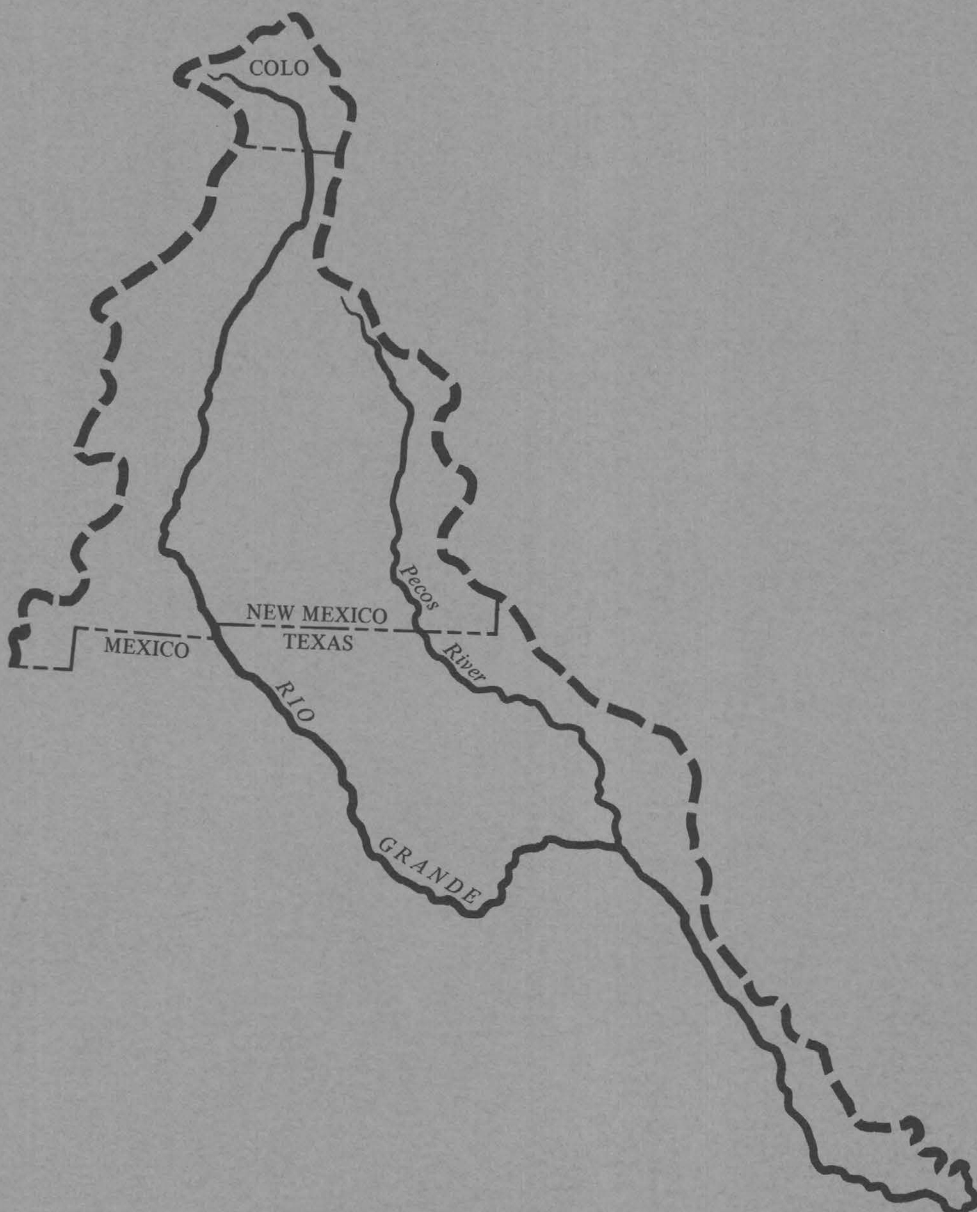
Summary Appraisals of the Nation's Ground-Water Resources— Rio Grande Region

GEOLOGICAL SURVEY PROFESSIONAL PAPER 813-D



Summary Appraisals of the Nation's Ground-Water Resources—Rio Grande Region

By S. W. WEST *and* W. L. BROADHURST

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A discussion of ground-water alternatives in water resource planning

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By S. W. WEST and W. L. BROADHURST

ABSTRACT

The Rio Grande is an interstate and international stream which begins in high mountains of Colorado, flows across New Mexico, and forms the boundary between Texas and Mexico. Precipitation ranges from 8 inches (20 cm) to more than 30 inches (76 cm), but irrigation is required for growing crops throughout the region.

The population of the region has been increasing rapidly, from 750,000 in 1929 to 1,700,000 in 1970, and it is expected to increase to 2,500,000 by 2020. The basic economy of the region was agricultural until recent years. Since 1950, the mining and petroleum industries have increased much more rapidly than agriculture.

Annual precipitation on the region is about 86 million acre-feet (110,000 hm^3); however, all but 4 million acre-feet (4,900 hm^3) is returned to the atmosphere by evapotranspiration. The ground-water reservoirs contain an aggregate of 5,800 million acre-feet (7,200,000 hm^3) of fresh and slightly saline water in storage, which could be withdrawn through wells. In contrast, the surface reservoirs have a combined storage capacity of only 18 million acre-feet (22,000 hm^3).

Thick deposits of valley fill in stream and intermontane valleys comprise the principal ground-water reservoirs. In most areas they are capable of yielding large supplies of water to wells. In some areas, limestone constitutes major aquifers.

Withdrawal of ground water in the region in 1970 was 2.7 million acre-feet (3,300 hm^3), of which 88 percent was used for irrigation. About 53 percent of the water withdrawn was consumed. Ground water has been "mined" in some areas, and severe declines in water levels have resulted.

The loss of water by evapotranspiration in wetlands and phreatophyte areas is 2.5 million acre-feet (3,100 hm^3) per year. In comparison, about 3.7 million acre-feet (4,600 hm^3) per year of surface water and ground water is consumed by man's activities.

Salvage of water lost to noneconomic evapotranspiration in wet and phreatophyte-infested areas offers the greatest possibility of improving the effective water supply in the region. Salvage of half the water lost would increase the effective supply by 1.2 million acre-feet (1,500 hm^3) per year. The usable water supply could be increased tremendously by drawing on the large reserve of ground water in storage, but this withdrawal could affect the flow of streams in some areas.

The region appears to offer several possibilities for utilizing underground space for purposes other than the withdrawal of water, such as waste disposal, artificial recharge, water-quality control, and development of geothermal energy.

Planners for ground-water management should have detailed information on the physical parameters that affect ground water, so improved management would be possible.

INTRODUCTION

Water resources are neatly catalogued, for convenience, as surface water and ground water. According to common usage, surface water is defined as any water on the land surface, regardless of whether it was derived directly from precipitation or from discharge of ground water. Ground water, in contrast, is defined as water below the land surface in the zone of saturation, regardless of whether it was derived from direct infiltration of precipitation or from infiltration of water flowing across or standing on the land surface. Traditionally, surface water has received more attention than ground water, because surface water is visible, is easily measured, and commonly can be diverted for use by gravity flow. Although ground water is out of sight, modern technology has provided tools for its measurement and utilization. Technology has also shown such a close relationship between surface water and ground water that they cannot be treated as separate sources of water. A change in the regimen of either will generally affect the other. In this report, the ground water is emphasized, because surface water has been fully appropriated and numerous structures exist for its regulation. In contrast, vast supplies of ground water lie beneath the surface.

In the past, much of the systematic planning for economic development or management of water resources has been straightforward and simple. The flows of principal streams were measured, and plans were drawn for diverting water from the streams to points of use. If variations in streamflow presented problems in meeting water demands, the situation was improved by building dams to regulate the streamflow by surface storage and controlled release.

Ground water has not been entirely ignored in water-resources development, but, in general, it has not been considered in systematic planning for total water management. Although ground water comprised 21 percent of the water used in the United States in 1970, planning for ground-water development has been limited to the municipal, water district, or private level, except for a few instances, and the impact of ground-water development on surface supplies has been largely neglected. This report attempts to place ground water in its proper perspective in regard to the total water resources.

This report is one of a series that will constitute a national compendium on ground water for the guidance of planners. New data for this appraisal were not collected. The many excellent reports dealing with the occurrence, development, and use of ground water for selected areas of the Rio Grande Region, from the headwaters to the mouth of the river, have been utilized. Also, unpublished data in the files of Federal, State, and other agencies and statements from many individuals concerned with the water problems of the region added to the information.

This report summarizes the knowledge of the ground-water resources of the region and evaluates deficiencies in our knowledge. The primary objectives are to direct attention to the locations and storage capacities of the principal ground-water reservoirs, to delineate the types of information needed for fuller evaluation of the opportunities for ground-water management, and to describe the role of ground-water reservoirs in meeting the region's water needs.

Although some of the water that falls as precipitation in the United States is used in Mexico and vice versa, that topic is not within the scope of this report. Of primary concern for this study are the water problems of the Rio Grande Region within the United States, including the drainage basin of the Pecos River and certain closed basins in Colorado, New Mexico, and Texas.

Numerous individuals in the district offices of the U.S. Geological Survey in Colorado, New Mexico, and Texas furnished many publications, permitted use of material being prepared for publication, and gave freely from their store of knowledge. Individuals in the New Mexico State Engineer Office provided unpublished records and reviewed the report.

Special thanks are extended to State officials and their staffs, including H. P. Burleigh, Executive Director of Texas Water Development Board; S. E. Reynolds, State Engineer of New Mexico; and C. J. Kuiper, State Engineer of Colorado. Data, assistance, and encouragement were received from many others. Grateful acknowledgement is extended to Dr. Gerald Thomas, President of New Mexico State University, Dr. John Clark, Director of New Mexico Water Resources Research Institute, and Jesse Gilmer, Texas member of the Rio Grande Compact Commission.

Most numbers in this report are given in English units followed by metric units in parentheses. The conversions to metric units were made as follows:

English			Metric	
Unit	Abbreviation	Multiplied by	Unit	Abbreviation
Acre	acre	0.4047	Hectare	ha
Acre-foot	acre-ft	.0012335	Cubic hectometre	hm^3
Foot	ft	.3048	Metre	m
Gallons per minute	gpm	5.45	Cubic metres per day	m^3/d
Inch	in.	2.54	Centemetre	cm
Mile	mi	1.6093	Kilometre	km
Square mile	mi^2	2.59	Square kilometre	km^2

Chemical concentrations are given only in metric units — milligrams per liter (mg/l). For concentrations less than 7,000 mg/l, the numerical value is about the same as for concentrations in the English unit, parts per million.

THE PHYSICAL SETTING

The Rio Grande is an interstate and international stream. It rises in southern Colorado, flows southward more than 400 miles (640 km) across New Mexico, and then forms the boundary between Mexico and Texas for about 1,250 miles (2,000 km) from El Paso to its mouth at the Gulf of Mexico (fig. 1). The total length of the river is about 1,800 miles (2,900 km).

The region ranges in altitude from sea level at the Gulf to a little more than 14,000 feet (4,300 m) on the higher peaks near the headwaters. The upper half of the region is characterized by disconnected mountain ranges and intervening intermontane valleys, except for the Pecos Valley, which lies mostly east of the principal mountain ranges. High hills and mountains or tablelands predominate locally in the northern half of the region. The southern half of the region is characterized by tablelands, canyons, and plains (fig. 2). The mountains and tablelands slope steeply, almost precipitously in some areas, toward the valley floors. Coalescing alluvial fans lie at the foot of many mountains and form intermediate slopes between the mountains and valley floors.

The altitude of irrigated lands averages about 7,700 feet (2,300 m) in the San Luis Valley, 5,000 feet (1,500 m) in the Albuquerque area, 3,800 feet (1,200 m) in the Las Cruces–El Paso area, 3,400 feet (1,000 m) in the Roswell-Carlsbad area, 2,600 feet (790 m) in the Pecos area, and only a few tens of feet in the coastal area.

Because of its geographic position and wide range in altitude, the region has a variety of climatic zones, including semitropic, arid, and arctic. As shown by available records, annual precipitation averages more than 30 inches (76 cm) in the mountainous headwaters

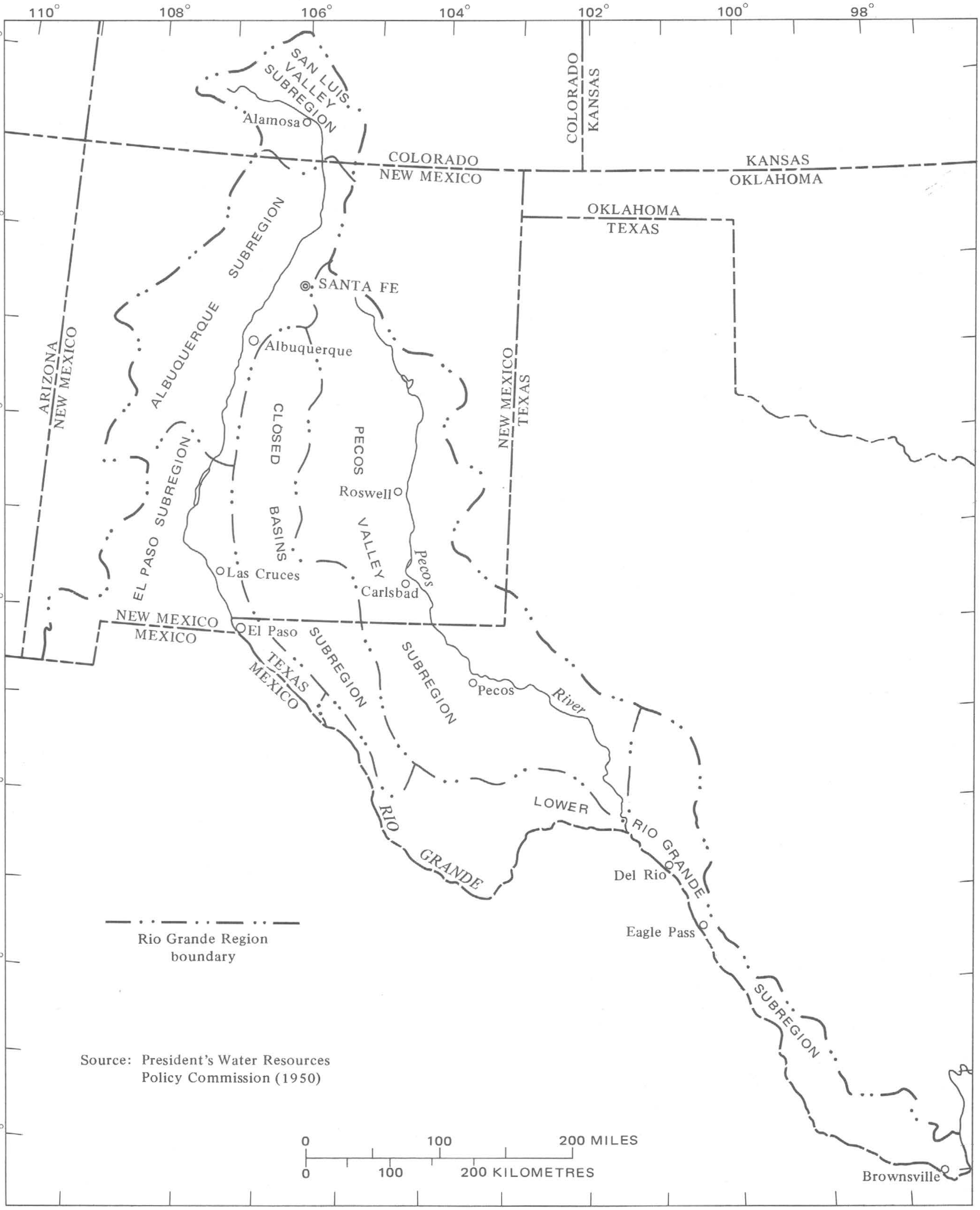


FIGURE 1. — The Rio Grande Region, showing six subregions based on physiography and ground-water resources.

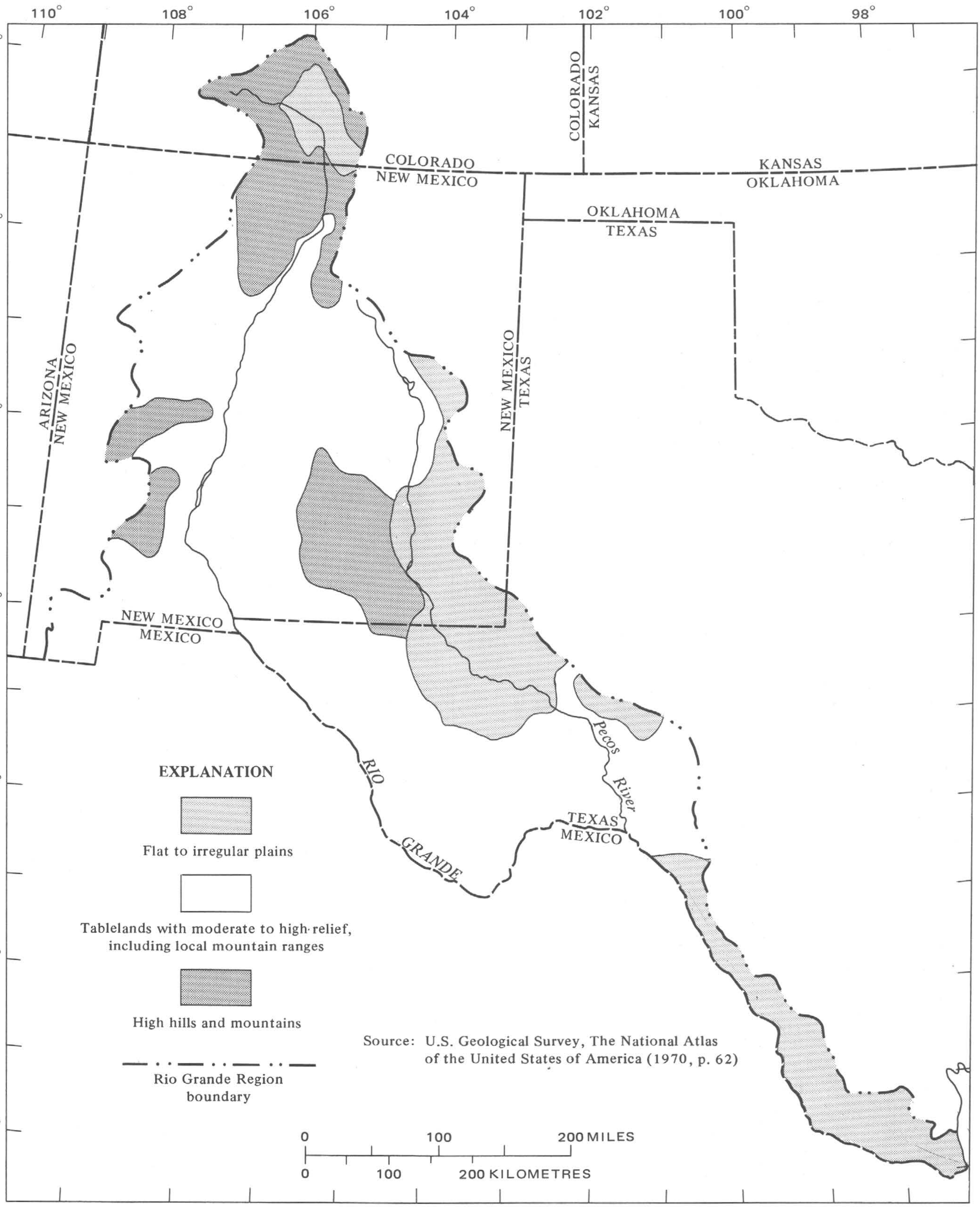


FIGURE 2. — Generalized terrain. Most of the region consists of tablelands with moderate to high relief. Mountains are limited mostly to the northern half of the region.

in Colorado and New Mexico, less than 8 inches (20 cm) in the intermontane valleys in Colorado, southern New Mexico, and western Texas, and about 25 inches (64 cm) along the Gulf Coast. Rainstorms of high intensity during summer are common throughout most of the region. Average precipitation for the entire basin is about 12 inches (30 cm) a year. That part of the basin within the United States has an area of approximately 135,000 square miles (350,000 km^2) — about 86 million acres (35 million ha). Therefore, total annual precipitation on the region averages about 86 million acre-feet (110,000 hm^3). But the considerable variability of precipitation from year to year and the recurrence of prolonged dry periods between wet periods create the major problems of water supply. Irrigation is required for growing crops throughout the region.

