 (L/s)/km of the stream valley in the longitudinal direction. Data analysis showed the following estimated gains from ground-water inflow for the indicated reaches (fig. 12):

Upstream from Rico	16 (L/s)/km
Rico to Dolores	10 (L/s)/km
Dolores to Cisco	3 (L/s)/km
Gateway to Cisco	15 (L/s)/km

Estimated total volume of ground-water inflow is 126 x 10^6 m^3/a, based on river baseflow adjusted for estimated diversion.

Data for the Gateway station, adjusted for inflow from the San Miguel River indicated a net loss in flow during much of the year between the Dolores and Gateway gages (fig. 10). This net loss may not be representative, because of the short duration of the record for the Gateway station. The gain estimated for the 36-km reach between Gateway and Cisco gages also may be questionable for the same reason. The data from the gage are not critical for the conclusions in the report.

Wells

Wells are comparatively sparse in the Dolores River basin. Reported yields, as shown in table 7, range from 0.06 to 84.4 L/min. One-fourth of these wells produce less than 1 L/min; one-sixth of these wells produce more than 4 L/min.

The town of Dolores obtains its public supply of water from a well (37/14-5da). Much livestock water is obtained from springs and surface water, obviating the need for only a few stock wells. One industrial well

Table 6.--*Average monthly flow in the Dolores and San Miguel Rivers in the Dolores River basin and vicinity*
[km, kilometers; L/s, liters per second]

Unit of measure	January	February	March	April	May	June	July	August	September	October	November	December
DOLORES RIVER												
Gage 7 km downstream from Rico, Colo. (1951-70)												
L/s	507.66	493.27	771.46	3,844.84	13,537.87	14,389.70	4,186.14	2,362.77	1,763.94	1,085.02	734.67	568.26
Gage at Dolores, Colo. (1951-70)												
L/s	1,299.82	1,415.85	2,725.57	17,312.53	40,962.84	33,086.95	10,718.63	7,185.37	4,763.46	2,683.12	1,862.42	1,471.88
Gage at Gateway, Colo. (1951-54; 1970)												
L/s	4,726.10	4,584.60	5,207.20	42,540.56	59,635.18	46,327.10	11,755.82	6,640.60	3,891.25	4,737.42	3,780.88	3,707.30
Gage at mouth near Cisco, Utah (1951-77)												
L/s	4,655.35	6,016.58	9,599.36	48,743.92	72,329.14	49,151.44	15,998.00	7,960.79	5,764.71	5,597.74	4,847.79	4,706.29
SAN MIGUEL RIVER												
Gage at Naturita, Colo. (1951-70)												
L/s	2,193.35	2,474.34	3,512.58	15,467.47	22,063.64	21,060.49	9,049.86	4,682.97	3,045.11	2,884.37	2,689.69	2,384.64
Gage 4 km downstream from Uravan, Colo. (1953-62; 1970; record for 1963-69 based on adjustment to Naturita gage record)												
L/s	2,218.82	2,756.19	4,563.55	17,296.91	25,397.10	22,434.05	8,953.93	5,076.87	3,799.24	3,319.59	2,790.43	2,357.76

