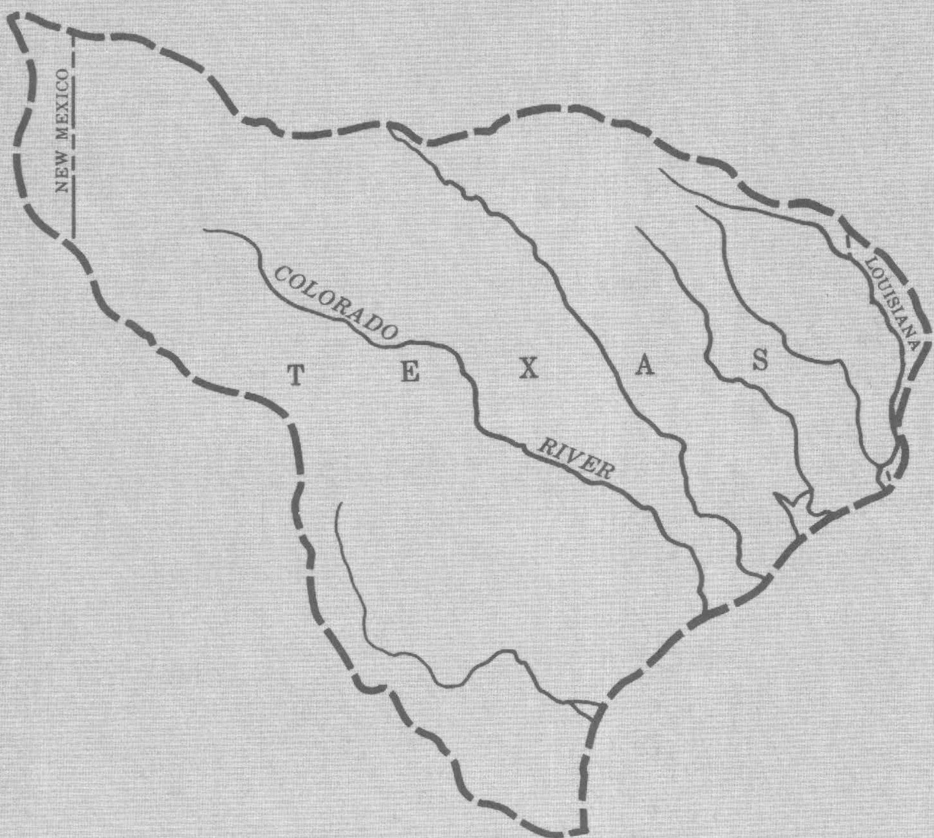
Summary Appraisals of the Nation's Ground-Water Resources—Texas-Gulf Region

GEOLOGICAL SURVEY PROFESSIONAL PAPER 813-F



Summary Appraisals of the Nation's Ground-Water Resources— Texas-Gulf Region

By E. T. BAKER, JR., *and* J. R. WALL

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A summary of the distribution, availability, and quality of ground water and its importance in the regional water supply

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By E. T. BAKER, JR., and JAMES R. WALL

ABSTRACT

Ground water in the Texas-Gulf Region is a large and important resource that can provide a more significant percentage of the total water supply of the region. Total water requirements within the region are projected to rise sharply from 14 million acre-feet (17 cubic kilometres) in 1970 to nearly 26 million acre-feet (32 cubic kilometres) in 2020. About half of the water used in 1970 was ground water.

An estimated total of 1.04 billion acre-feet (1,280 cubic kilometres) of recoverable water containing less than 3,000 milligrams per litre dissolved solids is stored above a depth of 400 feet (122 metres) in the aquifers of the region. In addition, part of an estimated 3.28 billion acre-feet (4,040 cubic kilometres) of water in storage below 400 feet (122 metres) is recoverable. Although not all of the ground water in storage is recoverable, a significant amount is available for development; and an enormous quantity is accessible should occasions prompt its use on a time-limited basis.

The total steady-state yield (amount of water that approximates the maximum perennial replenishment from precipitation) of the region's aquifers is about 4.6 million acre-feet (5.7 cubic kilometres) annually, or about 2.3 times the ground-water usage in 1970 if the large mining draft on the High Plains is not considered as part of the total steady-state yield. Because of the large quantity of recoverable groundwater in storage, the steady-state yield can be augmented for a very long time on a "deferred" basis, whereby the economic use of the water that is withdrawn from storage in excess of the steady-state yield may result in a strengthened economy.

An important goal in programs for meeting future water needs should be to identify the full potential of the available ground-water resources. The subsurface reservoirs may be utilized not only as sources of fresh and treatable water, but as storage facilities for other freshwater supplies and as possible sources of geothermal energy. Some saline-water reservoirs may be suitable for liquid-waste storage or disposal.

Large-scale and unregulated ground-water pumping may result in hydrologic problems such as declining water levels, streamflow depletion, and land-surface subsidence; but studies on proper development of the ground-water reservoirs could provide solutions to many of the problems. Water rights and other legal concepts should be based on sound hydrologic principles to assist development of water resources in an orderly and efficient manner.