Temperatures vary widely, depending on latitude and altitude, but the entire region experiences a high percentage of bright sunny days. Both Alburquerque and El Paso have at times boasted of more than 365 consecutive days during which the sun made an appearance, and each city has about 75 percent of maximum possible sunshine.

Evaporation of water from lakes and reservoirs in the region ranges from 42 inches (110 cm) in the San Luis Valley to 80 inches (200 cm) near Big Bend, Tex., depending on temperature, humidity, wind velocity, and depth of water. Water loss by evaporation from the Elephant Butte and Caballo Reservoirs in southern New Mexico is estimated to be 255,000 acre-feet (310 hm^3) per year (Sorensen and Linford, 1967), and the loss from all the storage reservoirs, including small ponds, and from streams is about 950,000 acre-feet (1,200 hm^3) per year (Meyers, 1962).

The average growing season ranges from 90-120 days in the San Luis Valley, Colo., to 365 days in the lowermost part of the region near the Gulf of Mexico. The length of growing season, the types of crops grown, and the amount and timeliness of precipitation significantly affect the amount of water required for growing irrigated crops.

Much of the region is sparsely vegetated, as would be expected in areas of low rainfall. The prevalent types of vegetation are grasses, desert shrubs, juniper, pinon, forest trees, and alpine shrubs, depending on the altitude of the land and the amount of precipitation.

The steep slopes, the high-intensity rainstorms in summer, and the sparse vegetation combine to cause rapid runoff and erosion. The resultant sediment loads of tributary streams tend to overload the Rio Grande, causing aggradation along a large part of its course in New Mexico and rapid filling of surface storage reservoirs.

THE ECONOMIC SETTING

Human occupation of the Rio Grande Region has a long and varied history. Parts of the region were inhabited by nomadic Indians for thousands of years before the first white men arrived. These nomads were replaced by pastoral Pueblo Indians, who built villages in the valleys and tilled nearby irrigated farms. The first Spanish colonists arrived in 1598, establishing the first white settlement in the region near the present San Juan Indian Pueblo, at the confluence of the Rio Chama and the Rio Grande. Many Spanish colonists followed, and numerous villages were established along the Rio Grande and its tributaries. Descendants of the Pueblo Indians and Spanish colonists still constitute a significant part of the population in the northern part of the region. Since the region became a part of the United States, it has experienced a large influx of people from all parts of the United States, as well as from several foreign countries.

For centuries the water supply in the Rio Grande and its tributaries was adequate to meet the small demands of the pastoral Indians and Spanish colonists. In the present century, the demands for water have been increasing dramatically, owing to extensive irrigation, new industries, rapid increase in population, and construction of numerous military facilities. The population of the region increased from 750,000 in 1929 to 1,700,000 in 1970 and is expected to increase to 2,500,000 by 2020. In addition to the resident population, thousands of tourists visit the region each year. Of particular interest to tourists are national parks (Carlsbad Caverns, N. Mex.; Big Bend, Tex.; and Guadalupe Mountains, Tex.), national monuments, state monuments, prehistoric Indian sites, other areas of historic interest, and areas of great scenic beauty. The principal population centers are Albuquerque, N. Mex., and El Paso, Tex. The distribution of population is shown in figure 3, and population trends are shown in figure 4.

From early Pueblo Indian times to recent years, the basic economy of the region was related to agriculture. Successful production of crops depended on irrigation, and most of the irrigated lands are on or adjacent to the flood plains of perennial streams (fig. 5). In some areas, irrigation with ground water has been pursued for many years. Water is a limiting factor in agricultural expansion, so the earnings from agriculture have not increased significantly during the last 20-30 years, because the surface water has been fully appropriated and ground-water development has been limited by small supplies or has been restricted to protect surface-water rights.

The earnings from economic activities that require less water per dollar of earnings than irrigation agriculture increased rapidly during 1950-70. These activities are expected to continue their growth, as shown in table 1. The

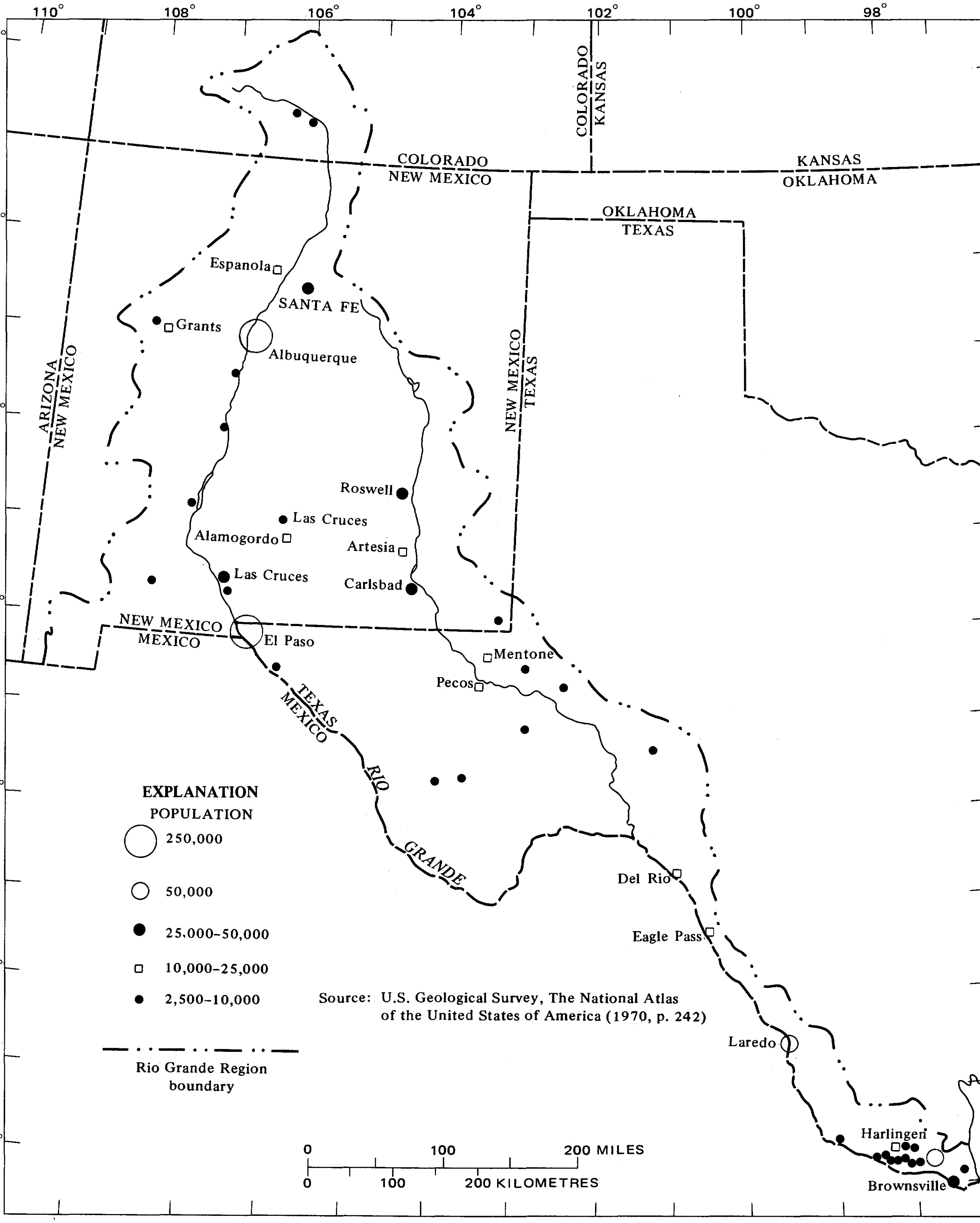


FIGURE 3. — Population distribution. Most of the population is concentrated along the major rivers — the Rio Grande and the Pecos River. The largest cities are Albuquerque, N. Mex., and El Paso, Tex.

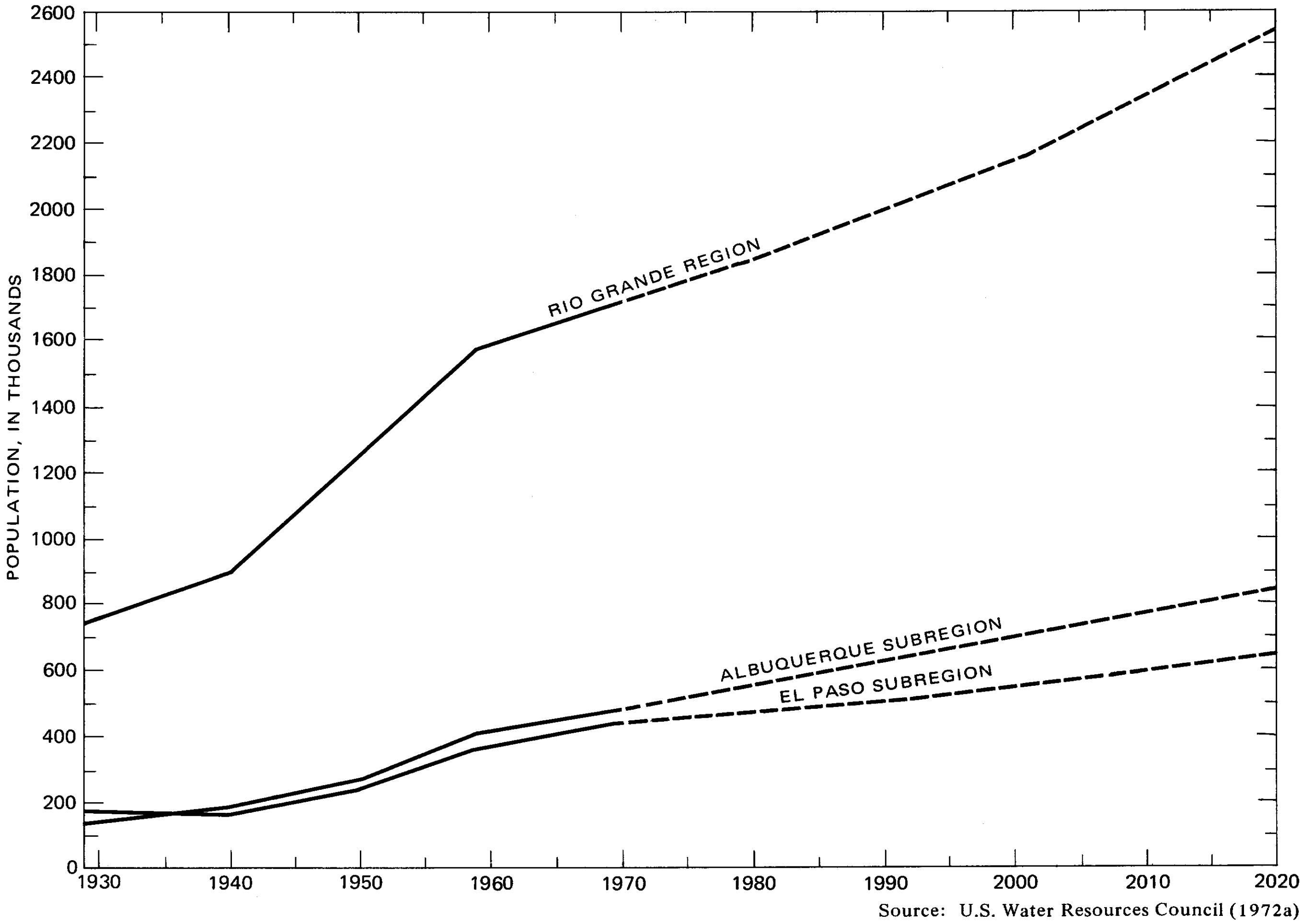


FIGURE 4. — Population trends. The population of the Rio Grande Region has been increasing rapidly, and the trend of the last decade is expected to continue for the next 50 years. Dashed lines indicate projected trends.

TABLE 1. — *Population, personal income, and industrial earnings: Historical and projected*

[Adapted from U.S. Water Resources Council (1972a). Values are based on the value of the dollar in 1967]

Year	1950	1969	1980	2000	2020
Population (midyear)	1,238,201	1,684,853	1,845,500	2,154,100	2,536,000
Per capita income	$1,503	$2,456	$3,597	$6,717	$12,274
Earnings per worker	$3,882	$5,665	$8,253	$14,639	$25,599
Industrial earnings (in thousands of dollars):					
Agriculture, forestry, fisheries	$286,783	$282,653	$287,200	$358,500	$628,300
Mining, oil, and gas	58,603	112,375	131,200	189,000	287,200
Contract construction	129,595	196,828	291,700	628,500	1,329,800
Manufacturing	107,846	276,003	413,800	843,900	1,761,600
Transportation and public utilities	142,256	229,654	330,900	638,800	1,256,900
Wholesale and retail trade	290,476	545,115	866,300	1,856,700	3,927,100
Finance, insurance, and real estate	47,158	131,629	208,700	455,900	980,500
Services	162,963	539,388	941,400	2,230,100	4,986,100
Government	334,698	1,089,227	1,790,000	4,039,700	8,649,600
Total	$1,560,382	$3,402,870	$5,261,600	$11,241,400	$23,807,600

distribution of minerals and petroleum is shown in figure 6. Innumerable sand and gravel quarries constitute a significant part of the mineral industry of the region, but they could not be shown in figure 6.

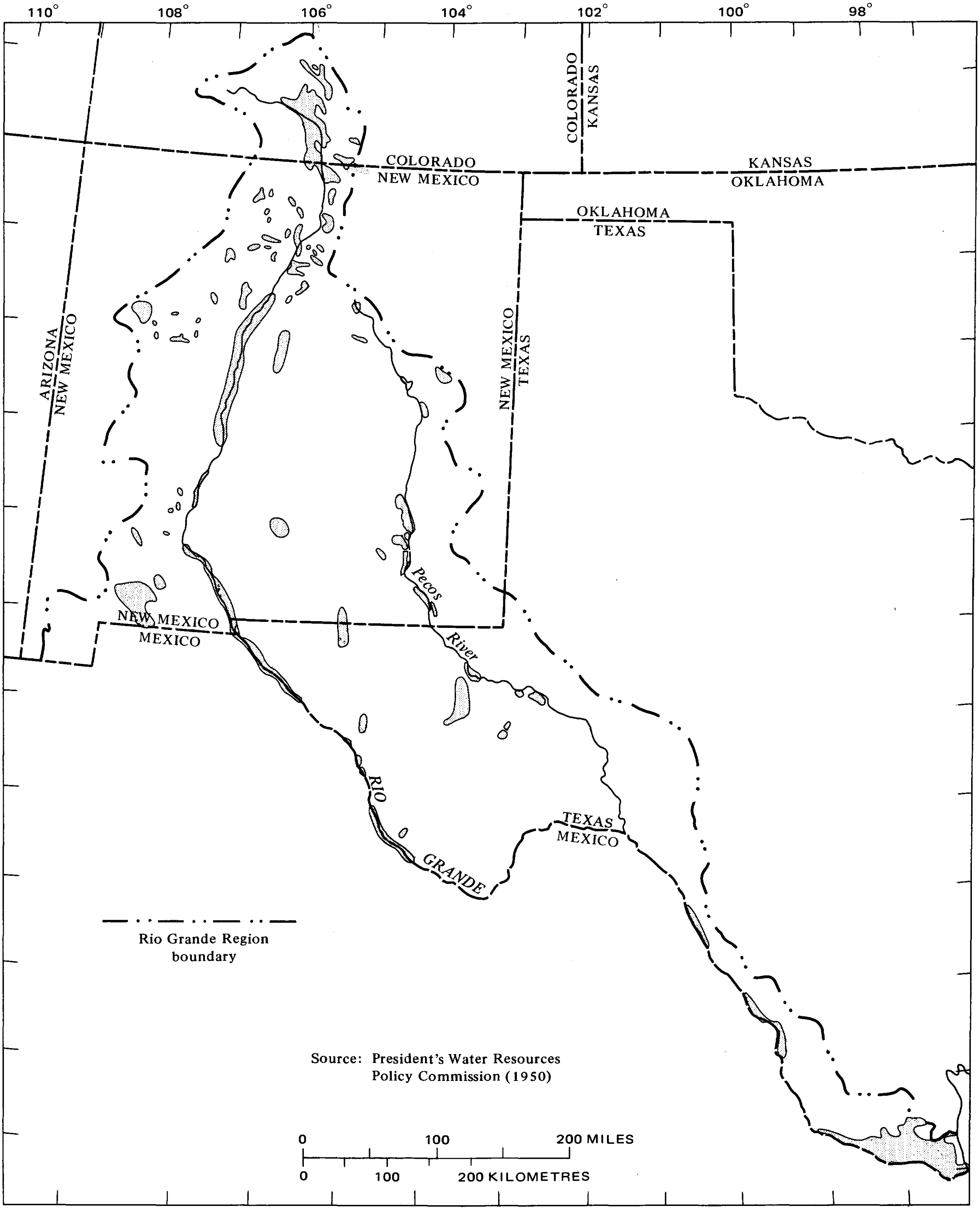


FIGURE 5. — Areas of irrigated land. Most of the irrigated land is alongside the Rio Grande and the Pecos River.