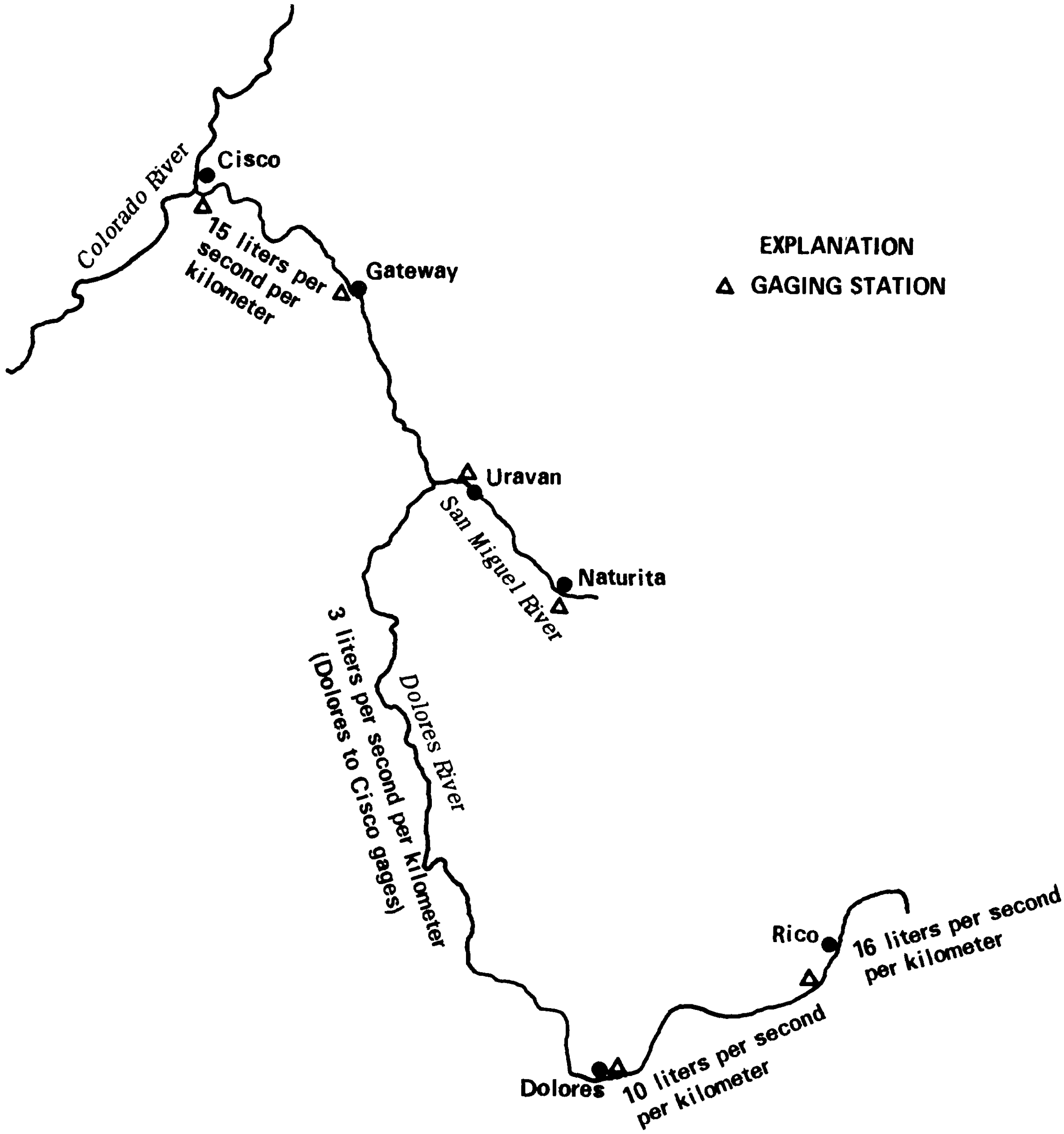

Figure 12.--Diagrammatic summary of estimated ground-water inflow to the Dolores River (in liters per second per kilometer of the stream valley in the longitudinal direction).

Table 7.--*Data for selected water wells*

[m, meters; cm, centimeters; L/min, liters per minute; µS, microsiemens per centimeter at 25° Celsius]

Well no.	Owner	Location	Altitude (m)	Well depth (m)	Diameter (cm)	Perforated interval (m)	Aquifer or hydrogeologic unit (table 1)	Yield (L/min)	Specific conductance (µS)	Depth to water (m)	Date	Use
COLORADO: T.N. - R.W.												
1.	Vernon Moores	15/103-1cba	1,951	15	17	11-14	Alluvial	0.63	---	10	03-23-69	Domestic
										7	05-23-80	
2.	Vernon Moores	15/103-2daa	1,941	15	17	11-15	do.	.63	---	6	04-04-69	Stock
										5	05-23-80	
3.	Lillie Joslin	15/103-28bcd	1,515	18	20	12-18	do.	.95	---	12	10-20-76	Domestic
										10	05-23-80	
4.	McDonald	15/103-31cda	1,469	20	17	3-14	do.	.95	---	6	02-24-71	Domestic
										5	05-23-80	
5.	Town of Dolores	37/14-5da	2,169	40	18	20-37	do.	3.15	560	2	10- 162	Municipal
										2	05-08-80	
6.	School Dist. #4	37/15-10ca	2,120	31	22	2-05	do.	4.73	---	4	05-18-60	Irrigation
										1	05-08-80	
7.	Montezuma Water	37/15-16dad	2,112	73	--	----	Mesozoic sandstone	--	---	2.4	----	----
8.	Montezuma Water	37/15-22bbb	---	56	--	----	do.	5.8	---	38	----	----
9.	Bassnet Home-stead	43/16-26bba	1,926	--	15	----	do.	.3	3,900	---	----	Stock
										9	05-02-80	
10.	Troy Rose	43/19-35bd	2,222	38	15	----	do.	.2	---	13	04-28-73	Stock
										10	05-02-80	
11.	F. Folk	43/20-25dda	2,048	52	15	----	do.	.06	---	17	10-29-72	Domestic
										30	05-02-80	
12.	Union Carbide	44/19-25acc	1,661	38	--	----	Alluvial	3.15	---	5	----	Industrial
13.	Union Carbide	44/18-30db	1,689	24	46	----	Mesozoic sandstone	1.9	---	5	01- -58	Mining
										3	05-02-80	
14.	Paradox Salt Co. Inc.	47/18-17ad	1,507	214	10	----	Evaporite confining beds	84.4	---	2	02-06-57	Industrial
										8	05-03-80	Brine
15.	Frederick Edwards	47/18-19aa	1,518	15	20	8-14	Alluvial	.63	360	9	02-08-61	Domestic
										9	05-03-80	
16.	Clint Oliver	47/19-2ba	1,594	12	30	0-12	do.	72.5	43,500	2	04-20-70	Irrigation
										--	05-03-80	
17.	G. W. Campbell	47/19-13daa	1,564	62	--	----	Mesozoic upper Paleozoic confining beds	--	---	35	----	----
18.	R. Latham	47/19-17bba	1,527	28	--	----	Alluvial	--	---	11.3	----	----
19.	Jesse Steele	48/19-29cd	1,689	27	--	----	do.	.95	---	10	03-13-64	Domestic
										2	05-12-80	
20.	Union Carbide	49/17-31caa	1,591	62	15	40-46	Mesozoic sandstone	1.3	---	46	01-15-61	Mining
										36	05-23-80	
										6	05-23-80	
21.	Union Carbide	49/17-33bca	1,768	24	15	18-24	do.	.63	---	46	01-15-61	Mining
										6	05-23-80	
22.	W. L. Swarnes	51/19-14bab	1,432	15	20	9-15	Alluvial	.63	---	8	03-15-69	Domestic
										5	05-23-80	
23.	R. H. Graham	41/19-15ad	1,417	15	20	6-14	do.	2.2	---	4	02-20-71	Domestic
										2	05-23-80	

(47/18-17ad) drilled into the Hermosa Formation, part of the salt confining bed, pumps a brine that is evaporated to recover the dissolved salt.

Because of the paucity of wells and the moderate production, the water that the wells produce comprises only a small part of the water discharged from the basin; total well discharge is estimated to be about 1×10^6 m^3/a.