Because significant amounts of ground water are available, the opportunities for expanded and conjunctive use of ground water and surface water should be considered in regional plans for water development and conservation. The complexities of water management and the difficulties of achieving an integrated system of total-water management will require additional technical information.

INTRODUCTION

PURPOSE OF THIS REPORT

The purpose of this report is to provide information on the importance of subsurface reservoirs in water-development and conservation plans in the Texas-Gulf Region (fig. 1). The report emphasizes the desirability of considering the ground-water and surface-water subsystems as closely related and equal parts of the water-supply system as a whole.

Most regional water-development plans are based on the use of surface water, which is highly visible and easily obtained, and for which legal procedures for allocation and management have been established for many years. The total water supply of a region, however, is contained in a complex system, and ground water in the Texas-Gulf Region is a large and important resource that could provide a greater percentage of the water used. The subsurface reservoirs may be utilized as sources of fresh and treatable water, as possible storage facilities for other freshwater supplies, and as possible sources of geothermal energy. Some saline aquifers may be suitable for storage of liquid waste.

Large-scale and unregulated ground-water pumping may result in hydrologic problems such as declining water levels, streamflow depletion, and land-surface subsidence. However, because significant amounts of water are available, the opportunities for expanded and conjunctive use of the ground-water resources should be considered in regional plans for water development and conservation.

The complexities of total water management and the difficulties of achieving a workable system are understandably numerous. Although a discussion of these complexities and difficulties is beyond the scope

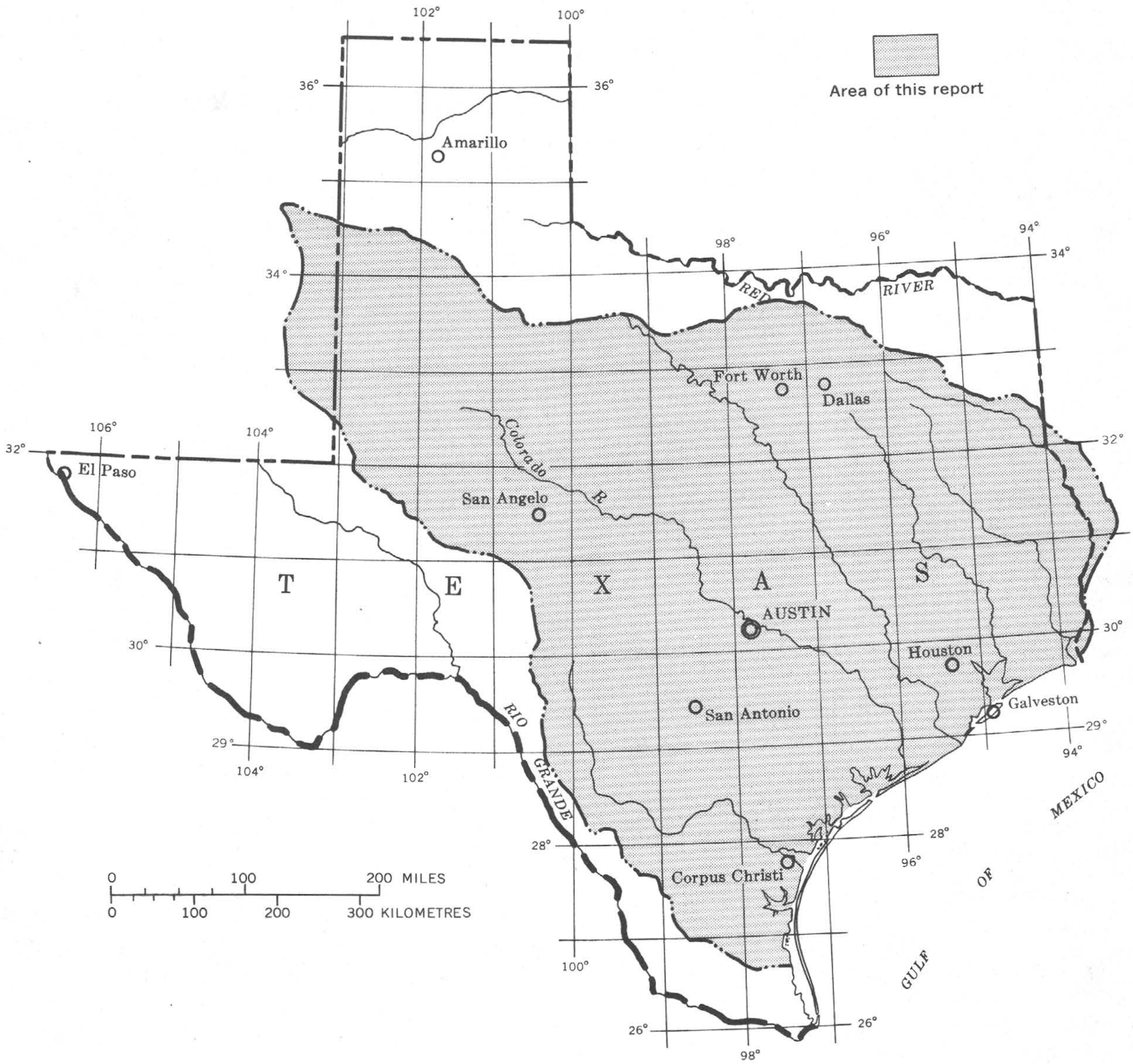

FIGURE 1.—Index map showing location of the Texas-Gulf Region.

of this report, such constraints affecting total water management should not be viewed as insurmountable barriers to future achievement. Nevertheless, efforts to accomplish an integrated system of ground- and surface-water management will require extensive technical and economic feasibility studies.