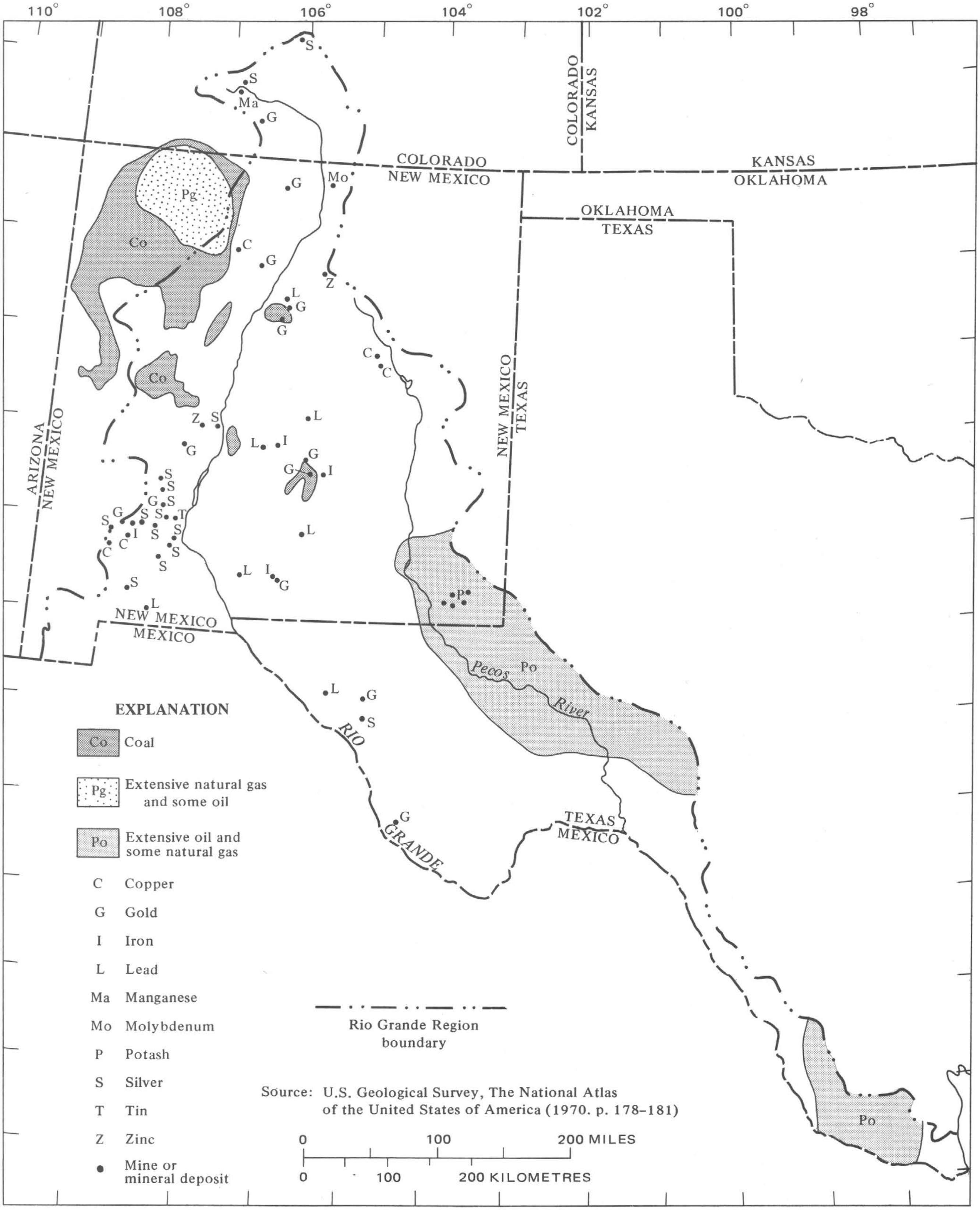


FIGURE 6. — Mineral and petroleum deposits. Extensive mineral deposits are found in the northern half of the region. Innumerable sand and gravel quarries are not shown.

THE LEGAL SETTING

Management of the surface waters of the Rio Grande Region is subject to international treaty, interstate compacts, and laws of three States. Management of ground water within each State is subject to regulation by that State.

In the late 1880's, water shortages experienced by Mexican users near Ciudad Juarez resulted in protests to the United States by Mexico, alleging that shortages resulted from increasing diversions for irrigation in New Mexico and Colorado. The International Boundary Commission, United States and Mexico, was directed to investigate the water situation in the upper Rio Grande, and as a result of that investigation, an embargo was placed on further surface-water development in the two States until the problem could be resolved. In 1906, the United States and Mexico negotiated a treaty whereby Mexico was guaranteed an annual delivery of 60,000 acre-feet (74 hm^3) of water in perpetuity, with the provision that the two Nations would share shortages in times of drought (Sorensen and Linford, 1967, p. 148).

Both the Rio Grande main stem and the Pecos River are subject to apportionment of surface water under interstate compacts. The Rio Grande Compact specifies that Colorado must deliver to New Mexico a specified quantity of water in proportion to water available at index stations in Colorado, and that New Mexico must deliver to Texas a specified quantity of water in proportion to water available at index stations in New Mexico. At times, both Colorado and New Mexico have been delinquent in water deliveries. The Pecos River Compact specifies the proportion of Pecos River water that New Mexico must deliver to Texas. Uncontrolled development of ground water in either the Rio Grande or the Pecos River valleys could make it impossible to deliver the specified quantities of surface water down the natural river channels; however, orderly development and management of the ground-water reservoirs in conjunction with management of the rivers could assure delivery of the specified quantities annually for the foreseeable future.

When the Colorado Constitution was adopted in 1876, it provided for appropriation of the water of natural streams not previously appropriated. All natural streams were declared to be the property of the public. The courts in Colorado have, in effect, defined "waters of a natural stream" by ruling that if the waters in question would reach a natural watercourse or were in a natural watercourse, they were waters of a natural stream. In cases involving water pumped from wells, some courts have adjudicated on the theory that underground waters are waters of a natural stream. Other courts have held that for adjudication purposes waters produced from wells are not waters of a natural stream (Sparks, 1970).

In 1965 the Colorado Legislature passed a new ground-water law. Section 148-18-1 of the law states:

> It is hereby declared that the traditional policy of the state of Colorado requiring the water resources of this state be devoted to beneficial use in reasonable amounts through appropriation, is affirmed with respect to the designated ground waters of this state, as said waters are hereinafter defined. While the doctrine of prior appropriation is recognized, such doctrine should be modified to permit the full economic development of designated ground-water resources. Prior appropriations of ground water should be protected and reasonable ground water pumping levels maintained, but not to include the maintenance of historical water levels. All ground waters in this state are therefore declared to be subject to appropriation in the manner herein defined.

The law also specifically prohibits the diversion of ground water outside the State for use within another State.

The State Engineer of Colorado administers the laws relative to the distribution of surface waters, including ground waters tributary thereto.

In 1969 the Colorado Legislature enacted a bill that revised the entire water code and allowed for the use of ground water in conjunction with surface water. It is now possible to change the point of diversion from a surface diversion to a well diversion.

By 1970, about 30,000 wells had been drilled in Colorado, none of which had adjudicated water rights. Under existing laws, if rights on the wells are adjudicated, they will be subordinate to all the surface decrees and generally will have a priority date later than 1950 (Sparks, 1970).

The Pueblo Indians in the Rio Grande Valley of New Mexico were operating acequias (community ditches) along perennial streams to support subsistence farming when Coronado led the first Spanish exploration through the area in 1540. From 1609 until 1680, Spanish colonists established several villages along the Rio Grande and its perennial tributaries and began the same type of subsistence farming that prevailed among the Pueblo Indians. When Mexico gained its independence from Spain in 1821, the territory including the Rio Grande Valley passed from Spanish to Mexican rule, but the water rights of both the Indians and the colonists were recognized by Mexico. The territory was ceded to the United States in 1848 by the Treaty of Guadalupe Hidalgo, and again the water rights of residents were recognized by the new government.

The Rio Grande Valley was still sparsely settled when ceded to the United States, so there was little competition for water, and the local acequias served the people well. With the influx of American settlers in the latter part of the 19th century, the competition for water became serious, so the Territorial Legislature of New Mexico passed the first legislation to regulate the appropriation of surface water in 1905, and the legislation was rewritten in 1907. Also in 1905, the legislature adopted an act to regulate the use of artesian wells and to prevent the waste of subterranean flows of water (Mechem, 1961).

When New Mexico became a State in 1912, the constitution contained the following sections pertaining to water rights:

1. All existing rights to the use of any waters in this state for any useful or beneficial purpose are hereby recognized and confirmed.

2. The unappropriated water of every natural stream, perennial or torrential, within the state of New Mexico, is hereby declared to belong to the public and to be subject to appropriation for beneficial use, in accordance with the laws of the state. Priority of appropriation shall give the better right.

3. Beneficial use shall be the basis, the measure and the limit of the right to the use of water.

The first ground-water statute was passed by the State in 1927. It provided that

All waters in the State found in underground streams, channels, artesian basins, reservoirs, or lakes, the boundaries of which may be reasonably ascertained by scientific investigations of surface indications, are hereby declared to be public waters and to belong to the public, and subject to appropriation for beneficial uses under the existing laws of this state relating to appropriation and beneficial use of waters from surface streams.

This law was declared invalid by the New Mexico Supreme Court, because it attempted to extend existing legislation by reference (Mechem, 1961). In 1931 the statute was reenacted in a form the court outlined in its opinion on the 1927 act. The 1931 statute was not challenged in the courts until 1949, and in 1950 the New Mexico Supreme Court upheld the statute (Mechem, 1961). It is still the law governing ground-water appropriation and use in New Mexico.

Under the New Mexico law, the State Engineer, after adequate evaluation, may declare an "underground water basin" and control further development of ground water in order to protect prior water rights. The State Engineer has declared 14 such basins in the Rio Grande Region, the largest of which extends on each side of the Rio Grande from Elephant Butte Reservoir to the Colorado–New Mexico line. The State Engineer defines and declares such basins whenever it becomes apparent that regulation is necessary to (1) prevent impairment of existing rights, (2) insure beneficial use of water, and (3) provide for an orderly development of ground-water reservoirs. The New Mexico Supreme Court has found that it is unreasonable to attempt a legal distinction between ground water and surface water, because of their interrelationship.

Texas does not have provisions for statewide administration and control of ground water in its legal code. The courts, in implementing statutes on the books, have in general applied the principle of the law of capture (riparian rights) in ground-water disputes (Dixon, 1961). In 1949 the Texas Legislature enacted the "Underground Water District Act" (Art. 7880-3c), which authorized water districts to take action to promulgate rules regarding the conservation and use of percolating ground water. However, the districts were not authorized to regulate the use of underground water in defined channels or the underflow of rivers, both of which are subject to appropriation the same as surface water. Districts can be created by the legislature, the Texas Water Rights Commission, and county commissioners' courts. Prior to creation of an underground-water conservation district, the Water Rights Commission must determine through studies conducted by the Texas Water Development Board that an underground-water reservoir, or subdivision thereof, having definable boundaries and meeting other predetermined requirements actually exists. The district is a corporate unit which can own property and act in all ways as an entity having financial and legal responsibilities. The initial legislation was amended in 1955 to strengthen the power of the districts with regard to well spacing, regulation of production, and prevention of waste (Dixon, 1961). This legislation was amended again in 1972.

THE GROUND-WATER SUPPLY

The total water supply of the Rio Grande Region is the sum of the surface-water runoff, the ground-water outflow (which is small), and the natural evapotranspiration. Annual precipitation averages about 12 inches (30 cm) on the 86 million acres (35 million ha) within the region; however, all but 4 million acre-feet (4,900 hm^3) of the precipitation returns to the atmosphere through natural evapotranspiration. The runoff, or water yield, of the region and part of the natural evapotranspiration represent the water that can be controlled or modified to a degree by man. For example, man may be able to intercept for economic use (agricultural, municipal, and industrial supplies) water that normally is lost to noneconomic consumption by native vegetation. Also, he may import more water or intercept for beneficial use the water that runs off to the Gulf of Mexico. A small amount of surface water is imported into the region by transmountain diversion.

The ground-water reservoirs of the region contain an aggregate of more than 5,800 million acre-feet (7,200,000 hm^3) of fresh (less than 1,000 mg/l dissolved solids) to slightly saline (1,000-3,000 mg/l dissolved solids) water in storage, which under the laws of nature is available to wells. In contrast, the surface reservoirs of the region have a combined storage capacity of only 18 million acre-feet (22,000 hm^3).

The ground-water reservoirs of the region can be classified on the basis of rock characteristics, physiography, and geographic distribution. For convenience of description, the rocks have been divided into four basic types: (1) valley fill — unconsolidated to poorly consolidated sand and gravel interbedded or in-

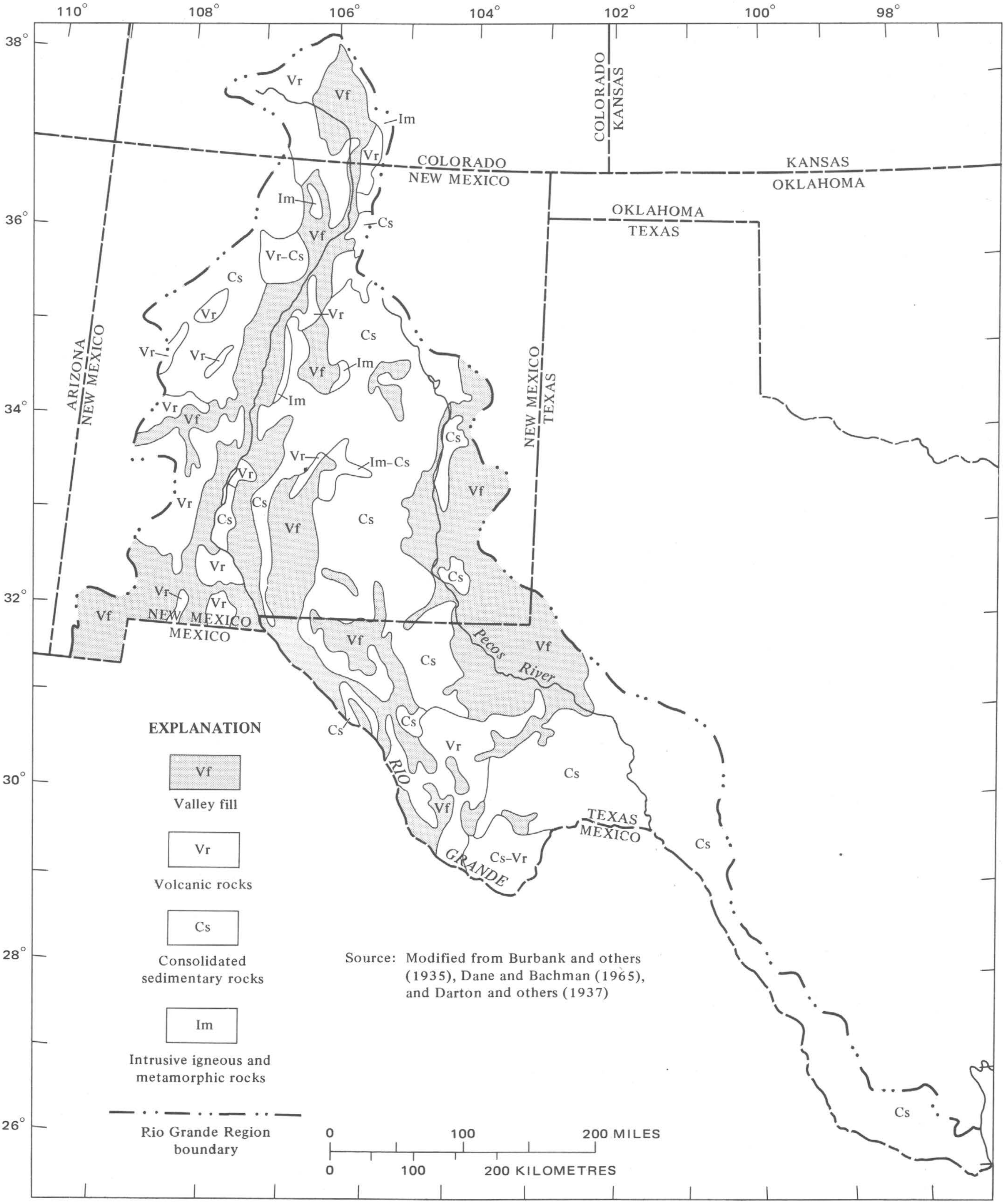


FIGURE 7. — Generalized distribution of geologic units. Valley fill comprises the principal ground-water reservoirs.

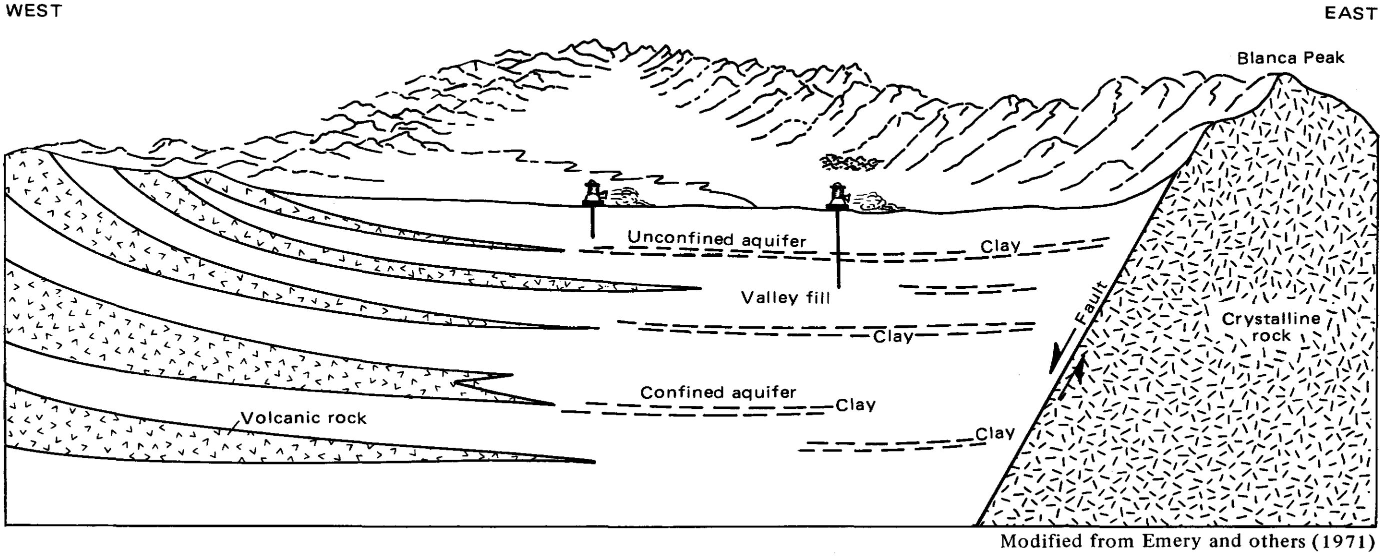


FIGURE 8. — The San Luis Valley. The valley is bounded by high mountains and is underlain by valley fill and volcanic rocks; the water table is within 12 feet (3.6 m) of land surface in most areas.

termixed with clay and silt; (2) volcanic rocks — primarily basalt but including other flow rocks, tuff, and small intrusive bodies; (3) consolidated sedimentary rocks — primarily shale and sandstone but including limestone, gypsum, and salt; and (4) crystalline rocks — intrusive igneous rocks and metamorphic rocks.

The intermontane valleys of the region have been partly filled with unconsolidated sand, gravel, and clay — termed "valley fill" — derived by weathering and erosion from the rocks in the adjacent mountains and from similar rocks in the mountains upstream (fig. 7). Alluvial deposits in the Pecos Valley are included in the valley-fill category, but the valley fill shown east of the Pecos River (fig. 7) is thin and is not a significant ground-water reservoir.

Locally, the valley fill is interbedded with basalt and other flow rocks derived from volcanic centers in and bordering the valleys. Large masses of basalt and andesite are common, especially in the northern part of the basin. The valley fill, including the interbedded volcanic rocks, is as much as 9,000 feet (2,700 m) thick in New Mexico and is reported to be more than 30,000 feet (9,100 m) thick in the north-central part of the San Luis Valley, Colo. (Gaca and Karig, 1966). The valley fill comprises the principal ground-water reservoir in the region. In most areas it is capable of yielding a few hundred to a few thousand gallons of water per minute to individual wells.

The mountains consist of volcanic rocks, consolidated sedimentary rocks, and crystalline rocks (fig. 7). The volcanic rocks commonly cap plateaus and low mountain ranges and lie above the regional water table. These rocks generally are not significant aquifers except where they are interbedded with or overlie valley fill. The consolidated sedimentary rocks form most of the hills and low mountains. Generally,these rocks are poor aquifers, but locally, beds of limestone containing extensive fractures and solution channels lie below the water table and yield large supplies of water to wells. In many areas the consolidated sedimentary rocks contain soluble minerals, such as halite and gypsum — the principal sources of dissolved solids in ground water. The crystalline rocks generally are dense and yield insignificant quantities of water to wells.

SAN LUIS VALLEY SUBREGION

The valley-fill ground-water reservoir in the San Luis Valley contains both unconfined and confined aquifers, which are separated in places by a clay series or by layers of volcanic rocks (fig. 8). These confining beds are discontinuous and lenticular, so it is difficult to differentiate between unconfined and confined aquifers except locally. This discontinuity in the clay series permits varying degrees of hydraulic connection between the aquifers; therefore, all the aquifers in the valley north of the San Luis Hills should be considered a single ground-water reservoir (Emery and others, 1971).