Inflow-Outflow Balance

During a multiyear period, most hydrologic systems approach dynamic equilibrium; that is, inflow equals outflow, and the volume of water in transient storage remains nearly constant. A water budget for the Dolores River basin is shown in table 8. Though the budget is incomplete, some useful conclusions can be obtained from it regarding the relative volumes of water for each of the inflow and outflow elements:

For the upper ground-water system--

1. Subsurface inflow of ground water is probably minor; the principal inflow is recharge from precipitation.
2. The principal element of ground-water outflow is discharge to the Dolores River, about 126×10^6 m^3/a;
3. All other elements of outflow are relatively small except for evapotranspiration, about 55×10^6 m^3/a; and
4. The total outflow from the system is about 190×10^6 m^3/a; this is about the magnitude of recharge from precipitation.

For the lower ground-water system--

1. Total inflow and outflow are about equal;
2. Because the salt confining bed is not permeable, almost all inflow to and outflow from the system is subsurface ground-water flow; and
3. The volume of water moving through the system is unknown, but it is probably nearly constant.

Summary of Flow Systems

Potentiometric contours of the upper ground-water system on plate 2 indicate that it is recharged in the higher, wetter parts of the basin, and that it discharges to the Dolores River and its tributaries. The river system functions as a drain for the upper ground-water system. No ground water is known to flow into or out of the drainage basin from adjacent areas; however, ground-water data along drainage-basin boundaries are meager.

The salt structures have minimal permeability and are ground-water flow barriers that trend diagonally across the basin, (fig. 2 and pl. 1); they cause compartmentation of the upper ground-water system into several partly connected flow systems. The potentiometric contours (pl. 2) generally are closely spaced, indicating a relatively small transmissivity or greater flow where the rocks forming the upper system have been thinned by erosion and local recharge is greater.

Table 8.--*Water budgets for the ground-water systems*

Budget element	Estimate (in millions of cubic meters per year)
Upper Ground-Water System	
Inflow	
Recharge from precipitation and runoff (computed by adjusted difference)	Unknown; probably large[1/]
Recharge from Dolores River	0
Subsurface inflow	Unknown; probably minor.
Total (rounded)	Unknown[1/]
Outflow	
Evapotranspiration	55
Springflow	4
Discharge to Dolores River	126
Subsurface outflow	0
Wells	1
Total (rounded)	190
Lower Ground-Water System	
Subsurface inflow	Unknown; might include minor recharge from precipitation in the eastern mountainous area.
Subsurface outflow	Unknown, but probably identical to inflow.

[1/] About equal to total outflow or 190 million cubic meters per annum.

Potentiometric contours for the lower ground-water system indicate flow from the southeast and north where individual aquifers crop out (fig. 11). These aquifers pinch out in the subsurface along most of the eastern edge of the basin. A minor quantity of recharge may enter the system by interformational leakage; however, most flow probably is from the southeast and the north. Ground-water in the lower system flows out of the Dolores River basin mainly into adjacent areas to the southwest. Some compartmentation of the lower ground-water system may result from the salt diapir structures; data are inadequate to demonstrate this compartmentation with any degree of accuracy.

Where Paradox salt beds have been squeezed upward into diapiric structures, the thinned confining unit adjacent to diapirs is less effective, and intersystem flow might occur. However, no evidence has been obtained to indicate flow between the lower and upper ground-water systems. The flow, if any, probably is very minor.

Altitude of the potentiometric surface for the upper ground-water system is greater than that of the potentiometric surface for the lower system, indicating a potential for downward movement of ground water in the Dolores River basin. However, the inferred potential for downward movement is subject to data deficiencies: (1) Altitudes of water levels used for contouring the upper system are mostly for unconfined aquifers, except near the Dolores River; and (2) only a few control points (table 4) were available for contouring the potentiometric surface in the lower ground-water system; contouring for the lower system is largely inferred. Hydraulic-head differences between the two systems may therefore be false, especially in areas distant from the river. The hydraulic head in the lower ground-water system probably is sufficiently great to raise fluid levels at least as high as deeper zones of principal saturation in the upper system; however, additional study is needed to verify this inference.

GENERAL CHEMICAL CHARACTER OF WATER

Most water-quality data in the Dolores River basin, presented in table 9, were obtained from unpublished files of the U.S. Geological Survey and from Feltis (1966). Water-quality data are meager or lacking in large parts of the area, and no data were obtainable for water in some of the hydrogeologic units. Water-quality data for areas outside, but near the Dolores River basin are presented in table 10.

In general, the concentration of dissolved solids in ground water depends on transit time or flow distance as the water migrates from recharge to discharge areas, and on the solubility of rock material through which the water migrates. Water close to recharge areas typically has smaller concentrations of dissolved solids compared with water close to discharge areas. Minerals such as gypsum and halite (salt), that are highly water-soluble, contribute greater quantities of dissolved matter to ground water coming into contact with these rocks. The following is a discussion of water quality for the various major hydrogeologic units for which chemical analyses are available.

Upper Ground-Water System

Water from sandstones in the upper ground-water system is typically a calcium bicarbonate water containing varying concentrations of sulfate. Water from units containing abundant shale, such as the Mesaverde Group, Mancos Shale, and Brushy Basin Member of the Morrison Formation, typically is a sodium bicarbonate water containing sulfate or chloride.

Water from alluvium has dissolved-solids concentrations ranging between 302 and 1,560 mg/L, based on results for 6 samples. The average dissolved-solids concentration in these samples was 770 mg/L. Water from alluvium may be characterized as calcium sulfate or calcium bicarbonate types, based on dominant cation and anions present. Gypsum and limestone probably are the major contributors of these ions. Sodium concentration was 130 mg/L or less,

Table 9.--*Summary of water quality for hydrogeologic units*

[Units in milligrams per liter except specific conductance, in microsiemens per centimeter at 25° Celsius, and pH, in standard units; S, spring; GW, well less than 150 meters deep; W, well greater than 150 meters deep]

Hydrogeologic unit selected and formations	Type of site	Number of samples	Dissolved solids		Specific conductance		Chloride (Cl)		Sulfate (SO_4)		pH	
			Range	Average	Range	Average	Range	Average	Range	Average	Range	Median
Upper aquifer system:												
Alluvium aquifer	GW	6	302-1,560	770	514-2,200	1,150	3.9-170	44	8.9-780	315	7.4-7.6	7.5
Mesaverde Group	S	1	----	3,760	----	3,600	----	130	----	2,300	----	7.7
Mancos Shale	S	4	6,070-6,530	6,270	9,500-12,000	10,500	3,100-3,300	3,170	110-140	130	6.8-6.9	6.8
Dakota Sandstone	GW	1	----	2,570	----	3,720	----	180	----	620	----	7.0
Morrison Formation:												
Brushy Basin Member	GW	2	1,830-4,040	2,940	2,750-5,620	4,180	94-120	107	480-1,200	840	6.9-7.6	7.2
Salt Wash Member	GW	1	----	297	----	515	----	14	----	55	----	7.8
Morrison, undivided	S	3	1,260-1,340	1,300	1,700-1,850	1,780	6.3-7.0	6.6	310-350	330	6.4-7.0	6.7
Entrada Sandstone	S	1	----	190	----	315	----	3.0	----	16	----	8.3
Wingate Sandstone	S	1	----	303	----	522	----	15	----	35	----	8.2
	GW	2	538-608	573	920-982	951	52-61	58	110-180	145	----	7.7
Middle Triassic[1/]	S	1	----	1,630	----	2,500	----	2.4	----	68	----	---
Chinle Formation	GW	1	----	1,800	----	2,420	----	170	----	1,000	----	7.5
Upper Pennsylvanian	S	5	2,700-2,790	2,750	3,100-4,700	3,520	2.3-4.3	3.5	900-1,000	940	6.8-7.0	6.9
	GW	1	----	2,250	----	3,050	----	2.4	----	810	----	7.0
Cutler Formation	W	4	4,957-7,909	6,420	----	----	240-3,680	2,240	313-3,100	1,120	6.8-10.4	8.7
Rico Formation	W	1	----	57,092	----	----	----	34,200	----	1,517	----	7.5
Salt confining beds:												
Hermosa Formation	W	9	72,190-185,318	136,100	----	----	62,400-115,440	83,400	769-10,100	2,140	7.0-8.0	7.5
Lower aquifer system:												
Leadville Limestone	W	6	46,199-217,000	101,200	----	----	26,000-129,000	63,000	1,750-10,090	3,470	6.3-7.8	7.1
Devonian rocks	W	1	----	299,590	----	----	----	180,000	----	1,820	----	6.6

1/ Possibly Kayenta Formation.

Table 10.--*Summary of water quality for hydrogeologic units near the Dolores River basin*

[Data mostly from Feltis, 1966, p. 50-59; Huntoon, 1977, p. 11; and Sumsion, 1971, p. 40; units rounded and in milligrams per liter except specific conductance, in microsiemens per centimeter at 25° Celsius and pH, in standard units]

Hydrogeologic unit and formation	Number of samples	Dissolved solids		Specific conductance		Chloride (Cl)		Sulfate (SO_4)		pH	
		Range	Average	Range	Average	Range	Average	Range	Average	Range	Median
Cretaceous confining beds:											
Mancos (?) Shale	1	---	4,150	---	5,640	---	215	---	---	---	---
Mesozoic sandstone aquifer:											
Morrison Formation	4	517-13,900	4,150	1,100-2,030	1,570	13-8,040	2,040	97-806	437	7.9	7.9
Entrada Sandstone	6	204-14,300	5,790	271-19,400	5,100	2-5,390	1,670	8.2-2,410	945	7.1-8.4	7.7
Navajo Sandstone	12	108-827	340	197-812	392	2.4-49	14.6	6.8-394	68	7.1-8.3	7.7
Kayenta Formation	2	189-220	204	353-374	363	6.2-21	13.6	14-25	20	7.4-8.2	7.8
Wingate Sandstone	9	164-680	322	296-3,760	1,000	8.3-112	34.7	24-97	44	7.3-8.6	7.7
Mesozoic and upper Paleozoic confining beds:											
Chinle Formation	4	4,980-20,800	12,900	---	---	530-10,500	5,510	270-1,830	1,030	7.5-8.1	7.8
Moenkopi Formation	5	1,410-18,100	10,400	1,680	---	28-6,140	3,590	324-2,030	1,010	7.0-7.7	7.4
Cutler Formation	15	237-6,010	2,300	386-3,970	1,880	6.2-1,000	252	1.8-2,900	1,050	6.0-8.1	7.0
Rico Formation	4	236-583	354	405-1,020	609	4.1-170	49	13-57	27	7.6-7.8	7.7
Salt confining beds:											
Hermosa Formation[1/]	8	23,900-398,000	174,000	---	---	7,800-250,000	107,000	49-7,840	2,310	4.4-8.7	7.0
Lower Paleozoic aquifer:											
Leadville Limestone	32	7,360-327,000	94,700	---	---	1,140-196,000	55,200	120-52,000	4,120	5.0-7.7	6.5

[1/]Upper member and Paradox Member of the Hermosa Formation are considered to be part of the overlying and underlying confining units respectively (table 1).

and chloride was 170 mg/L or less: concentrations of sodium and chloride are generally small indicating that halite (salt) deposits have a minor effect on the quality of water in the alluvium.