Recharge to the unconfined aquifer is mainly by infiltration of irrigation water from canals, ditches, and fields and by upward leakage from the confined aquifer. Some water percolates from the many streams flanking the valley, but very little precipitation on the valley floor recharges the unconfined aquifer. Natural discharge from this aquifer is by evapotranspiration and seepage to streams.

The principal source of recharge to the confined aquifer is seepage from mountain streams that flow across the alluvial fans flanking the valley floor. At the edge of the valley the clay series is absent, permitting recharge to beds that constitute the confined aquifer in the main part of the valley. The mountain streams show significant losses as they cross the porous surface of the fans. The confined aquifer underlies most of the valley, and the water has sufficient head to flow at the land surface. The natural discharge from the confined aquifer is by springs and by upward leakage through the confining beds into the unconfined aquifer. A small amount discharges as underflow into New Mexico.

The ground-water reservoir in the San Luis Valley underlies about 2 million acres (809,000 ha). It ranges in thickness from a featheredge around the rim of the valley to as much as 7,000-9,000 feet (2,100-2,700 m) beneath much of the area and to a reported thickness of more than 30,000 feet (9,100 m) locally (Gaca and Karig, 1966). If we assume the average thickness of the permeable deposits to be 5,000 feet (1,500 m), the volume of reservoir material is 2 million × 5,000, or about 10 billion acre-feet (12 million hm^3), and if the average specific yield is 0.2 (20 percent), the amount of water in storage in the reservoir available to wells is about 2 billion acre-feet (2.5 million hm^3).

In 1967 about 2,800 wells in the San Luis Valley yielded more than 300 gpm (1,635 m^3/d) each. Of this total, 2,160 were completed in the unconfined aquifer. In addition to the large-capacity wells, there are more than 7,000 small-capacity flowing wells. The annual water income to the San Luis Valley averages about 2.5 million acre-feet (3,100 hm^3); about 1.5 million acre-feet (1,800 hm^3) is streamflow derived chiefly from snowmelt in the surrounding mountains, and about 1 million acre-feet (1,200 hm^3) is from precipitation on the valley floor. Annual discharge of water from the valley also averages 2.5 million acre-feet (3,100 hm^3) — about 2 million acre-feet (2,500 hm^3) by evapotranspiration and about 500,000 acre-feet (620 hm^3) as flow across the State line (table 2). The streamflow at the State line averages 445,000 acre-feet (550 hm^3), and ground-water underflow is 55,000 acre-feet (68 hm^3). About half the evapotranspiration is noneconomic; that is, it does not contribute to the growth of plants having economic or commercial value. Much of the noneconomic consumption is by phreatophytes in areas where the depth to water is less than 12 feet (3.6 m).

According to Powell (1958), the quality of water in the confined aquifer is generally better than that in the unconfined aquifer. The concentration of dissolved solids in 41 samples from the confined aquifer ranged from 70 to 437 mg/l, and the concentration in 271 samples from the unconfined aquifer ranged from 52 to 13,800 mg/l. The least mineralized water in the unconfined aquifer occurs on the west side of the valley. The mineral concentration increases toward the sump area of the closed basin, probably because of solution from the rocks and concentration by evapotranspiration in areas having a shallow water table.

ALBUQUERQUE SUBREGION

The valley fill in the Rio Grande depression, which underlies about 5,000 square miles (13,000 km^2), or 3,200,000 acres (1,300,000 ha), comprises the principal ground-water reservoir in the Albuquerque subregion (fig. 9). The thickness of the fill is not well known, but it may average about 4,000 feet (1,200 m). The maximum thickness is probably about 9,000 feet (2,700 m) (Dinwiddie, 1967). The estimated volume of recoverable fresh ground water in storage in this and other ground-water reservoirs is 2,300 million acre-feet (2,800,000 hm^3); an additional 540 million acre-feet (670,000 hm^3) of recoverable slightly saline water is in storage, making a total of 2,800 million acre-feet (3,400,000 hm^3) of fresh

TABLE 2. — *The water budget*

Subregion	Income		Outgo			Storage capacity	
	Surface-water inflow (ac-ft per yr)	Surface-water yield (ac-ft per yr)	Surface-water outflow[1] (ac-ft per yr)	Evapotranspiration: Man's activities (ac-ft per yr)	Evapotranspiration: Wetlands and phreatophytes (ac-ft per yr)	Surface water (ac-ft)	Ground water[2] (ac-ft)
San Luis Valley	0	1,500,000	500,000	1,000,000	1,000,000	400,000	2,000,000,000
Albuquerque	500,000	1,500,000	[3]990,000	300,000	400,000	230,000	2,800,000,000
El Paso	[4]730,000	200,000	260,000	500,000	500,000	2,500,000	230,000,000
Lower Rio Grande	[5]620,000	700,000	0	1,000,000	200,000	14,000,000	20,000,000
Pecos Valley	0	1,700,000	360,000	800,000	280,000	650,000	410,000,000
Closed Basins	0	[6]0	0	130,000	100,000	0	290,000,000
Total (rounded)		5,600,000		3,700,000	2,500,000	18,000,000	5,800,000,000

[1]Includes some ground-water underflow.
[2]Recoverable fresh and slightly saline ground water in storage.
[3]Surface flow at San Marcial above Elephant Butte Reservoir.
[4]Surface flow below Elephant Butte Reservoir.
[5]The sum of surface-water outflow from both the El Paso and the Pecos Valley subregions.
[6]Some runoff from mountainous areas, which infiltrates the ground or evaporates in playas.

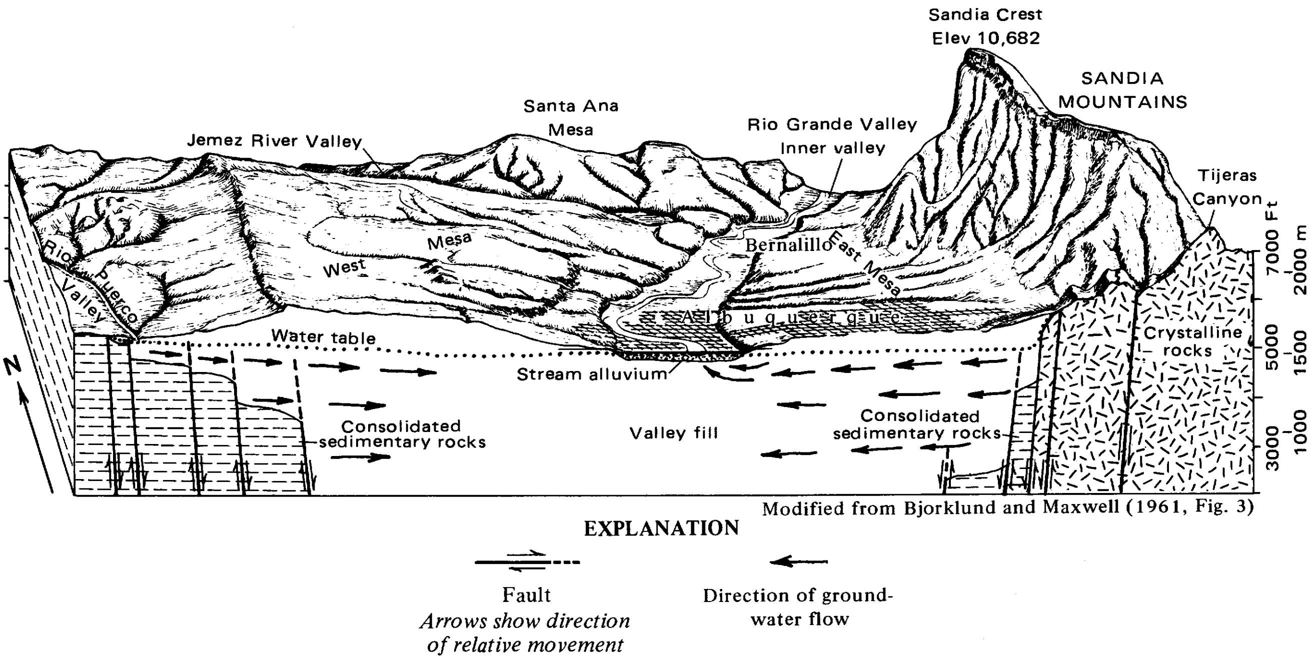


FIGURE 9. — The Rio Grande Valley at Albuquerque, N. Mex. High mountains bound the valley on the east; agricultural lands and the older part of the city are in the inner valley, where the water table and the river level coincide.

and slightly saline water in storage (based on a specific yield ranging from 5 to 15 percent) (table 2).

The yield of 83 large-discharge wells that tap the valley fill in the Albuquerque area ranges from 240 to 2,000 gpm (1,300 to 11,000 m^3/d) and averaged 860 gpm (4,700 m^3/d) (Bjorklund and Maxwell, 1961). Volcanic rocks in the northern part of the subregion locally yield water to wells. Consolidated sedimentary rocks are not significant aquifers, except in the Rio San Jose valley near Grants, N. Mex., where yields of more than 2,000 gpm (1,300 m^3/d) per well have been obtained from limestone (Gordon, 1962).

Recharge in the subregion is from precipitation on the valley fill and associated volcanic rocks, from infiltration of surface water diverted for irrigation, and from intermittent runoff during intense rainstorms. In the northern part of the subregion, some recharge is from runoff of snowmelt.

The chemical quality of ground water varies widely in this subregion. A study of municipal water supplies in New Mexico (Dinwiddie and others, 1966a, b) revealed that the concentration of dissolved solids in municipal or community water supplies in this subregion ranges from 125 to 2,620 mg/l and that the water supply for 23 communities exceeds the concentration of 500 mg/l recommended for public water supplies by the U.S. Public Health Service (1962). The quality of municipal water supplies is probably an indication of ground-water quality in general, although even higher concentrations can be expected locally, because public supplies are generally drawn from the best water available. The water in the valley fill of the Rio Grande Valley is better in quality than in most of the tributary valleys along the west side of the subregion.

EL PASO SUBREGION

A bedrock high in the vicinity of Elephant Butte Reservoir tends to separate the ground-water reservoirs in the Albuquerque subregion from those in the El Paso subregion. Some ground water is forced to the land surface where the valley fill becomes narrower and thinner in this area. A section across the Rio Grande Valley and adjacent areas near Elephant Butte Reservoir is shown in figure 10.

As in the San Luis Valley and the Albuquerque subregions, the major ground-water reservoir in the El Paso subregion is valley fill. The thickness of the fill and interbedded volcanic rocks in the Las Cruces area is locally more than 5,000 feet (1,500 m) and probably averages at least 3,000 feet (910 m) (fig. 11). The valley fill narrows in the vicinity of El Paso but widens again into the Hueco bolson east of the Franklin Mountains and in broad band alongside the Rio Grande down to Fort Quitman. The fresh and slightly saline ground water stored in these reservoirs is about 230 million acre-feet (280,000 hm^3). (table 2).

Individual wells in the Las Cruces–El Paso area yield as much as 3,000 gpm (16,400 m^3/d) and average about 1,000 gpm (5,400 m^3/d). Farther down the valley the

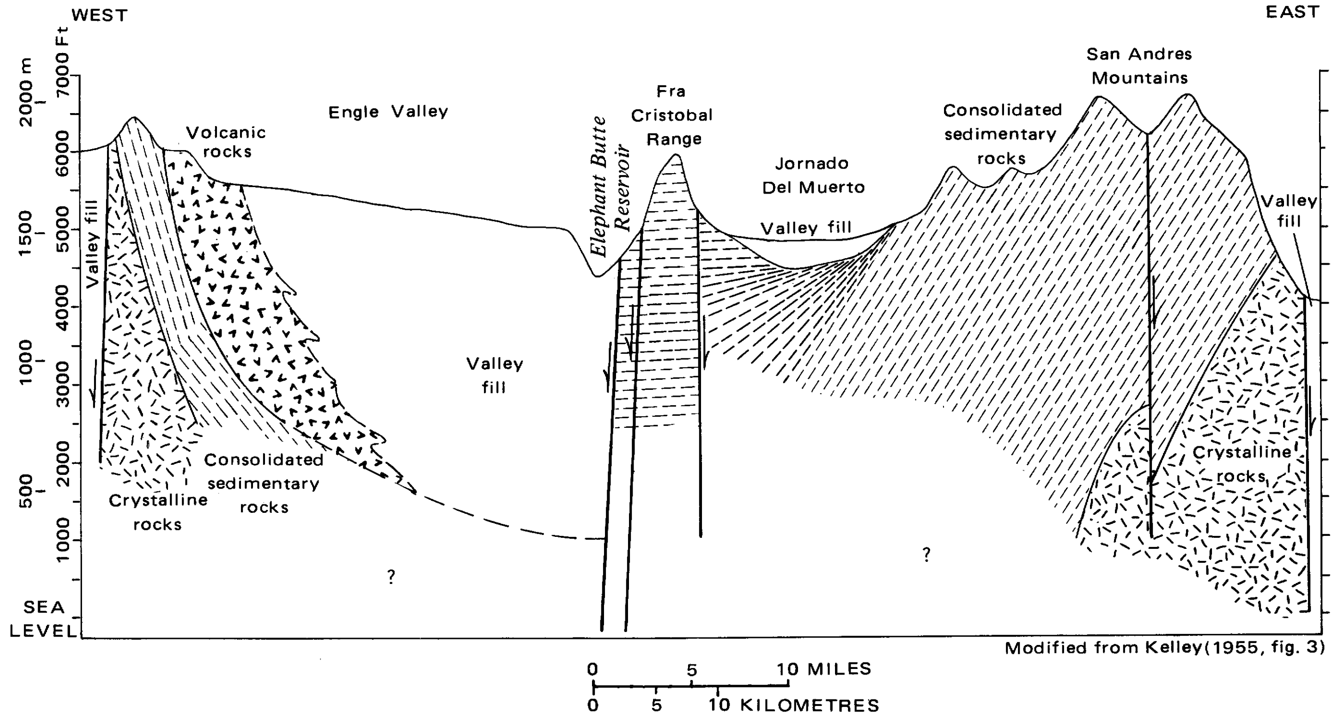


FIGURE 10. — The ground-water reservoir in valley fill at Elephant Butte Reservoir in New Mexico. The ground-water reservoir is thinner and narrower here than at most places in New Mexico.

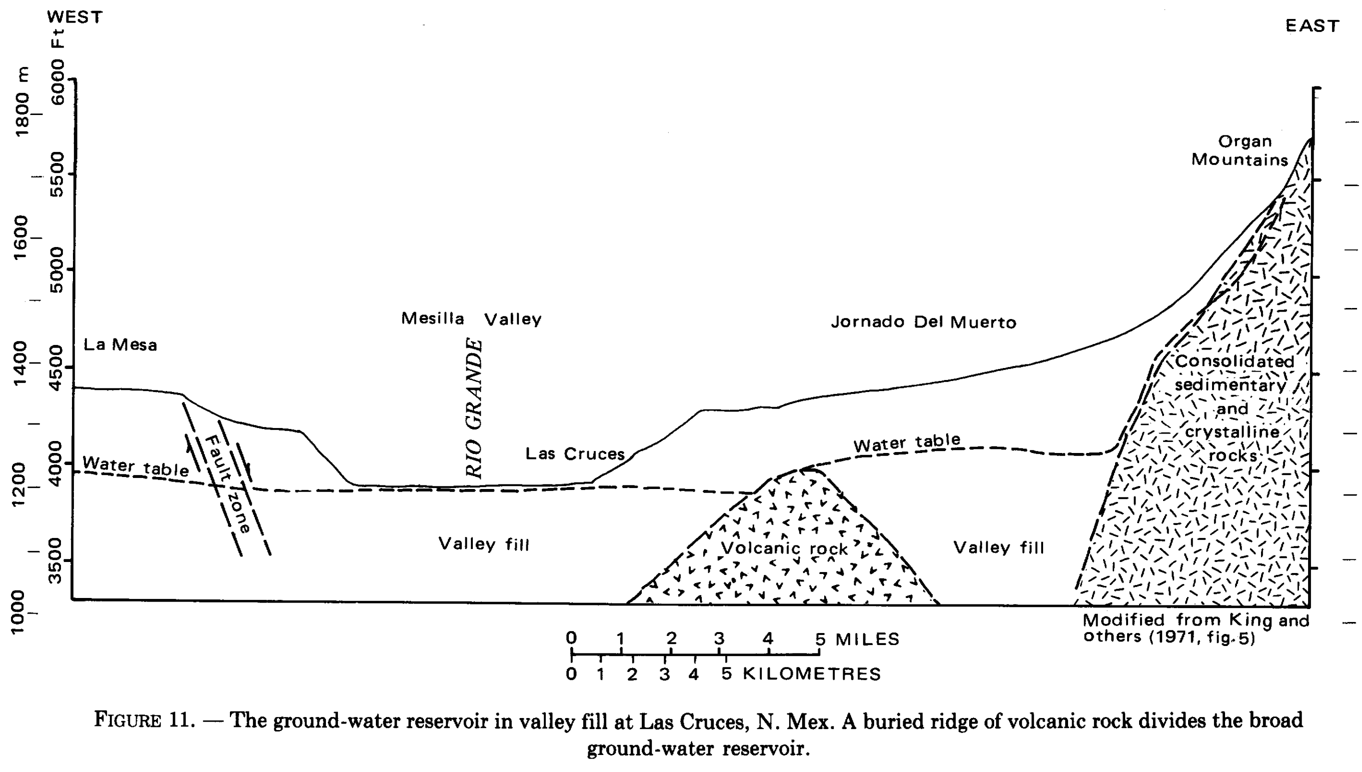


FIGURE 11. — The ground-water reservoir in valley fill at Las Cruces, N. Mex. A buried ridge of volcanic rock divides the broad ground-water reservoir.

yields are much smaller, ranging from about 100 to 500 gpm (54 to 2,700 m^3/d) (Davis and Leggat, 1965).

Recharge is relatively small, because the subregion is in the minimum rainfall belt. Infiltration from surface water diverted for irrigation locally provides significant recharge.

The chemical quality of water in the valley-fill aquifers in the El Paso subregion varies widely, both laterally and vertically. The water in the shallow alluvial deposits along the river generally contains higher concentrations of dissolved solids than the water in the underlying older fill, but the salinity may increase at depths of a few thousand feet in the older fill. The dissolved solids in water in the river alluvium have been concentrated by evapotranspiration in areas where the water table is shallow and by return of irrigation water, which contains dissolved soil salts and fertilizers. The concentration of dissolved solids in ground water of the Las Cruces–El Paso area ranges from about 200 to more than 6,000 mg/l (Davis and Leggat, 1965).

PECOS VALLEY SUBREGION

Consolidated sedimentary rocks, which consist of shale, sandstone, limestone, gypsum, and salt, predominate in the Pecos Valley subregion. Beds of limestone and, locally, gypsum are excellent aquifers in some areas. However, extensive deposits of gypsum and salt contribute large quantities of dissolved solids to the water in the subregion. The valley fill constitutes productive aquifers where it is thickest, such as in the Roswell basin (fig. 12) and in several areas between the Texas–New Mexico line and Girvin, Tex.

The quantity of fresh and slightly saline ground water in storage in the subregion is about 410 million acre-feet (510,000 hm^3) (table 2). Most of the water is stored in valley-fill and sandstone reservoirs; but in the Roswell and Carlsbad areas, some 10 million acre-feet (12,000 hm^3) is stored in limestone and gypsum reservoirs, and an equal amount is stored in limestone and sandstone in the Texas part of the subregion.