Water from the Mesaverde Group had a dissolved-solids concentration of 3,760 mg/L, based on a chemical analysis of one spring sample. Water from the underlying Mancos Shale had a dissolved-solids concentration ranging from 6,070 to 6,530 mg/L, based on chemical analyses of four samples from one spring. The Mesaverde and Mancos yield waters that generally contain large dissolved-solids concentrations. Water from the Dakota Sandstone had a dissolved-solids concentration of 2,570 mg/L, based on one well sample. The underlying Burro Canyon Formation had a dissolved-solids concentration of 504 mg/L, based on one sample from a spring a few miles west of the study area.

Characteristics of water from stratigraphic units in the upper ground-water system from Morrison Formation downward in the sequence through the Rico Formation are shown in tables 9 and 10.

Salt Confining Bed

The salt confining bed is the Paradox Member of the Hermosa Formation; however, oil-test well data did not define sources of the water samples by member. Therefore, data for the three members of the Hermosa Formation are grouped together in table 9. In general, the large concentrations listed in this table may be either water from overlying or underlying beds, water from interbeds in the Paradox Member (Mayhew and Heylmun, 1965, p. 9), or possibly contaminated drilling fluid. Water samples from the reportedly undivided Hermosa Formation had dissolved-solids concentrations ranging from 72,190 to 185,318 mg/L, based on nine drill-stem tests from three oil wells in the western part of the area. Large chloride concentrations (62,440 to 115,400 mg/L) indicate that these samples are from zones in or near the Paradox Member.

Lower Ground-Water System

Water from the Leadville Limestone, the most permeable part of the lower Paleozoic aquifer, had dissolved-solids concentrations ranging from 46,199 to 217,000 mg/L, based on six drill-stem tests from five oil wells in the western part of the area. Large chloride concentrations (26,000 to 129,000 mg/L) may result from contamination from the Paradox Member during drilling and drillstem testing (R. J. Hite, U.S. Geological Survey, oral commun., 1979).

Water Quality of Streams in the Dolores River Area

Data on water quality for the Dolores River and its tributaries are presented in table 11. The data are listed in upstream order, starting with the Dolores River near Cisco; the data are sparse and scattered throughout the area. Location of the sample sites are shown in figure 13. Data obtained

Table 11.--*Summary of water quality for streams*

[L/s, liters per second; mg/L, milligrams per liter; µS, microsiemens per centimeter at 25° Celsius]

Sample location	Date	Discharge (L/s)	Dissolved solids (mg/L)	Specific conductance (µS)	Chloride (mg/L)	Sulfate (mg/L)	pH
Dolores River near Cisco	1-05-78	2,830	2,020	3,580	860	320	8.4
	2-03-78	4,300	3,350	5,600	1,500	530	7.2
	3-31-78	35,100	714	1,100	190	200	7.5
	4-27-78	213,500	183	300	16	41	7.4
	9-28-78	991	6,020	9,000	2,700	970	8.1
	10-26-78	3,290	2,860	4,880	1,200	570	7.9
	8-24-79	5,240	1,820	3,150	680	400	8.3
Dolores River at Gateway	10-14-77	-----	1,600	2,300	330	670	6.6
West Creek	01-03-78	-----	231	420	5.4	17	8.5
Salt Creek	01-03-78	-----	43,000	50,000	24,000	2,200	8.2
	07-15-80	1.9	------	54,000	28,000	2,200	7.9
Blue Creek	01-03-78	-----	300	580	19	20	8.6
Roc Creek	01-03-78	-----	824	1,590	360	63	8.5
	07-16-80	42	------	1,507	340	67	8.4
Mesa Creek	01-04-78	-----	823	1,240	36	320	8.3
San Miguel River at Uravan	01-19-77	2,747	594	780	7.4	300	7.9
West Paradox Creek	01-04-78	-----	1,000	1,365	37	530	8.4
Dolores River at Slick Rock	01-03-78	-----	493	800	87	140	---
Disappointment Creek	01-03-78	-----	6,940	8,000	150	4,600	---
Beaver Creek	01-04-78	-----	491	640	6.9	150	---
West Dolores River near Stoner	01-04-78	-----	413	750	100	47	---
Stoner Creek	01-04-78	-----	166	360	0.9	22	---