Wells completed in either the limestone or the valley fill in the Roswell basin generally yield more than 300 gpm (1,600 m^3/d) each, and yields of 1,000-3,500 gpm (5,400-19,000 m^3/d) are common. The limetone aquifer has outcrops west of the Pecos River near Roswell, N. Mex., that accept recharge readily from direct precipitation and from surface flow. The overlying valley-fill aquifer is recharged by upward leakage of artesian water from the limestone aquifer and by infiltration of a part of the water used for irrigation.

The chemical quality of ground water varies widely in the subregion, ranging from fresh to briny (less than 1,000 to more than 35,000 mg/l). All or part of the water supply for 16 communities in the New Mexico part of the subregion contains more than 500 mg/l dissolved solids. The concentration of dissolved solids in municipal supplies ranges from 150 mg/l in the northern part to 2,410 mg/l for one community in Chaves County. The chemical quality of public water supplies in the Texas part of the subregion is comparable.

In some areas, as fresh ground water is withdrawn it is replaced by more saline water, which mixes with the fresh water in storage and causes a general deterioration in water quality.

CLOSED BASINS SUBREGION

The closed basins subregion comprises the Estancia, the Jornada del Muerto, and the Tularosa basins in New Mexico and the Salt basin in New Mexico and Texas. All these basins have internal surface drainage, but some water may move underground to adjacent basins or subregions.

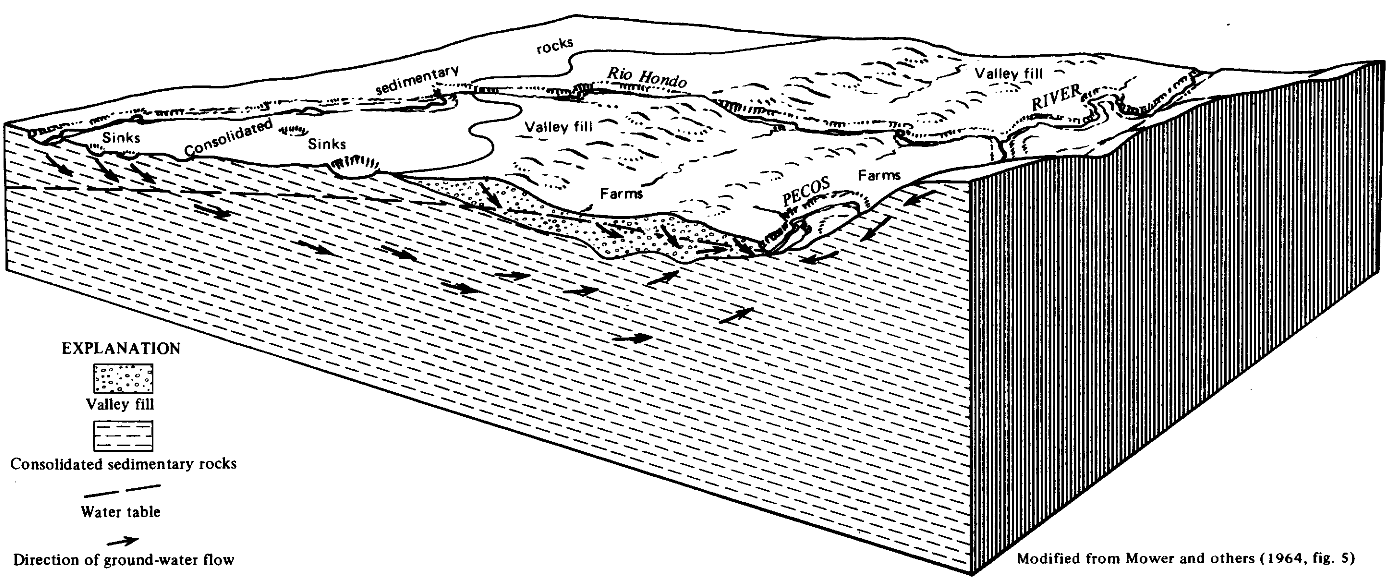


FIGURE 12. — The complex relationship between the ground-water flow system and the surface water in the Pecos Valley at Roswell, N. Mex.

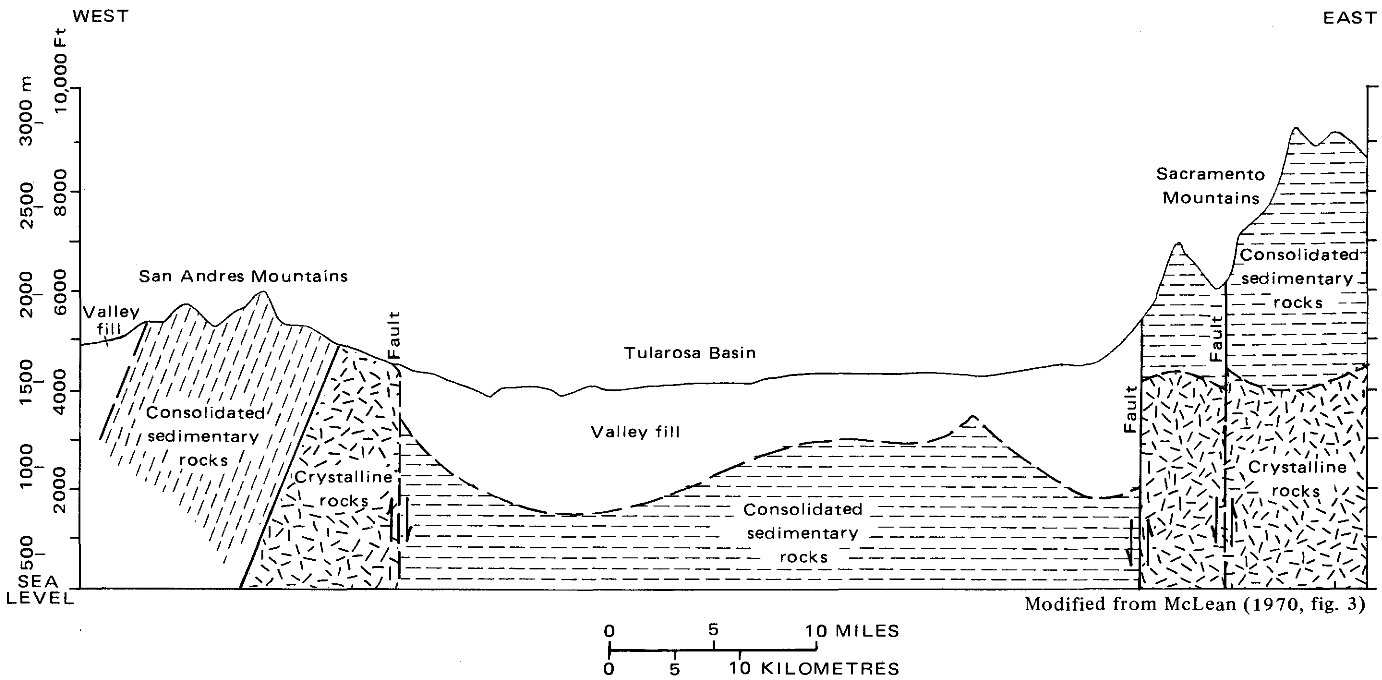


FIGURE 13. — The ground-water reservoir in valley fill of the Tularosa basin in New Mexico. The reservoir is large, but fresh water is found only in narrow bands adjacent to the mountains.

Valley fill predominates in the closed basins and constitutes the principal ground-water reservoirs. The fill consists of both alluvial deposits at the foot of the mountains and lake deposits in the central part of each basin, except in the Jornada del Muerto basin. The lake deposits consist of silt, clay, and evaporites, especially gypsum. These evaporites are a common source of high salinity in ground water in the central parts of the basins. The valley fill commonly is thin around the margins but may be a few thousand feet thick in the deeper parts of the basins. A generalized section across the Tularosa basin is shown in figure 13. Yields as large as 2,400 gpm (13,000 m^3/d) have been obtained from individual wells in the fill, and yields of several hundred gallons per minute are common.

Limestone constitutes an important aquifer in the northern part of the Salt basin, where it is a source of water for irrigation.

The volume of fresh and slightly saline ground water stored in the closed basins is summarized below:

Basin	*Volume (ac-ft)*
Estancia	10,000,000
Jornada del Muerto	110,000,000
Tularosa	150,000,000
Salt	20,000,000
Total	290,000,000

In addition to the fresh and slightly saline water in storage, large volumes of more saline water are stored in each of the basins. McLean (1970) estimated that about 60 million acre-feet (74,000 hm^3) of water with a dissolved-solids content of more than 3,000 mg/l is in storage in the Tularosa basin. Similar estimates for the other basins have not been made. The fresh water (less than 1,000 mg/l) is limited to narrow bands in the valley fill next to mountain ranges of most basins. The concentration of dissolved solids in ground water ranges from about 200 mg/l to more than 100,000 mg/l.

A study of public water supplies in southeastern New Mexico by Dinwiddie (1963) showed that the supplies for 16 communities in the New Mexico part of the subregion contain concentrations of dissolved solids higher than 500 mg/l. Public supplies have not been developed in the Jornada del Muerto.

LOWER RIO GRANDE SUBREGION

The ground-water reservoirs in the lower Rio Grande subregion are insignificant in comparison with those in the other subregions. Most of the aquifers are consolidated sedimentary rocks consisting of sandstone and limestone (Brown and others, 1965). In the northernmost and the southernmost parts of the subregion, stream alluvium along the Rio Grande is the principal aquifer (Baker, 1965). The estimated quantity of fresh and slightly saline water in the subregion is only 20 million acre-feet (25,000 hm^3)(table 2).

The yields of wells in this subregion are highly variable depending on the type of aquifer. Yields range from a few tens of gallons per minute to as much as 3,000 gpm

(16,000 m^3/d). Beds of limestone are the most productive.

The water generally contains from a few hundred to a few thousand milligrams per liter dissolved solids.

WITHDRAWAL AND CONSUMPTION OF GROUND WATER

Withdrawal of ground water in the Rio Grande Region in 1970 was 2,700,000 acre-feet (3,300 hm^3), in comparison to a withdrawal of 4,300,000 acre-feet (5,300 hm^3) of surface water (fig. 14). The largest part of the ground water (88 percent) was used for irrigation (fig. 15). About 180,000 acre-feet (220 hm^3) (5 percent) of the ground water withdrawn was used for public supplies (ground water furnished 58 percent of all the public supply requirements). The largest metropolitan areas (Albuquerque and El Paso) depend entirely on ground water as a source of public supplies. The average per capita use of public supplies in the region is 228 gallons per day, or 0.86 m^3/d (Murray and Reeves, 1972). Ground water withdrawn for all uses other than irrigation and public supplies was only 7 percent (fig. 15). Of the total water withdrawn from all sources for all uses, 53 percent was consumed and 47 percent returned to the streams or ground-water reservoirs (fig. 16).

About 680,000 acre-feet (840 hm^3) of ground water was withdrawn for use in the San Luis Valley in 1970, mostly for irrigation (fig. 14). Of this amount, about half (340,000 acre-feet, or 420 hm^3) was consumed, and half was returned to the ground-water reservoir. In comparison, about 1 million acre-feet (1,200 hm^3) of ground water was lost by noneconomic evapotranspiration from wetlands and phreatophyte areas (Emery and others, 1971) (table 2).

Withdrawal of ground water in the San Luis Valley has not significantly affected the quantity of water in storage. In fact, the amount of ground water in storage has been greatly increased, owing to extensive use of surface water for irrigation.

The amount of ground water withdrawn in the Albuquerque subregion in 1970 was 160,000 acre-feet (200 hm^3), but only 67,000 acre-feet (83 hm^3) of the water withdrawn was consumed (figs. 14 and 16). The remainder (93,000 acre-feet, or 110 hm^3) returned to the river or the underground reservoir. About 400,000 acre-feet (490 hm^3) of water per year is lost to noneconomic evapotranspiration in this region (table 2). Overall changes in ground-water storage have been insignificant. In some areas the quantity of ground water in storage has increased, owing to infiltration of surface water diverted for irrigation, and in other areas the quantity in storage has decreased, owing to extensive withdrawal of ground water.

The amount of ground water withdrawn in the El Paso subregion in 1970 was 390,000 acre-feet (480 hm^3) (fig. 14), of which about one-fourth was for municipal, industrial, and military uses and the remainder was for irrigation. Pumpage exceeds recharge in the Mesa and artesian well fields, and water levels have declined more than 60 feet (18 m) (fig. 17). However, in both the upper and the lower valleys, where most of the pumping is for irrigation and the amount of ground water pumped annually varies inversely with the amount of surface water available, water levels have fluctuated a few feet but show no overall decline.

The amount of ground water withdrawn for use in the Pecos Valley subregion in 1970 was about 480,000 acre-feet (590 hm^3) in New Mexico and 680,000 acre-feet (840 hm^3) in Texas (fig. 14). About 55 percent, or 638,000 acre-feet (790 hm^3), was consumed, and the remainder was returned to the ground-water reservoir.

The estimated loss of water by noneconomic evapotranspiration along the main stem of the Pecos River in New Mexico is 185,000 acre-feet (230 hm^3) per year (Sorenson and Borton, 1967a), and the loss along the main stem in Texas is about 90,000 acre-feet (110 hm^3) per year (table 2). An additional 5,000 acre feet is lost from tributaries and closed depressions.

Ground water has been extensively "mined" in several areas, especially near Roswell and Carlsbad, N. Mex., and in Pecos and Reeves Counties, Tex. (fig. 17). The rate of "mining" in the Roswell basin, is estimated to be 120,000 acre-feet (150 hm^3) annually (Sorensen and Borton, 1967a). Water levels have declined as much as 225 feet (68 m) in the artesian aquifer in the Roswell basin and more than 300 feet (91 m) in Reeves and Pecos Counties, Tex., since ground-water development began.

The amount of ground water withdrawn for use in the closed basins in 1970 was 200,000 acre-feet (250 hm^3) (fig. 14). More than 50 percent of this was consumed, and the remainder was returned to the ground-water reservoir. Most of the water was used for irrigation, but about 9,000 acre-feet (11 hm^3) was for public supplies, including military supplies.

Evapotranspiration losses in the New Mexico part of the closed basins subregion is only 50,000 acre-feet (62 hm^3) per year — mainly as direct evaporation from playas in the Estancia basin (Sorensen and Borton, 1967b). An equivalent amount probably is evaporated from playas in the Texas part of Salt basin.

The amount of ground water withdrawn in the lower Rio Grande subregion in 1970 was 85,000 acre-feet (100 hm^3) (fig. 14), mostly for supplemental irrigation in the coastal area. Data are not available to show percentage consumed or water-level changes effected.

Table 2 summarizes, by subregions, the water supply, the water consumed by man's activities and by evapotranspiration from wetlands and phreatophyte

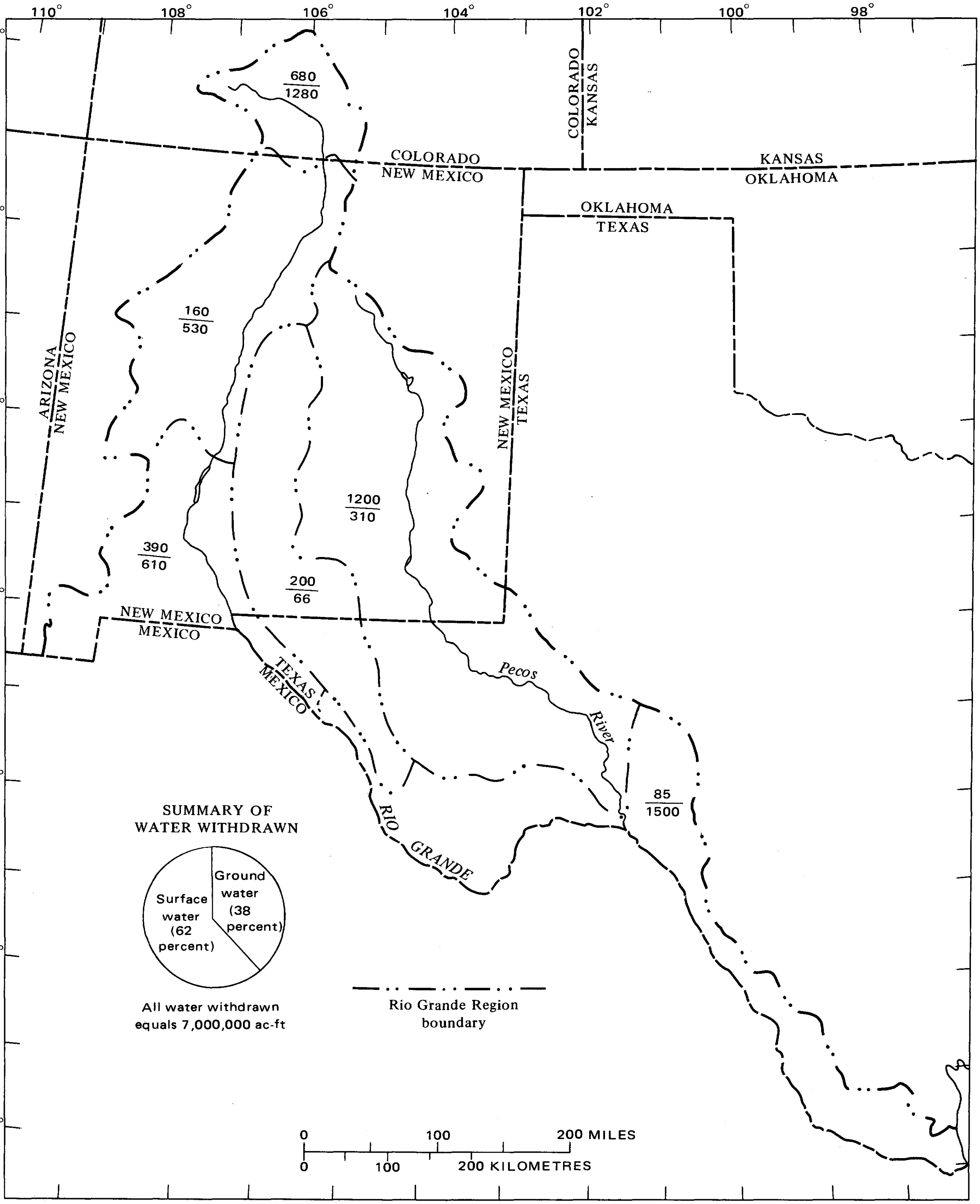


FIGURE 14. — Ratio between ground water withdrawn (upper number) and surface water withdrawn (lower number). The ratio varies widely from one subregion to another. Units are thousands of acre-feet.