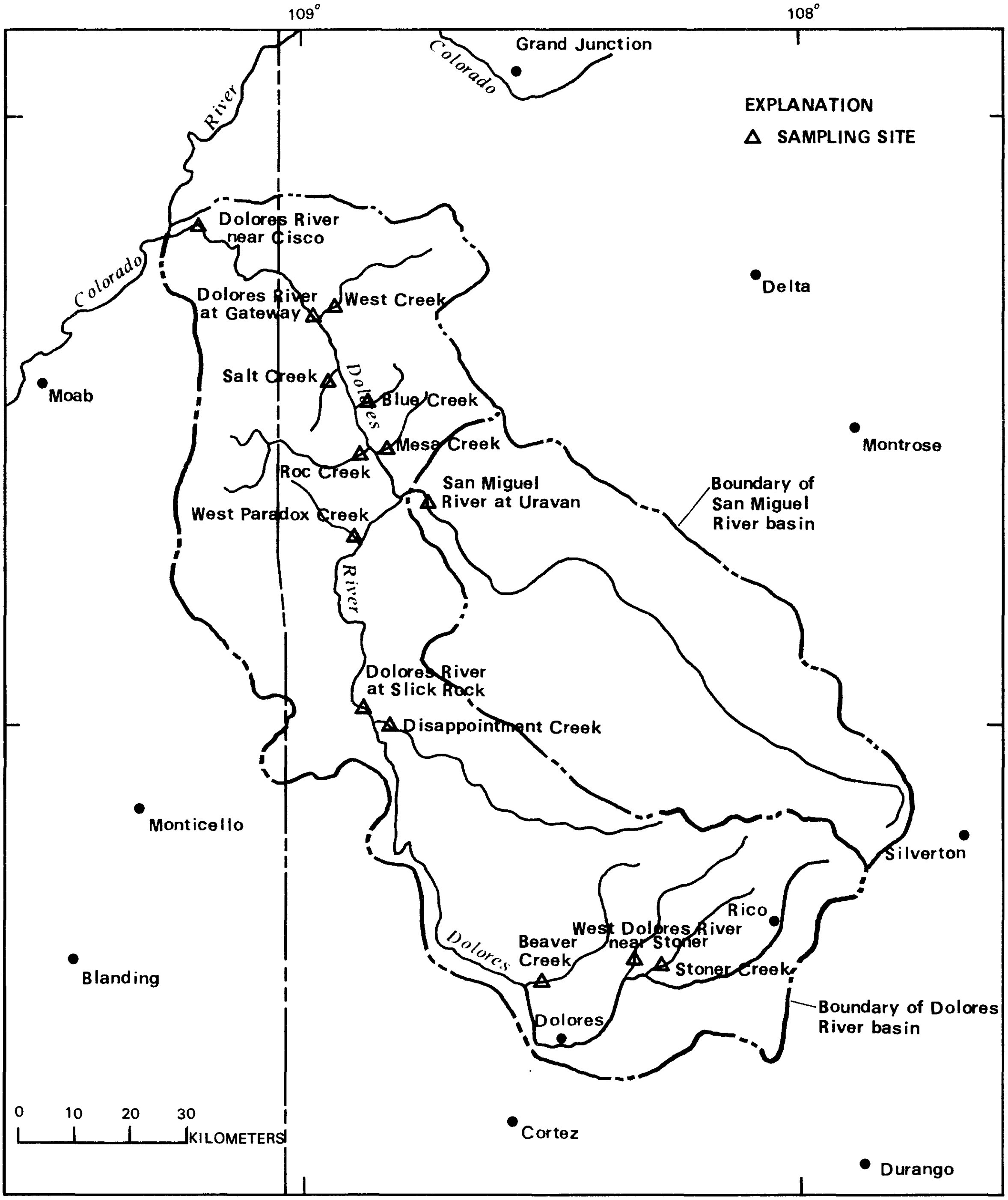

Figure 13.--Location of sampling sites for water-quality analyses of streams in the Dolores River basin and vicinity.

in January during low-flow periods are more representative of natural conditions than data obtained during the irrigation season.

The Dolores River contains a mixture of water from several different rock terrains, across which both the Dolores River and its tributaries flow. The river water contains calcium, sodium, sulfate, bicarbonate, and chloride as the predominant ions, from Slick Rock, Colorado, to Cisco, Utah, near the mouth of the river. In the headwaters, at West Dolores River near Stoner, Colorado, predominant ions are similar, except for sulfate. Between Slick Rock and Cisco during a low-flow period during the first week in January 1978, chloride and sulfate concentration increased downstream. At Slick Rock, concentration of dissolved solids was 493 mg/L, chloride was 87 mg/L, and sulfate was 140 mg/L; at Cisco, dissolved solids was 2,020 mg/L, chloride was 860 mg/L, and sulfate was 320 mg/L, based on two analyses. The large increase in chloride concentration probably resulted from surface- and ground-water inflow from the salt-anticline regions, such as Paradox Valley and Sinbad Valley. The large sulfate concentration comes from tributaries north and east of the Dolores River; the large chloride concentration comes from the area of salt anticlines west of the river.

Streams draining terrains that contain Mesozoic sandstones between the Wingate Sandstone and the Dakota Sandstone, including some shale in the Morrison Formation, generally contain calcium bicarbonate water if the streams do not flow across shale in the Morrison Formation. The streams generally contain calcium bicarbonate sulfate water if they flow across both sandstone and shale. West Creek and Blue Creek contain calcium bicarbonate water. San Miguel River and Mesa Creek contain calcium bicarbonate sulfate water.

Streams draining terrains containing both Mesozoic sandstones and the Mancos Shale or Mesaverde Group generally contain greater concentrations of chloride and sulfate than do streams that drain terrains of Mesozoic sandstones. Chloride concentrations ranged from 6.9 to 150 mg/L; sulfate ranged from 47 to 4,600 mg/L in this area, based on water samples from the West Dolores River, Beaver Creek, and Disappointment Creek. Disappointment Creek contained especially large concentrations of chloride and sulfate, because it flows across alluvium developed from the Mancos Shale in the center of the Disappointment Valley syncline.

Streams that drain salt anticlines and Mesozoic sandstone terrain surrounding the salt anticlines generally contain large concentrations of chloride and sodium. Salt Creek contained as much as 28,000 mg/L of chloride; Roc Creek contained as much as 360 mg/L of chloride, based on the analyses in table 11. West Paradox Creek contained only 37 mg/L of chloride, even though it flows through the eroded Paradox Valley anticline; this chloride concentration may be due to the stream flowing across alluvium and not across salt beds in the anticline. Chloride concentrations in streams in this area ranged from 37 to 28,000 mg/L; the greatest concentration probably was from ground-water influx to the river as it crosses Paradox Valley.

RELATIONSHIPS OF FLOW SYSTEMS TO SALT BEDS

Flow systems in the main alluvial valleys within the study area are of particular interest because of their relationship to anticlinal salt structures. These valleys, which include Paradox, Sinbad, and Disappointment Valleys, are the result of plastic upflow of these salt beds and subsequent collapse of overlying strata, with later deposition of moderately extensive alluvial deposits. Cap-rock units composed of gypsum, anhydrite, and carbonate rocks of the Paradox Member of the Hermosa Formation are beneath the alluvium; in a few small areas, these are exposed within the collapsed structures. Because of collapse after solution of halite beds, these cap-rock units are chaotic. Each valley has extensive faulting along its margins; additional faults in the central parts of the valleys are obscured by alluvial cover. Each valley receives considerable recharge from rainfall and runoff; springs also discharge from alluvium at the lower ends of the valleys. In the following paragraphs, data collected from streams, springs, and wells in each valley are analyzed.