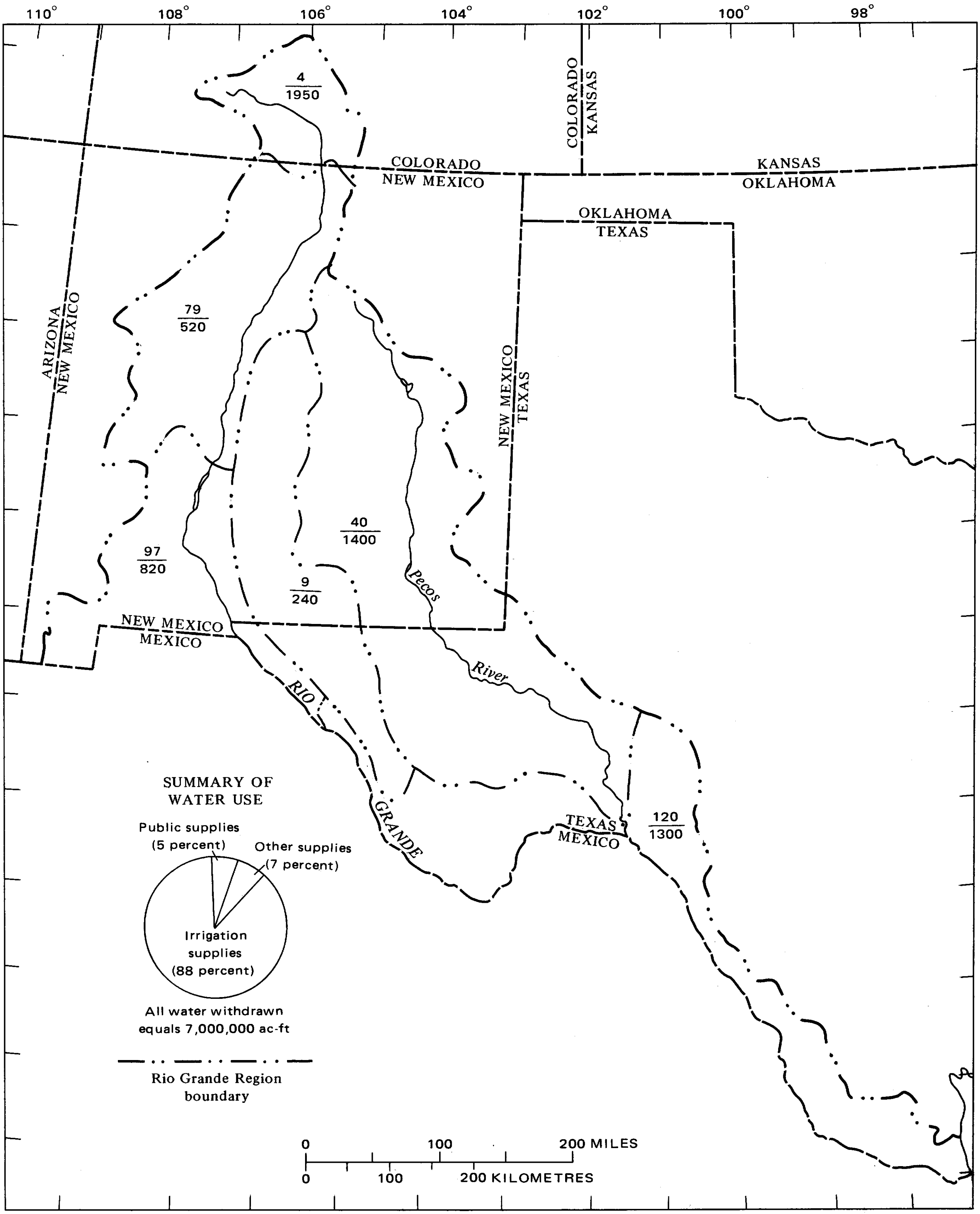


FIGURE 15. — Ratio between water withdrawn for public supplies (upper number) and water withdrawn for irrigation (lower number). The ratio is larger in the Albuquerque and El Paso subregions than in the others. Units are thousands of acre-feet.

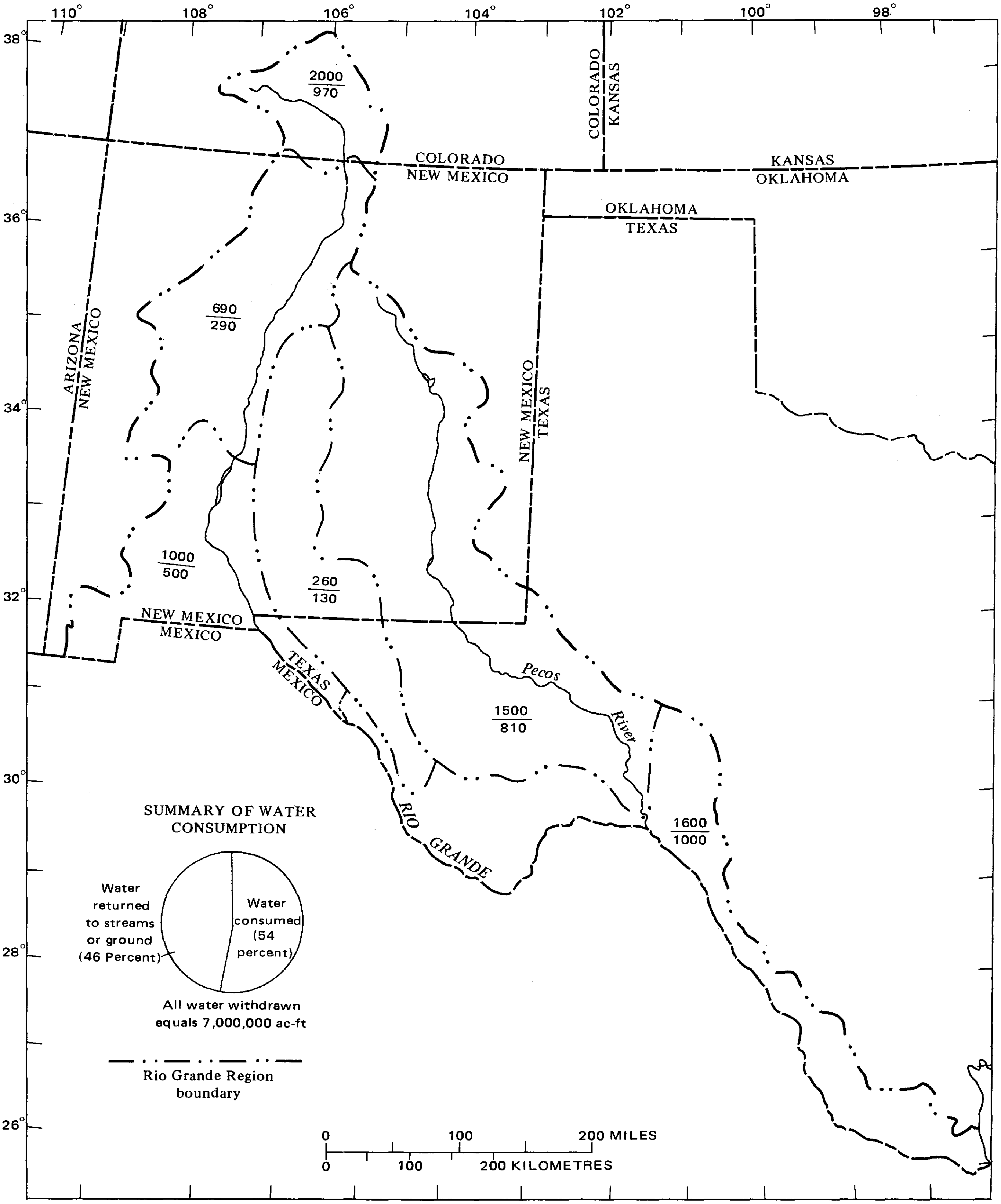


FIGURE 16. — Ratio between water withdrawn (upper number) and water consumed (lower number). About half the water withdrawn is consumed. Units are thousands of acre-feet.

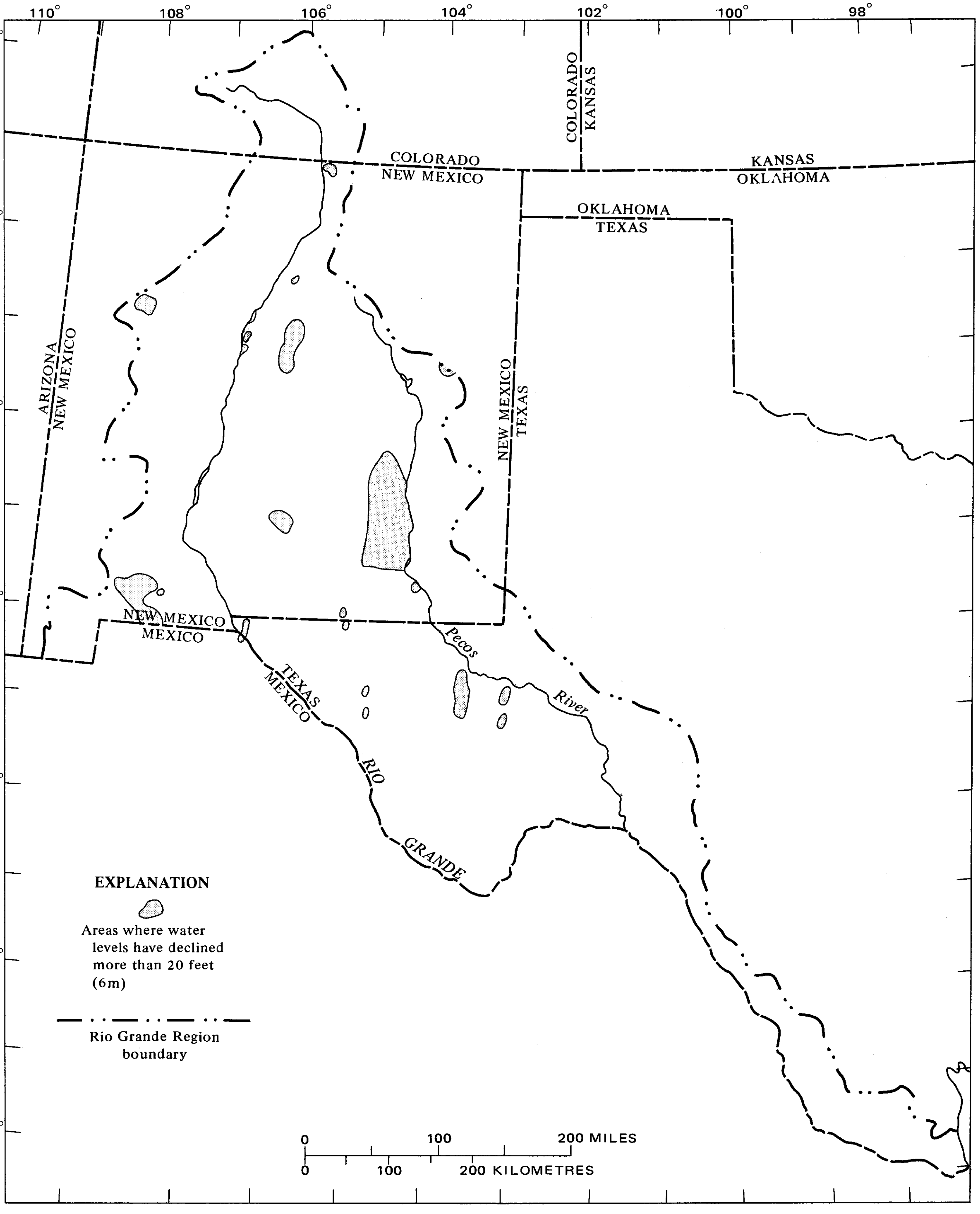


FIGURE 17. — Areas of water-level decline. Water levels have declined more than 20 feet (6 m) in many areas, owing to overdraft of ground water.

areas, and the surface and subsurface storage capacity. This tabulation shows that more than half as much water is consumed by evapotranspiration in wetlands and areas infested with phreatophytes (2.5 million acre-feet, or 3,100 hm^3, per year) as is consumed by man's activities (3.7 million acre-feet, or 4,600 hm^3, per year).

Man's use of water commonly creates potential sources for ground-water pollution. The areas of highest potential for pollution due to man's activities are in irrigated areas, in areas of mining and petroleum production, and in the large metropolitan areas.

In general, the water underground is less susceptible to pollution than the water in streams and lakes. If ground water does become polluted, the pollution is likely to persist much longer than a similar pollution of surface water.

The most widespread pollution from man's activities in the region results from irrigation. When fields are irrigated, part of the water is evaporated from the soil or transpired by the crops, leaving a greater concentration of salts in the remaining water. Also, part of the fertilizer added to fields is dissolved and carried down to the ground-water reservoirs. Another major source of pollution from man's activities is sewage effluent from cities and individual home sewage systems. The sewage effluent may cause bacterial pollution as well as chemical pollution. Effluents from industrial plants, mines, and oil fields commonly contain high concentrations of dissolved solids and require special management to avoid severe pollution of ground water.

Soluble minerals in the host rocks are the principal sources of dissolved solids in ground water in the Rio Grande Region. Large areas in the region are underlain by consolidated sedimentary rocks that contain gypsum and salt or by valley fill derived by erosion of those rocks. These minerals have caused large quantities of ground water in the region to become unfit for many uses, especially in the Pecos Valley and closed basins subregions. In ground-water discharge areas, the salts in the water are further concentrated by evapotranspiration. In some areas, saline ground water is discharged to streams and transported to other areas, where it reenters the ground and causes a deterioration in the chemical quality of the water in those areas.

POSSIBLE ALTERNATIVES IN GROUND-WATER MANAGEMENT

Management and use of water under any alternative has both beneficial and adverse effects. In planning water management, the effects and the related cost of each alternative should be considered.

The use of ground water for meeting the water demands of a region is a possible alternative in water-management planning that should be considered, keeping in mind that ground water and surface water are actually a single resource. Ground-water reservoirs can be used for input, storage, and withdrawal of water the same as surface reservoirs. General alternatives that should be considered in planning ground-water management are described below.

Under natural conditions, water from precipitation and surface flow infiltrates the ground and moves slowly underground toward points of discharge at lower elevations. In general, underground storage space is available in recharge areas, but the underground reservoirs are completely filled and are spilling in the discharge areas, generally along major stream valleys or in natural lakes or playas. Ground-water discharge provides the base flow of perennial streams, and the ground-water contribution throughout the year may exceed the direct overland flow of water.

The principal beneficial effect of maintaining full ground-water reservoirs relates directly to the maintenance of surface streams or base flow. Wet areas and associated phreatophytes, sustained by ground-water discharge, provide unique habitats for many species of wildlife. Free-flowing springs and spring pools are common in many ground-water discharge areas. The circulating ground water also flushes soluble salts from the underground reservoirs and soil zones.

Adverse effects of maintaining full ground-water reservoirs include benefits foregone from lack of potential economic development, inability of many areas to support a human population at desirable places to live, and limited space for storage of additional water during periods of excess precipitation and streamflow. The closed basins subregion is dependent almost entirely upon withdrawal of ground water for human habitation. On the other hand, much water is lost by evaporation in the closed basins, and the concentration of salts in the water in and near discharge areas is increased by evaporation, causing a general degradation of water quality.

The principal aquifers in the Rio Grande valley and its major tributaries are directly connected with the streams. The dominant beneficial effect of utilizing ground water from a stream-connected aquifer is assurance of a water supply whenever the need is greatest and, thus, the maximum potential economic return from water use. Ground water use can also assure a water supply for large human populations at desirable places to live, such as at Albuquerque and El Paso. Lowering of the water table through extensive ground-water withdrawals in areas of ground-water discharge can reduce significantly the quantity of water lost by noneconomic evapotranspiration and provide additional space for underground storage of water during periods of excess precipitation and streamflow. Ground water requires little treatment for human consumption, as it is free of sediments and generally free of bacteria.

The principal adverse effect of ground-water withdrawal from stream-connected aquifers is reduction in streamflow due to interception of natural ground-water discharge and to induced infiltration from streams. Lowering of water levels by extensive ground-water withdrawal can adversely affect wildlife habitats that are dependent on wet areas and phreatophytes. However, water levels could be lowered several feet in many areas without destroying all the phreatophytes, because of the ability of some to grow roots to tens of feet to obtain their water supply. Lower ground-water levels would dry up some springs and spring pools. A deterioration in water quality would result from extensive withdrawals of ground water in some parts of the Rio Grande Region.

The induced infiltration from streams could be controlled by constructing lined canals for transport of surface water past areas of ground-water pumping.

Aquifers in the closed basins subregion generally are isolated from perennial streams. Ground-water withdrawal from these aquifers can be limited to an amount equal to or less than the average discharge that can be intercepted, thus assuring a relatively small yield of water indefinitely; or ground-water withdrawal can exceed the average discharge (commonly termed "mining" of ground water), thus providing a larger supply of water during a finite period of time.

The principal beneficial effect of developing ground-water supplies from aquifers that are isolated from streams is provision of water for economic development and for human populations where no other source of water exists. Lowering of ground-water levels in areas of natural discharge can salvage water otherwise lost to noneconomic evapotranspiration. Lowering of water levels will also provide additional storage space, which can be refilled by recharge during periods of excess precipitation and runoff. Otherwise, the excess runoff would enter playa lakes and be lost from the basin by evaporation.

Continuous withdrawal of ground water in excess of the natural discharge that can be intercepted will have the adverse effects of increasing depths to water and increasing pumping lifts. The lower water levels may dry up natural wet areas in some basins. Dewatering of unconsolidated sediments may cause subsidence of the land surface due to accelerated compaction of the sediments. Deterioration in water quality in closed basins, due to migration of saline water from discharge areas to areas of extensive ground-water withdrawal, is common. Continuous pumping of ground water in excess of the replenishment rate will eventually deplete the water supply, as happens when any resource is mined.

Because ground water and surface water are so closely related in most of the Rio Grande Region, any alternative for ground-water development must recognize the effects of the development on the surface-water supplies, and ideally, should integrate the two sources of supply into a plan for conjunctive use of ground water and surface water. The following descriptions of potential management of ground water are based primarily on physical factors and do not fully consider the legal constraints.

Once the policy for governing the utilization of ground-water reservoirs is established, all possibilities for management of the water within that policy should be considered. The rate of economic return per unit of water used varies widely from one type of use to another, but water supplies for some uses are critical, regardless of cost. After water supplies to meet critical needs have been allocated, should further allocations be based on the maximum rate of economic return per unit of water consumed until all the demands have been met in order of highest return? Broadhurst (1964) prepared the following rates of economic returns for the specified uses on the plains of west Texas:

Type of use	*Gross return (dollars per ac-ft of water used)*
Irrigaton of crops:	
Grain sorghum	$50- 100
Cotton	100- 200
Vegetables	1,500-2,000
Secondary recovery of oil	[1]20,000

[1]Based on the use of one barrel (42 gal) of water to recover one barrel of oil and on a market value of $3.00 per barrel for oil.

Obviously, the uses that provide the highest economic returns have relatively small demands. Regardless of how the water supply is allocated, maximum efficiency in water use should be achieved to stretch the supply as far as possible. The largest potential for increasing the effective water supply by improving efficiency is related to irrigation of croplands. Better efficiency in irrigation could salvage considerable quantities of water commonly lost by evaporation and runoff from irrigated fields.

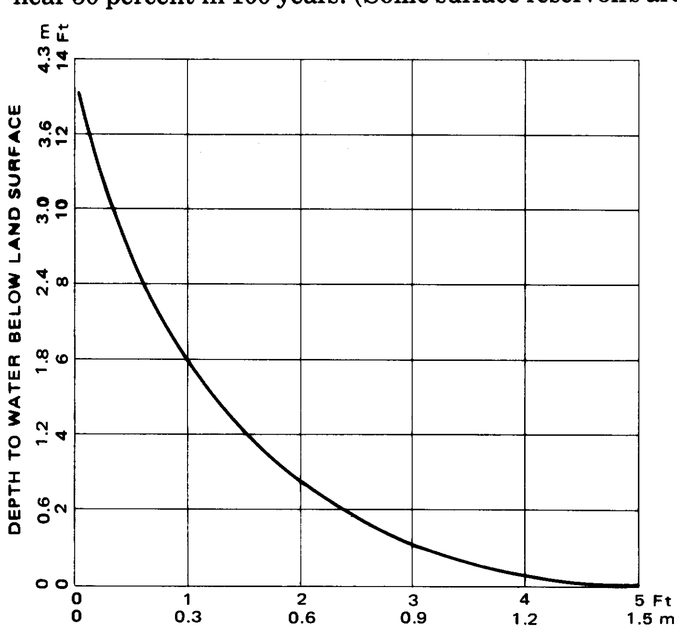
The salvage of water lost to noneconomic evapotranspiration in wet and phreatophyte-infested areas (table 2) offers the greatest possibility of improving the water-supply situation in the region.

SAN LUIS VALLEY SUBREGION

The Closed Basin Division of the San Luis Valley Project, proposed by the U.S. Bureau of Reclamation (1963), contemplates salvaging about 101,000 acre-feet (124 hm^3) of water annually, of which 86,000 acre-feet (106 hm^3) would be pumped ground water (mostly from a salvage area of 109,00 acres, or 44,000 ha) and 15,000 acre-feet (18 hm^3) would be surface water. According to the Bureau of Reclamation plan, "Under the assumptions of schedule of construction (1965) and continuation of the average rate of debit accrual and the estimate of annual water salvage, the accrued debit of Colorado would be offset in about 35 years."

If 86,000 acre-feet (110 hm^3) of water can be salvaged annually from the salvage area of 109,000 acres (44,000 ha), what are the prospects of salvaging 1 million acre-feet (1,200 hm^3) a year from the 1.5 million acres (610,000 ha) where the water table is less than 8 feet (2 m) below ground surface? This question seems reasonable when 1 million acre-feet (1,200 hm^3) of water per year is being lost from the valley by noneconomic evapotranspiration. Under such a salvage program, the accrued debit of Colorado could be offset in a year or two, or additional economic development based on use of ground water would be possible. An electric-analog model of the valley has been constructed, and several alternatives of ground-water management should be evaluated with the model. The sharp decrease in the rate of evapotranspiration in the San Luis Valley as the water table is lowered is shown in figure 18.

In addition to the saving of water through increased efficiency in irrigation and through salvage operations, consideration should be given to withdrawal from ground-water storage. The ground-water reservoir contains about 2 billion acre-feet (2.5 million hm^3) of water in storage. Withdrawal of 2 million acre-feet (2,500 hm^3) a year would cause only a 10 percent decrease in storage in 100 years. Most large surface reservoirs in the Rio Grande region are being filled with sediment at rates near 50 percent in 100 years. (Some surface reservoirs are currently being filled at the rate of 100 percent in 100 years.) Although the capacity of a surface reservoir being filled with sediment is continually decreasing, ground-water reservoirs retain indefinitely a nearly constant storage capacity and can be used again and again to store and recover water.



Source: Emery and others (1971)

FIGURE 18. — Relationship between the rate of water loss by evapotranspiration and the depth to the water table in the San Luis Valley. The rate decreases dramatically as the water table gets deeper.

ALBUQUERQUE SUBREGION

An approach to improving the water-supply situation in the Albuquerque subregion could be an expansion of conjunctive use of ground water and surface water, which is already being practiced to some extent. Because of the physical connection between the river and the ground-water reservoir, withdrawal of large quantities of ground water in some reaches would cause a reduction in streamflow. On the other hand, a large part of the 400,000 acre-feet (490 hm^3) of water now being lost annually to noneconomic evapotranspiration probably could be salvaged by lowering ground-water levels in the wetlands and phreatophyte areas of the subregion.

Lowering the ground-water level below the bed of the river would cause losses from the river, but once the ground-water level is below the river, additional lowering would not cause a further increase in loss of water from the river. However, ground water that normally would discharge into the river would be intercepted before it reaches the river. Water losses from the river could be controlled in areas where the water table is lowered by diverting into an artificial, lined channel the amount of streamflow needed to satisfy downstream rights. Excess flow could follow the natural channel to recharge the ground-water reservoir. The economics of this approach have not been analyzed.

The increasing demand for water in the Albuquerque subregion could be met readily by drawing on the large volume of water stored in the underground reservoirs. About 65 million acre-feet (80,000 hm^3) of ground water could be withdrawn in the subregion by uniformly lowering the water level 100 feet (30 m) in the valley fill. This approach could more than double the water supply for the next 90 years, even if all the water withdrawn is consumed, which rarely is true. An additional 400,000 acre-feet (490 hm^3) per year would be salvaged in the process because evapotranspiration in wetlands and phreatophyte areas would be eliminated.

Large reserves of coal and natural gas have been mapped in and adjacent to the Albuquerque subregion (fig. 6). Development of these resources for electrical power generation to help meet the rapidly growing demand for electrical energy in the Southwest could be enhanced by drawing on salvaged water or on the large reserves of ground water in storage.

Some, and possibly all, of the wetlands and phreatophyte areas are considered by many to be ecologically desirable. Therefore, a uniform lowering of water level in the ground-water reservoir would not be reasonable. However, a program of ground-water withdrawal could be designed to lower the water levels significantly more than 100 feet (30 m) in some areas and significantly less, or none, in selected wet and phreatophyte areas. This approach would not permit as much salvage of water normally lost to noneconomic evapotranspiration. Some areas would be conducive to maintaining wildlife habitat by surface irrigation, which would use much less water than is now lost by evapotranspiration.

A program could be designed also to utilize the ground-water reservoir to replace part of the surface storage. Water levels could be lowered by pumping ground water into lined canals or pipes for delivery to points of use, and excess surface water could be used for recharging the underground reservoirs by infiltration, either directly from the streambed or indirectly from spreading areas or recharge ponds in areas favorable for infiltration. This approach has the advantage of salvaging water normally lost to evaporation from surface reservoirs (255,000 acre-feet, or 310 hm^3, per year from Elephant Butte and Caballo Reservoirs), but it increases the available supply only in the amount of this salvage. Surface reservoirs have recreational values which may justify large evaporation losses. However, many recreationists prefer a small reservoir of constant size to a larger reservoir of widely varying size, and at some places surface reservoirs could be regulated for nearly constant size by utilizing underground storage for part of the water.

Sewage effluent from municipalities and individual homes in the Rio Grande Valley and its principal tributaries contributes to the salt load in streams and underground reservoirs. The principal chemical constituents added to the water are phosphates and nitrates. Methods of removing these constituents are being studied by several organizations at the Federal, State, and local level. One method being investigated is the spraying of treated effluent on irrigated fields, where much of the phosphates and nitrates are adsorbed in the soil and used by the crops. An excess of water is applied to the land so that a large part returns to the ground-water reservoir after the phosphates and nitrates have been adsorbed. This process might work very well on the types of soils in much of the subregion.

The water supply of the subregion possibly could be improved to some extent with better watershed management, that is, with control of the types and density of vegetation growing on the watershed.

EL PASO SUBREGION

Conjunctive use of ground water and surface water has been practiced by individuals in the Elephant Butte irrigation district for many years. Irrigation water from Elephant Butte Reservoir is used when the supply is adequate, but when surface water is in short supply, more than 90 percent of the land receives supplemental ground water from privately owned wells (Sorensen and Linford, 1967). Part of the water applied to irrigated fields returns to the ground-water reservoir carrying soluble soil salts and fertilizers. Consequently, the chemical quality of shallow ground water has deteriorated extensively, some now containing as much as 6,000 mg/l dissolved solids. A systematic approach to total water management, including mixing of the shallow ground water with deeper water of better quality or with surface water possibly would improve the general quality of irrigation and municipal water.

Evaporation loss from Elephant Butte and Caballo Reservoirs averages about 255,000 acre-feet (310 hm^3) per year (Sorensen and Linford, 1967). This loss could be reduced significantly by storing more of the water underground and reducing the surface area of these reservoirs. Elephant Butte Reservoir is used extensively for recreation, which must be considered in any alternative plan for water management. The recreational value of the reservoir possibly would be improved by maintaining a smaller surface area of a constant level.

Large amounts of water are lost by evapotranspiration from wetlands and phreatophyte areas. Much of this water could possibly be salvaged by lowering the water table in selected areas.

Population has been increasing rapidly in the Las Cruces and El Paso areas, creating problems in both municipal water supply and sewage disposal. The water-supply problem at Las Cruces primarily involves poor quality of the shallow ground water. This problem can be solved by drilling deeper wells to get below the zone influenced by return of poor quality water from irrigated fields. The water supply for El Paso is placing a heavy demand on local ground-water supplies, but large quantities of fresh ground water are available in surrounding areas. The long-term effects of ground-water withdrawal have been evaluated through use of an electric-analog model as part of a cooperative study of the City of El Paso, the Texas Water Development Board, and the U.S. Geological Survey (Leggat and Davis, 1966). A new model to incorporate recently obtained data is being constructed to further refine the analysis of ground-water management possibilities and resultant effects in the area.

Treated sewage effluent in the subregion probably could be used for irrigation — the nitrates and phosphates being used by plants, and the excess effluent returning to the ground-water reservoir.

Because the chemical quality of ground water in the subregion is highly variable, consideration should be given to mixing the water of best quality with water of inferior quality to stretch the supply of usable water.

An interagency study of the subregion, involving both State and Federal agencies, is currently (1973) in process. This study, termed the "Rio Grande Regional Environmental Project," is considering a full range of potential resource-development plans, including the water resources. Various alternatives in water management will be a part of this study.

PECOS VALLEY SUBREGION

The effective supply of water in the Pecos Valley subregion could be increased, and the chemical quality of the water improved, by reduction of evapotranspiration from wetlands and phreatophyte areas and by reduction of evaporation from surface storage reservoirs. Salvage of 50 percent of the water now lost in these processes would increase the effective supply by 140,000 acre-feet (170 hm^3) per year.

The loss of water to evapotranspiration possibly could be reduced by lowering the water table in the wetlands and phreatophyte areas. However, the salinity of the water in some of the phreatophyte areas is too high for direct use of the water, and desalination might be required before it could be used beneficially. In some areas of intensive pumping, withdrawal of saline water and subsequent desalination would reduce the encroachment of saline water into fresh-water zones.

If it were decided to salvage evapotranspiration loss, some wetlands possibly should be preserved, such as those at the Bitter Lakes National Wildlife Refuge and the Bottomless Lakes State Park. A sparse stand of salt cedars and cottonwoods could be preserved in selected areas at small loss of water by evapotranspiration by lowering the water table slowly to an optimum level. Control of ground-water levels could prevent the spread and revegetation of salt cedars.

Water salvaged by control of wetlands and phreatophytes could be used to meet the increasing demand for public water supplies, to supplement short supplies of irrigation water, or to irrigate new lands. Water salvaged by reduction of evaporation losses from surface storage reservoirs also could be used for these purposes.

The volume of water stored in surface reservoirs, and thus the quantity of water lost by evaporation, could be reduced by controlled recharge to and withdrawal from the ground-water reservoirs. The limestone aquifer in the Roswell basin has a large capacity for receiving, storing, and transmitting water. This approach to water storage would necessarily have to guarantee delivery of water to satisfy prior rights to diversion of surface water.

The overdraft, or "mining," of ground water has resulted in significant decreases in ground water in storage and has caused increased pumping lifts. This overdraft could be alleviated by sufficient salvage of water now lost through evapotranspiration, by artificial recharge to the ground-water reservoir, or by reduction of irrigation. Salvaged water, as described above, could replace some of the ground water being pumped and reduce the ovedraft. Artificial recharge could alleviate the overdraft, but the supply of water that might be available for this purpose is limited. Eventually, reducing the irrigated acreage may become necessary, but that would have a severe adverse impact on the economy of the area.

Local floods have caused serious problems in parts of the subregion. Under favorable circumstances, the floodwaters could possibly be diverted to recharge areas before they reached populated areas and irrigated farms. However, the floodwaters of the region have been appropriated, and these rights would have to be protected. The floodwaters generally carry heavy loads of sediment, and the storage capacity of surface reservoirs is reduced by accumulation of sediment trapped during floods. In contrast, the capacity of underground reservoirs is not reduced significantly by deposition of sediments on the land surface.

The high salinity of much of the water in the Pecos Valley subregion is one of the most serious water problems. It is difficult to manage the fresh water so it does not become mixed with the abundant saline water, which in effect reduces the supply of fresh water. One approach to improving the water quality without reducing the total water supply significantly is pumping and desalting in areas of saline-water discharge or in areas where saline water is encroaching into fresh-water zones of underground reservoirs. An experimental desalting plant to obtain data on the feasibility of desalting water of a chemical character prevalent in the subregion has been operated successfully at Roswell. Another possible approach is pumping the more saline water into evaporation ponds. At one place, near Malaga Bend, brine that normally discharges into the Pecos River has been intercepted by pumping the water from a well and discharging it into a natural depression. The effect of this experiment is still being evaluated.

Elimination of evaporation from wetlands and transpiration by phreatophytes would improve the quality of water. The salts are concentrated by these processes, and the salts eventually return to the principal water systems, contaminating more of the freshwater supply. Evapotranspiration could be reduced in many areas by lowering the water table.

Management of the scarce water supplies of the subregion possibly could be improved by regarding all the sources of supply and storage facilities as a single system, managed for the maximum benefit of all users. However, this approach would require considerable reorganization of the complex managerial structures for water that are now in operation.

CLOSED BASINS SUBREGION

The large supply of saline water in the closed basins subregion offers an opportunity for economic development that could utilize the saline water. One possibility might be utilization of the water for cooling in powerplants. The unconsumed water from the cooling facilities could be reinjected into the underground reservoirs at adequate distances from the withdrawal points to permit heat dissipation before the water returns to the production wells, thus minimizing the consumption of water. The amount of fresh water required for the operation could be provided by desalting. Large supplies of fresh water for other uses also could be obtained by desalting the saline water.

Ground water has been "mined" in a large area of the Estancia basin. The water table has been lowered as much as 50 feet (15 m) in areas of maximum withdrawals. The overdraft could be alleviated to some extent by inducing recharge to the ground-water reservoir during the infrequent periods of surface runoff and by dispersing some of the pumping to areas of natural discharge. The quantity of water being lost by evaporation from the playas is more than the quantity of water being consumed by beneficial uses, and most of the water lost is from natural ground-water discharge.

Ground water also has been "mined" in parts of Salt basin. Water levels have declined as much as 20 feet (6 m) in the New Mexico part and as much as 75 feet (23 m) in the Texas part. Additional artificial recharge and dispersal of pumping to discharge areas in this basin could possibly reduce the overdraft of ground water. Some natural ground-water discharge has already been intercepted by pumping.

LOWER RIO GRANDE SUBREGION

Because of the limited quantity of fresh ground water and the generally adequate supply of surface water in the lower Rio Grande subregion, no further consideration is given to possible alternatives in this subregion.

SPECIAL UTILIZATION OF UNDERGROUND SPACE

Underground space can be used for more than providing a normal water supply. In many parts of the region, thick accumulations of valley fill lie above the water table, and the average porosity of this unsaturated material is equivalent to, or higher than, that of the saturated material. By constructing spreading ponds, excess surface flow from rainstorms could be diverted in favorable areas for artificial recharge into the unsaturated fill. Thus, the volume of water in storage could be increased significantly in some localities. Also, air could be pumped from thick unsaturated material for air conditioning buildings, because the air at a given depth below land surface has an almost constant temperature throughout the year.

Diversion of excess surface water to recharge facilities can regulate the flow of streams without the use of large surface storage facilities. The water recharged into the ground during periods of excess surface flow will eventually finds its way to a nearby stream as extra ground-water discharge.

Introduction of excess surface water of good chemical quality into aquifers containing water of inferior quality can improve the general quality of the ground water. This approach would have the greatest potential for quality improvement in the Pecos Valley and closed basins subregions.

As the war against pollution mounts, the interest in underground storage of wastes is growing. Underground space above the zone of saturation or in impermeable materials can be used for storage of solid wastes in favorable areas, where vaults can be excavated and kept dry. If deemed necessary, wastes stored in this manner can be recovered at any time. Liquid wastes can be stored in saturated materials, where adequate safeguards, such as enclosing impermeable beds, are present. These conditions exist in many localities in the region where the consolidated sedimentary rocks or the valley fill are thick and highly variable in permeability. Underground disposal of wastes requires thorough testing and analysis of the receiving environment before the safety of disposal can be assured.

The Anaconda Co. has operated an injection well for disposal of uranium-mill effluent near Grants, N. Mex., since December 1960 (West, 1972). The injection interval is sandstone, separated from all fresh-water aquifers by relatively impermeable, thick beds of mudstone and anhydrite. Large areas in the Rio Grande region should have similar features which would permit safe disposal of liquid chemical wastes.

Release of cooling water from thermal electric plants and some types of industrial plants has caused severe problems of thermal pollution of nearby streams in many areas of the United States. The ground-water reservoirs in the valley fill of the Rio Grande Region could be used as receptacles for thermal waters from these types of plants. If the thermal water were injected into the valley fill at considerable distances from discharge points, either natural discharge points or wells, the heat would be dissipated to the rocks and the atmosphere before the water could reach the surface again.

Development of geothermal energy is another special utilization of underground space. In favorable geothermal areas, natural steam can be withdrawn through wells and used to drive turbines for generation of electricity. Experiments to evaluate the injection of cool water into dry geothermal areas for conversion of the water to steam and recovery of the steam for driving turbines are underway, but the outcome is open to speculation. In some parts of the world, geothermal waters are used directly for space heating of homes, offices, and greenhouses.

Several geothermal areas have been identified along the margins of the Rio Grande depression, but they have not been adequately explored to evaluate their potential for energy development. The largest and best known geothermal area in the region is the Jemez Mountains area of northern New Mexico. Hydrologic studies of that area were begun recently (1972).

Experiments indicate that in favorable areas both heating and cooling of buildings can be accomplished by direct use of ground water from different depths. Shallow ground water, which commonly is cool, can be obtained in summer for cooling buildings and can be reinjected at greater depths for conservation of the water. Warm water from greater depths can be obtained for heating buildings in winter and can be reinjected at shallow depths to maintain the balance between withdrawal and injection. The thick permeable valley fill in the Rio Grande Valley should be favorable for this application.

INFORMATION NEEDED FOR PLANNING GROUND-WATER MANAGEMENT

Much work has been done toward evaluating the ground-water resources of the Rio Grande Region, as indicated by the references at the end of the report and by figure 19, but much more remains to be done before systematic planning for ground-water management can be accomplished. The types of information needed for systematic planning are summarized on the following pages.

Planners for ground-water management must recognize the close relationship of ground water and surface water. The planner must have detailed information on: (1) the flow characteristics of streams; (2) the position of the streambed in relation to the water table; (3) infiltration rates from streams, canals, ditches, and irrigated fields; (4) potential infiltration rates from recharge ponds or spreading areas; (5) the contribution of ground-water discharge to streams; (6) the chemical quality of ground water and surface water; and (7) the changes in ground-water storage due to past management of the water resources. Typically, use of surface water causes an increase in ground-water storage, because some water is lost to infiltration, and use of ground water causes a decrease in storage, which varies as a function of ground water withdrawn and consumed.

The quantity of recoverable ground water in storage to different depths should be determined, as it represents the reserves available for development. Rough estimates of ground-water storage in the major aquifers of the Rio Grande Region have been made to show the water resources in general perspective. However, more accurate information is needed in areas to be considered for systematic ground-water management.

The physical properties of aquifers control the quantity of water that can be stored or yielded, the rate at which water can be added to or withdrawn from the underground reservoirs, and the change in water levels that will result from withdrawal of a given volume of water. The mineral content of aquifer materials largely controls the chemical quality of the ground water. The physical properties of the aquifers should be determined by imposing a hydrologic stress to the system (pumping) and measuring the response of the system (water-level changes). Useful information has already been obtained by pumping from individual wells or from well fields and measuring water-level changes. Additional information could be obtained from existing wells. In some areas the depth and spacing of wells are inadequate for acceptable tests, and special test wells are needed.

The depth to water and the pumping lifts that will be required must be known in order to estimate pumping costs.

Valley-fill aquifers, the predominant type in the Rio Grande Region, commonly contain extensive beds or lenses of clay and silt. When water is withdrawn from these aquifers, slow drainage of water from the clay may permit its compaction. If the clay beds comprise a significant part of the valley fill, the compaction due to withdrawal of water may result in subsidence of the land surface. Therefore, a determination of total clay thickness and laboratory determination of hydraulic and mechanical properties of the clays would be needed.