Sinbad Valley, the most northerly of the three valleys, trends northwestward. Part of the collapsed anticline is floored by the Paradox Member of the Hermosa Formation over which Salt Creek flows. Salt Creek flows the length of Sinbad Valley before turning eastward through a canyon to the Dolores River. Specific conductance of the water in Salt Creek at the upper end of the canyon was 50,000 µS in July 1980; about 1 km farther downstream, conductance increased to 54,000 µS. Specific conductance of the spring issuing from the alluvium into upper Salt Creek was 50,000 µS in July 1980. Based on these results, dissolution of gypsum and salt occurs by ground water as it moves through alluvium in the upper reach of the valley; more dissolution of evaporites occurs as ground water flows through beds of the Paradox Member and into Salt Creek.

Paradox Valley, south of Sinbad Valley, also is a collapsed, diapiric salt structure. The Paradox Valley structure trends northwestward en echelon to Sinbad Valley structure to the north, and to the Salt Valley anticline to the northwest, out of the study area. Outcrops of the Paradox Member are limited in exposure near the southeastern end of the valley, but are widespread in hills near the center of the valley.

Elsewhere in the study area, three other collapsed-valley drainage systems contribute water, in significant quantities to the Dolores River. The Disappointment Creek system drains a large area east of the Dolores River. The system is perennial throughout most of its reaches. Water is lost by evapotranspiration via phreatophytes (pl. 2), but a sufficient influx of water occurs from seeps and springs from the sandstones into which the stream is incised to maintain at least a small flow in the lower middle reach throughout most of the year. In a few places, flow for short distances may occur as underflow through the alluvium.

Ground-water circulation in the lower ground-water system, in rocks beneath the Paradox Member of the Hermosa Formation, probably is not greatly affected by the salt-bearing beds. Some of the synclinal folds could create local barriers; however, very little borehole data exist for these synclines. If salt were squeezed vertically downward through cracks in carbonate beds, this could explain the occurrence of briny and brackish water in the Leadville Formation in Paradox basin. Other possible reasons for the salty water in the lower Paleozoic aquifer is found in the General Chemical Character of Water section of this report.

SALT DISSOLUTION IN DOLORES RIVER DRAINAGE BASIN

Hite and Lohman (1973) recognized that permanence of the salt deposits was an important aspect in considering the Paradox basin for waste storage. Lohman (Hite and Lohman, 1973, p. 38-42) analyzed the salt load of the Dolores River as follows:

> "Some idea of the rate of dissolution of salt from the crests of salt anticlines may be obtained from measurements of the discharge rate and chloride content of the Dolores River, the Colorado River and several tributaries of the Colorado that drain structures in which salt bodies are exposed. Five of the larger salt anticlines of the Paradox basin--Gypsum, Lisbon, Paradox, and Sinbad Valleys and the Dolores anticline--are drained by the Dolores River (fig. 2). At a gaging and sampling station 9 miles above the mouth, the Dolores carried an average of 528 tons per day of sodium chloride during 16-year period of record--1954 through 1969.
>
> "The remaining salt anticlines of the Paradox basin are drained by the Colorado River, but the determination of the additional salt load picked up by the Colorado below the mouth of the Dolores is hampered by lack of records. For only 1 year, 1952, is it feasible to determine both the load carried by the Dolores River (measured at Gateway, Colorado), and the net load added to the Colorado below the Dolores (between Dewey Bridge and Hite, Utah):

Tons per day of NaCl		
	3,450	Carried by Colorado River at Hite (below Paradox basin)
984		Carried by tributaries of Colorado River between junction with Dolores River and Hite
+2,340		Carried by Colorado River above junction with Dolores River
3,324	-3,324	Tonnage of NaCl not from Paradox basin
	126	Tonnage from Paradox basin exclusive of Dolores River
	+544	Carried by Dolores River near junction with Colorado River
	670	Average tonnage of NaCl carried daily (in 1952) from Paradox basin by Colorado River

> "The 670 tons per day would include all the common salt for 1952 from all salt anticlines including the Meander anticline in Cataract Canyon. Note that the value for the Dolores River at Gateway, 544 tons is comparable to the average value of 528 tons 9 miles above the mouth,

as mentioned earlier,so the total value should be the right order of magnitude.

"The chloride content of the Dolores River is derived in part from dissolution of halite from Gypsum Valley, Paradox Valley, and Sinbad Valley anticlines. Two other anticlines, the Dolores and Lisbon Valley, are also drained by the river but the Paradox Member is not exposed in these structures and there is no evidence of recent salt removal taking place. Solution of halite probably is taking place from the first three anticlines over a combined surface area of about 130 square miles. This area of active salt removal is obtained by measuring the prominent collapsed parts of each anticline. The average yearly load of nearly 200 thousand tons of chloride by the Dolores River represents removal of halite from an area of 130 square miles at a rate of about 0.0009 foot per year. If this rate of removal continued over a period of 1 million years, 900 feet of halite rock would be stripped from each of the three anticlines. This calculated rate of removal is probably excessive because: (1) it does not take into consideration that a considerable percentage of the sodium chloride carried by the Dolores River may be derived from rocks younger than the Paradox Member; and (2) salt is probably being removed from a much wider area than that on which surface collapse has become conspicuous.

"The cap rock of the salt anticline provides another means of estimating rate of salt removal. The average thickness of cap rock over these structures is about 1,000 feet. Allowing for the increase in volume that results when anhydrite is converted to gypsum, the present 1,000 feet of cap rock would represent about 750 feet of residual nonchloride material after the dissolution of salt from the anticline core. Because the original core of these anticlines average about 25 percent nonchloride material, 750 feet of residual nonchloride material would remain after the dissolution of salt from about 3,000 feet of halite-bearing rock. At the rate of 900 feet per million years, it would take 3.3 million years to remove this much halite, suggesting that the cap rock started developing in the early Pliocene. The age of the cap rock is unknown. Cater (1970, p. 65) stated, 'Collapse of the crests of the salt anticlines occurred in two stages apparently widely separated in time. The first followed perhaps rather closely the Late Cretaceous folding. The second stage followed epeirogenic uplift of the entire Colorado Plateau in the middle and late Tertiary, and this stage is still continuing.' If the cap rocks as we see them now began forming at the close of the Cretaceous, about 65 million years ago, then the removal rate of halite would have been 46 feet per million years. If accretion of the cap rocks did not begin until the epeirogenic uplift of the Colorado Plateau, which, according to Hunt (1956, p. 27), began during Miocene, about 20 million years age, then removal of salt proceeded at the rate of 150 feet per million years. The question of cap-rock age is further complicated by data from drill holes on the crests but outside the collapsed parts of the anticlines. One drill hole on the southern end of the Paradox Valley anticline (Petroleum Production Board Government 1 in sec. 19, T. 45 N., R. 15 W., Colo.) penetrated the Cutler Formation underlain by 290 feet of

Paradox cap rock. Another drill hole on the northern end of the Salt Valley anticline (Defense Plant Corp., Reader 1, in sec. 4, T. 22 S., R. 19 E., Utah) penetrated the Morrison Formation underlain by 650 feet of Paradox cap rock. At Lisbon Valley anticline, a thin cap rock is overlain by the upper member of the Hermosa Formation, about 250 million years old. These and other relationships between cap rock and overlying strata of Mesozoic and Paleozoic age suggest that at least part of the cap rock over the Gypsum Valley, Paradox Valley, and Sinbad Valley, anticlines may have developed during Permian time and has probably received continuous additions since that time. Considering then that a cap rock with a present-day thickness of 1,000 feet might be the result of dissolution of halite through a period of 250 million years, the rate of halite removal might be as slow as a 3 feet per million years.

"In summary, the exact rate of halite removal from the Paradox salt anticlines is difficult to determine but a range of 3 to 900 feet per million years is suggested. The preponderance of available evidence suggests that the actual rate lies within the lower half of the range."

FURTHER STUDIES

Further studies could be undertaken to increase understanding of the hydrologic systems in the Dolores River area. In order of increasing importance, these are:

1. To facilitate understanding of the flow pattern in the upper ground-water system, a more complete inventory of the wells in the area is needed. In this reconnaissance investigation, only a small percentage of the wells in the study area were examined. Almost all the static water levels were obtained from drillers' logs.

2. To understand the relationship of salt and other evaporites to ground water in the alluvium and cap rocks within the collapsed salt structures, a program of drilling and of testing of water quality could be undertaken. Although some wells producing water from the alluvium are completed within these collapsed structures, notably in Paradox Valley, they do not penetrate underlying bedrock. A few carefully selected well sites drilled through the alluvium and into the underlying bedrock, could yield considerable information about the thickness of salt, cap rock, or other bedrock in the subsurface overlying the collapsed structure. Information also could be collected for any changes in water quality with depth.

3. To understand flow of the lower ground-water system and its relationship to the Paradox Member (salt confining bed), exploratory holes are needed in synclinal areas. The little information now available for the lower ground-water system was obtained from deep wells drilled for oil exploration. These wells have been drilled consistently on anticlinal structures. Data from these wells are from areas where salt is the thickest. Also, ground-water flow through these lower hydrogeologic units may be diverted or interrupted by these structures. Deep test wells drilled off the crests of

selected anticlinal structures would produce information on the degree of thinning, and the characteristics of the salt away from the areas of maximum upward flowage. Information also would be obtained on the quality and movement of ground water on the flanks of these anticlines. This information cannot be obtained from present well data, because of uneven distribution of exploratory wells.

4. An evaluation of the lower ground-water system on a larger regional scale would greatly enhance understanding of this flow system. A reconnaissance of recharge areas for the Mississippian rocks to the north, northeast, and east would be the initial phase of this study. A reconnaissance of discharge areas, particularly in the vicinity of Grand Canyon, would help in understanding regional flow patterns.

CONCLUSIONS

Storage of radioactive waste in salt deposits of Paradox basin has been considered for several years. The major purpose of the current reconnaissance studies of the basin is to establish a hydrogeologic framework, largely with available information, to serve as a basis for further studies to determine the feasibility of storing radioactive waste.

Principal findings of this study that are pertinent to an assessment of the suitability of the hydrogeologic systems to store and contain radioactive waste are as follows:

1. Water in the upper ground-water flow system discharges to the Dolores River, a major tributary of the Colorado River.
2. Extensive, thick salt deposits effectively separate the upper and lower ground-water systems within the Paradox basin part of the study area.
3. Where salt deposits are absent, the potential may exist for downward (and perhaps locally, upward) leakage between systems.
4. Very little if any recharge occurs to the lower ground-water system within the study area; subsurface inflow to this system comes from the north and the southeast.
5. Active solution of salt and other evaporites by surface and ground water is occurring from the area of Big Gypsum Creek downstream to the vicinity of Fisher Creek.
6. Water in the upper ground-water system generally is fresh, except where it is affected by solution of evaporites.
7. Disruptions of ground-water flow by folds and contiguous faults are common in the upper system. Such disruptions of flow are not known in the lower system, perhaps because available hydrologic data for the lower ground-water system is scanty.
8. Fresh ground water is dissolving abundant halite and gypsum from the crests of the Paradox, Gypsum, Sinbad, and Fisher Valleys salts anticlines. These evaporites are being transported out of the basin via stream discharge. Salt solution in cap-rock areas might as slow as 1 meter per million years.

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