Chemical analyses of ground water from many areas are needed to define the variations in quality, both laterally and vertically, within the aquifers. Variations in chemical quality of water within an aquifer can lead to intermixing of fresh and saline water as fresh water is withdrawn, because saline water moves into space previously occupied by fresh water. Withdrawal of saline water reverses the situation but has the same net effect.

Wetlands and phreatophyte areas should be mapped in detail, and the quantity of water lost by evapotranspiration should be determined as accurately as possible. The significance of these areas as wildlife habitats should be evaluated. Eradication of phreatophytes by mechanical means and selective elimination by controlling ground-water levels should be appraised in relation to wildlife habitats and potential for water salvage.

The responses of water-resource systems to the many potential hydrologic stresses can best be analyzed by employing an electric-analog or digital model, or a com-

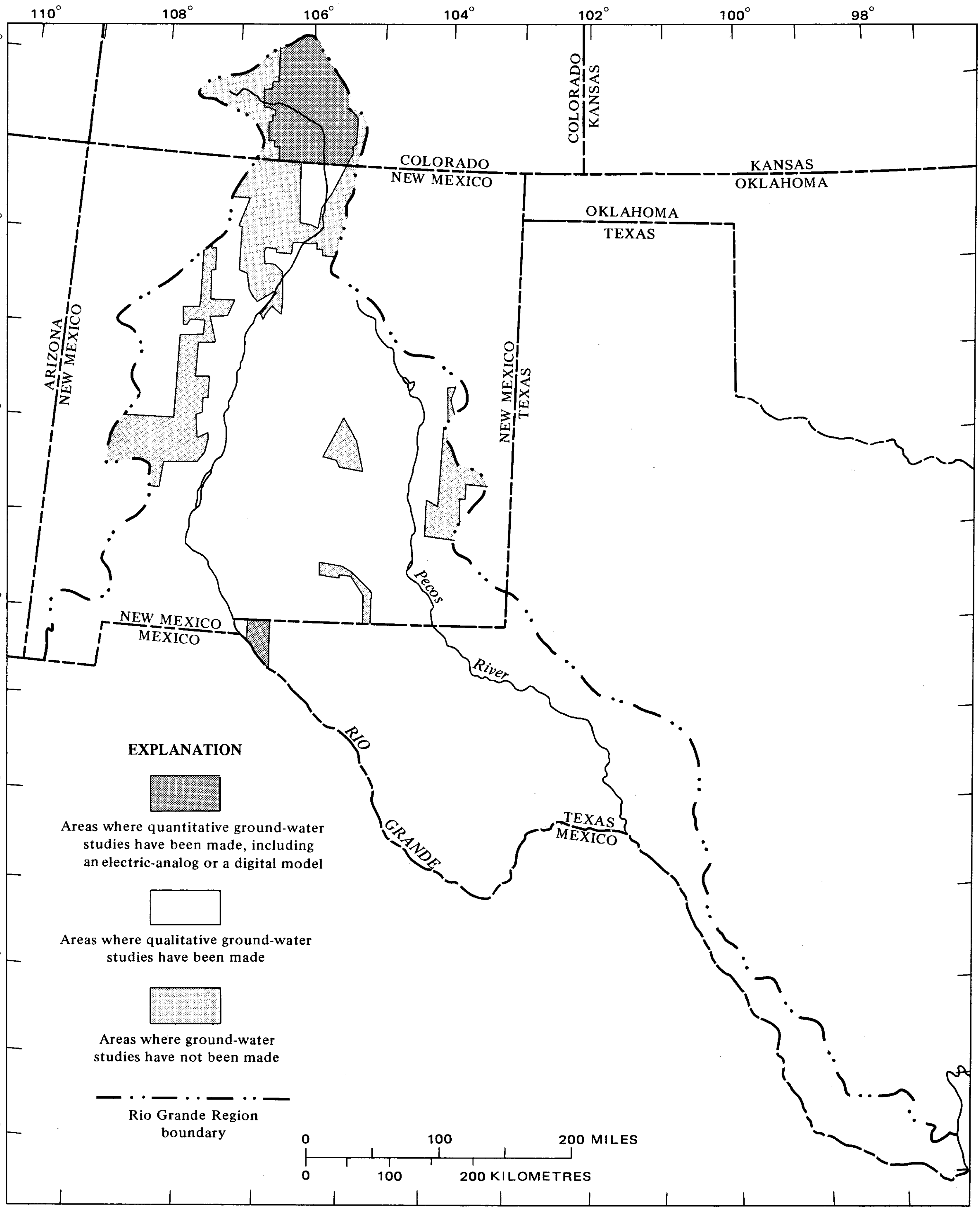


FIGURE 19. — Areas in which ground-water studies have been made. Quantitative studies have been made in only two areas, and several areas have not had even qualitative studies.

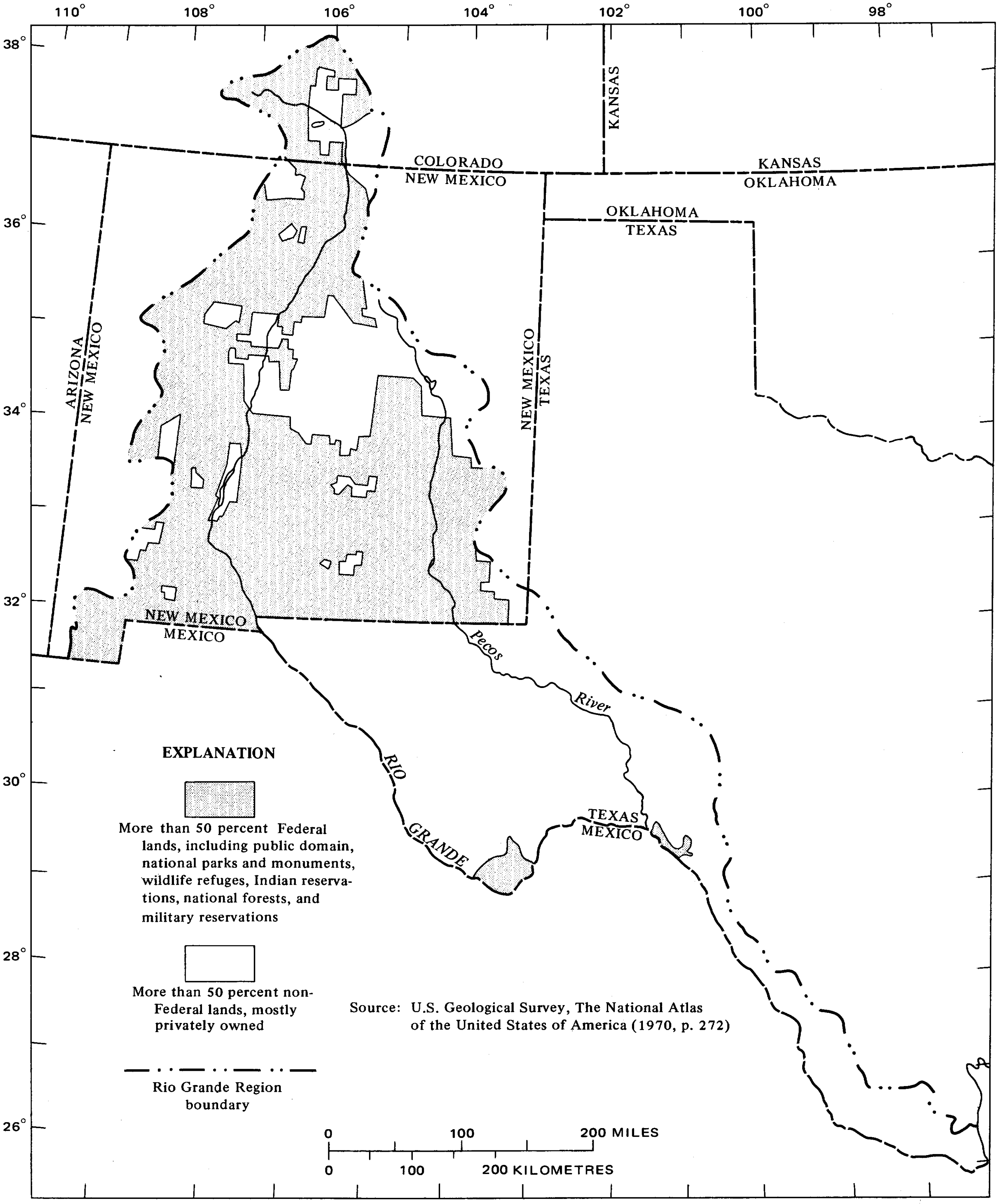


FIGURE 20. — Land ownership or control. Most of the land in New Mexico is owned or controlled by the Federal Government, and most in Texas is privately owned.

bination of the two, to simulate the ground-water reservoir. Once the models are completed and verified with historic records, the effects of alternative plans for water management and optimum locations, spacing, and depths of wells can be readily analyzed.

Information on the benefits and costs, both economic and environmental, is needed for evaluation of alternative plans for water management. The planners and the public should be aware of the benefits and costs of water use and the value of benefits foregone if the water is not used. The cost analysis of a proposed project should include: (1) the cost of the investigative program; (2) the cost of the construction program; and (3) the cost of the operational program, including the cost of monitoring the response of the water-resource system. Any proposed project, regardless of benefits and costs, must be acceptable within legal, social, and ecological constraints.

Once a water-resource project becomes operational, the response of the system to the new stresses should be monitored. The monitoring data very likely will show that modifications of the models are necessary to improve the predictive capability of the models. Depending on the actual response of the water-resource system, minor modifications in operations, as well as modifications of the models, may be necessary.

In some instances it might be possible to increase the effective supply of water by improved watershed management or by weather modification. These possibilities should be thoroughly evaluated as part of comprehensive water-resources planning.

All facets of data acquisition and analysis should be thoroughly documented with written reports for future use and current transfer of knowledge.

The Federal Government should have a strong interest in more detailed evaluation of the ground-water resources and possible alternatives in water use, as more than 50 percent of the land in the New Mexico part of the region is Federally owned or administered (fig. 20).

The types of studies needed in various parts of the region to provide critical information for planning systematic ground-water management are outlined in figure 21.

SUMMARY AND CONCLUSIONS

The Rio Grande is an interstate and international stream which begins in the mountains of Colorado, flows across New Mexico from north to south, and forms the boundary between Mexico and Texas for 1,250 miles (2,000 km). The region ranges in altitude from sea level at the Gulf of Mexico to more than 14,000 feet (4,300 m) in the headwaters area. Annual precipitation ranges from 8 to more than 30 inches (20 to more than 76 cm), depending on altitude and latitude. Irrigation is required for growing crops throughout the region. Evaporation rates are generally high, causing an annual water loss of 950,000 acre-feet (1,200 hm^3) from reservoirs, ponds, and streams.

The Rio Grande Valley in New Mexico has been inhabited for thousands of years, first by Indians, then Spaniards, and, later, Americans. Crops have been irrigated since the early part of this millenium. From earliest times, most of the Indian and Spanish agriculture in northern New Mexico has been based on subsistence farming, and the farms have become smaller as the land was divided amongst each new generation. The American settlers established larger farms or ranches, and, subsequently, many have been combined to create even larger ones.

The population of the region has been increasing rapidly in this century, from 750,000 in 1929 to 1,700,000 in 1970. It is expected to increase to 2,500,000 by 2020. The basin economy of the region was traditionally agricultural until recent years, but agricultural development is now increasing very slowly. Since 1950 the mining and petroleum industries have increased much more rapidly than agricultural development.

Management of surface waters in the region is subject to international treaty, interstate compacts, and the laws of three separate States. Management of ground water is subject to the laws of the State in which the ground water occurs, and the laws of each State are quite different.

The renewable water supply of the region is the sum of the surface-water runoff, the ground-water outflow (which is small), and the natural evapotranspiration. Annual precipitation on the region is 86 million acre-feet (110,000 hm^3); however, all but 4 million acre-feet (4,900 hm^3) is returned to the atmosphere by evapotranspiration.

The ground-water reservoirs of the region contain an aggregate of about 5,800 million acre-feet (7,200,000 hm^3) of fresh and slightly saline water in storage, which could be withdrawn through wells. In contrast, the surface reservoirs have a combined storage capacity of only 18 million acre-feet (22,000 hm^3).

Thick deposits of valley fill in stream and intermontane valleys of the region comprise the principal ground-water reservoirs. In most areas they are capable of yielding large supplies of water to wells. In some areas, consolidated sedimentary rocks, particularly limestone, yield a few hundred to a few thousand gallons per minute of water to wells. The largest ground-water reservoirs are in the San Luis Valley and Albuquerque subregions, each of which contains about 2 billion acre-feet (2,500,000 hm^3) of fresh and slightly saline water.

The chemical quality of water in the valley-fill aquifers varies widely. The dissolved solids in water in

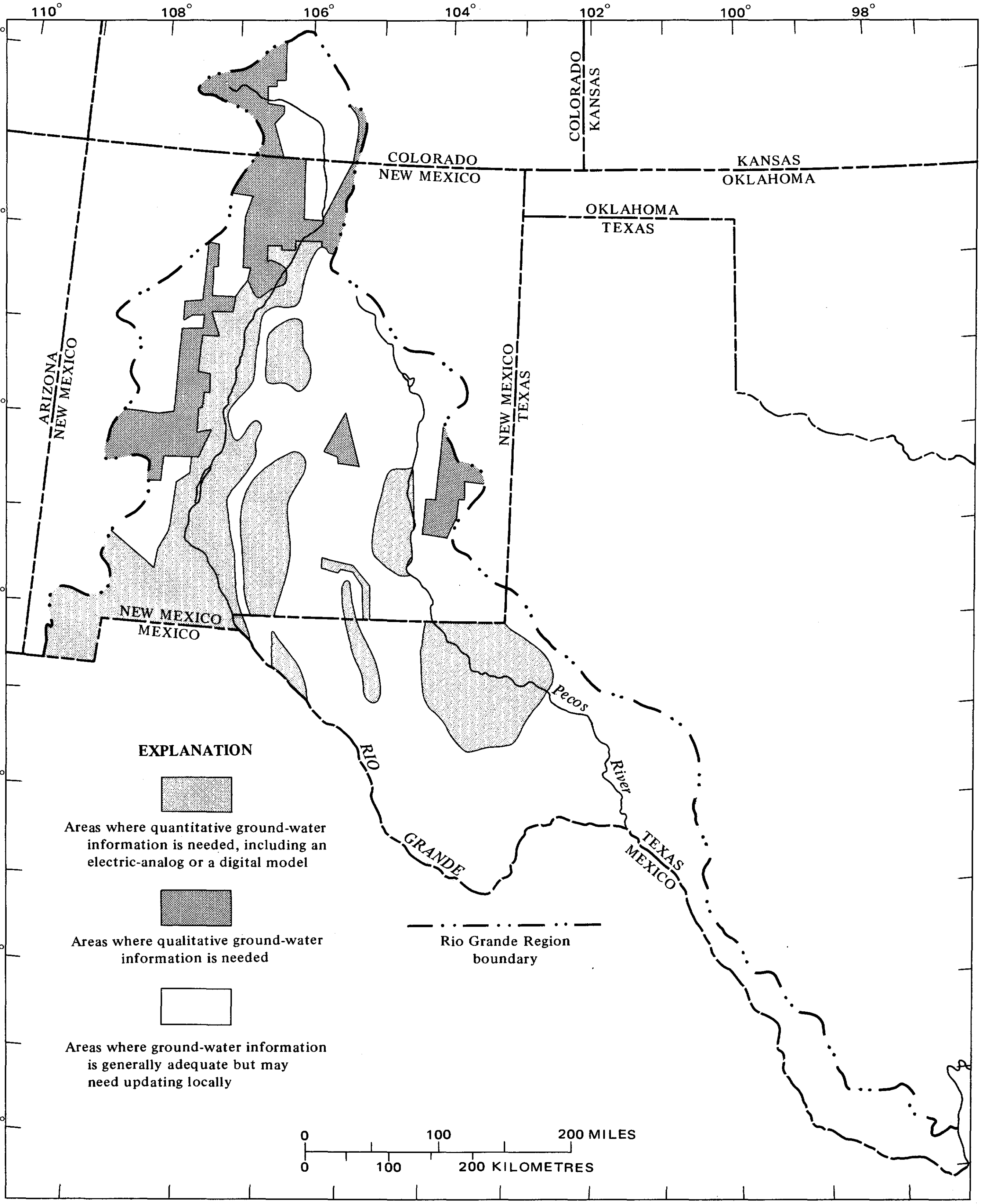


FIGURE 21. — Types of studies needed.

the shallow aquifers have been concentrated by water loss due to evapotranspiration and by return of water containing fertilizers from irrigated fields to the ground-water reservoir. The water at great depths in the valley fill also may have high concentrations of dissolved solids. The water of best quality generally is at intermediate depths. In the Tularosa basin, most of the water contains 3,000 to more than 35,000 mg/l.

Withdrawal of ground water in the region in 1970 was 2.7 million acre-feet (3,300 hm^3). The major part (88 percent) of this water was used for irrigation. Of the water withdrawn, 53 percent was consumed, and 47 percent was returned to the streams or ground-water reservoirs.

Ground water has been extensively overdrawn, or "mined," in several areas, especially near Roswell, N. Mex., and in Pecos and Reeves Counties, Tex., and severe decline in ground-water levels have resulted.

The loss of water by evapotranspiration in wetlands and phreatophyte areas is about 2.5 million acre feet (3,100 hm^3) per year in the region. In comparison, 3.7 million acre-feet (4,600 hm^3) of water is consumed by man's activities.

Ground water and surface water are really a single resource — water — although they commonly are treated separately. Ground-water reservoirs can be used for input, storage, and withdrawal of water the same as surface reservoirs, but ground water in storage constitutes a large reserve that can be withdrawn at any time. Alternatives that should be considered in ground-water management include: (1) maintenance of full ground-water reservoirs, (2) withdrawal of ground water from stream-connected aquifers, and (3) withdrawal of ground water from aquifers isolated from streams. Each alternative has definite beneficial and adverse effects that must be considered.

Because ground water and surface water are so closely related in most of the region, any alternative plan for ground-water development must recognize the effects of this development on the surface-water supplies and preferably should integrate the two sources of supply into a plan for conjunctive use of both the ground water and the surface water.

The salvage of water lost to noneconomic evapotranspiration in wet and phreatophyte-infested areas offers the greatest possibility of improving the effective water supply in the region. Salvage of half the water lost would increase the effective supply by 1.2 million acre-feet (1,500 hm^3) per year. However, salvage of this water could adversely affect the wildlife habitat.

The usable water supply for the region could be increased tremendously by drawing on the large reserve of ground water in storage. Pumping of ground water in many reaches of the streams could cause seepage losses from the streams. However, if the economics were favorable, these losses could be prevented by diverting the streams into lined channels.

Withdrawal of ground water, thus provision of more storage space underground, could help to regulate streamflow at times of excess flow and in some places could prevent floods. Water that enters the ground-water reservoirs during periods of excess surface flow would be available for later use. Storage of excess water underground has the added advantage of leaving the sediment behind on the land surface rather than letting it accumulate in the surface reservoirs.

The large supplies of saline water in parts of the region should have a market for some uses. Removal of the saline water would prevent its mixing with fresh water.

Development of geothermal energy appears to offer possibility for meeting part of the energy requirements of the future. Preliminary studies indicate geothermal areas at several places in the region.

Planners for ground-water management must recognize the close relationship between ground water and surface water and must have detailed information on the physical parameters that control or affect each supply. Large-scale development without adequate evaluation, planning, and wise management can be disastrous.

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