GEOGRAPHIC SETTING OF THE TEXAS-GULF REGION

The Texas-Gulf Region comprises an area of 173,000 mi^2 (448,000 km^2) in Texas, New Mexico, and Louisiana. About 95 percent of the area is in Texas. The region includes 10 major river basins and 8 intervening coastal basins (Texas Water Development Board, 1968) within the physiographic provinces of the Great Plains, the Central Lowland, and the Coastal Plain (pl. 1A).

The climate of the Texas-Gulf Region is marked by extremes in precipitation and evaporation—climatic elements that to a large degree determine the availability of both ground water and surface water. Average annual precipitation ranges from slightly more than 56 in (1,420 mm) in extreme southeastern Texas and southwestern Louisiana to slightly less than 16 in (410 mm) on the High Plains of New Mexico (pl. 1B).

Average annual net water-surface evaporation (effective evaporation loss obtained as total evaporation minus precipitation) ranges from zero in

Louisiana, where precipitation completely offsets total evaporation, to between 60 and 80 in. (152–203 cm) in west Texas and New Mexico (pl. 1B).

Streamflow, which is influenced primarily by precipitation, varies considerably. The average annual streamflow is about 30 million ac-ft (37 km^3), about two-thirds of which originates in the eastern one-fourth of the region. During a wet year (1941), total runoff was about 65 million ac-ft (80 km^3). During a dry year (1956), total runoff was only about 8 million ac-ft (10 km^3). Low flow of the streams, however, is controlled to a large degree by ground-water outflow, which tends to stabilize streamflow during periods of little or no runoff.

The economy of the Texas-Gulf Region is in a period of transition and rapid expansion marked by increasing population, urbanization, and industrialization. The economy has evolved from a largely noncommercial base through periods dominated first by commercialization of agriculture and later by development of mineral resources, principally oil and gas. Agriculture, though proportionately a smaller part of the economy than previously, continues to contribute a large share of the region's total income.

Increased opportunities for industrial employment, coupled with decreased personnel requirements in agriculture, has radically shifted the distribution of the population. Just prior to World War II, about half the population of the Texas-Gulf Region was in urban areas. During the next 30 years, the population shifted so strongly to urban areas that about four-fifths of the 1970 population of 9.7 million was urban. About one-third of the total population in 1970 was in the four largest cities—Houston, Dallas, San Antonio, and Fort Worth.

The concentrations of the population along the interior and coastal margins of the Coastal Plains, together with projections of large increases in the populations of these areas, are particularly significant aspects of the problems of water and related land-resource planning.

METRIC CONVERSIONS

For those readers interested in using the metric system, metric equivalents of English units of measurements are given in parentheses. The English units used in this report may be converted to metric units by the conversion factors given in table 1.

THE CHALLENGE OF MEETING FUTURE WATER REQUIREMENTS

The demands for water in the Texas-Gulf Region have increased rapidly over the past several decades and are expected to increase more rapidly in the future. By 2020, the population of the region is projected to be 22 million, a 125-percent increase over 1970 (Texas Water Development Board, written commun., 1974). The effects of the population growth upon demands for water will be intensified by urbanization and by industrial and agricultural expansion. The total-water requirements projected to 2020 for municipal supply, industrial use, and irrigation will rise sharply from 14 million ac-ft (17 km^3) in 1970 to nearly 26 million ac-ft (32 km^3) in 2020 (fig. 2). The needs for irrigation are pro-

TABLE 1.—*Factors for conversion from English to metric units used in this report*

From			To obtain	
Unit	Abbreviation	Multiply by	Unit	Abbreviation
acres	ac	4,047	square metres	m^2
		0.004047	square kilometres	km^2
acre-feet	ac-ft	1,233	cubic metres	m^3
		.000001233	cubic kilometres	km^3
barrels	bbl	.159	cubic metres	m^3
		.000159	cubic kilometres	km^3
cubic feet	ft^3	.02832	cubic metres	m^3
feet	ft	.3048	metres	m
gallons	--------	.003785	cubic metres	m^3
		3.785×10^{-12}	cubic kilometres	km^3
gallons per minute	gal/min	.06309	litres per second	l/s
inches	in	2.540	centimetres	cm
		25.4	millimetres	mm
miles	mi	1.609	kilometres	km
pounds per square inch	lb/in^2	.07031	kilograms per square centimetre	kg/cm^2
square miles	mi^2	2.59	square kilometres	km^2

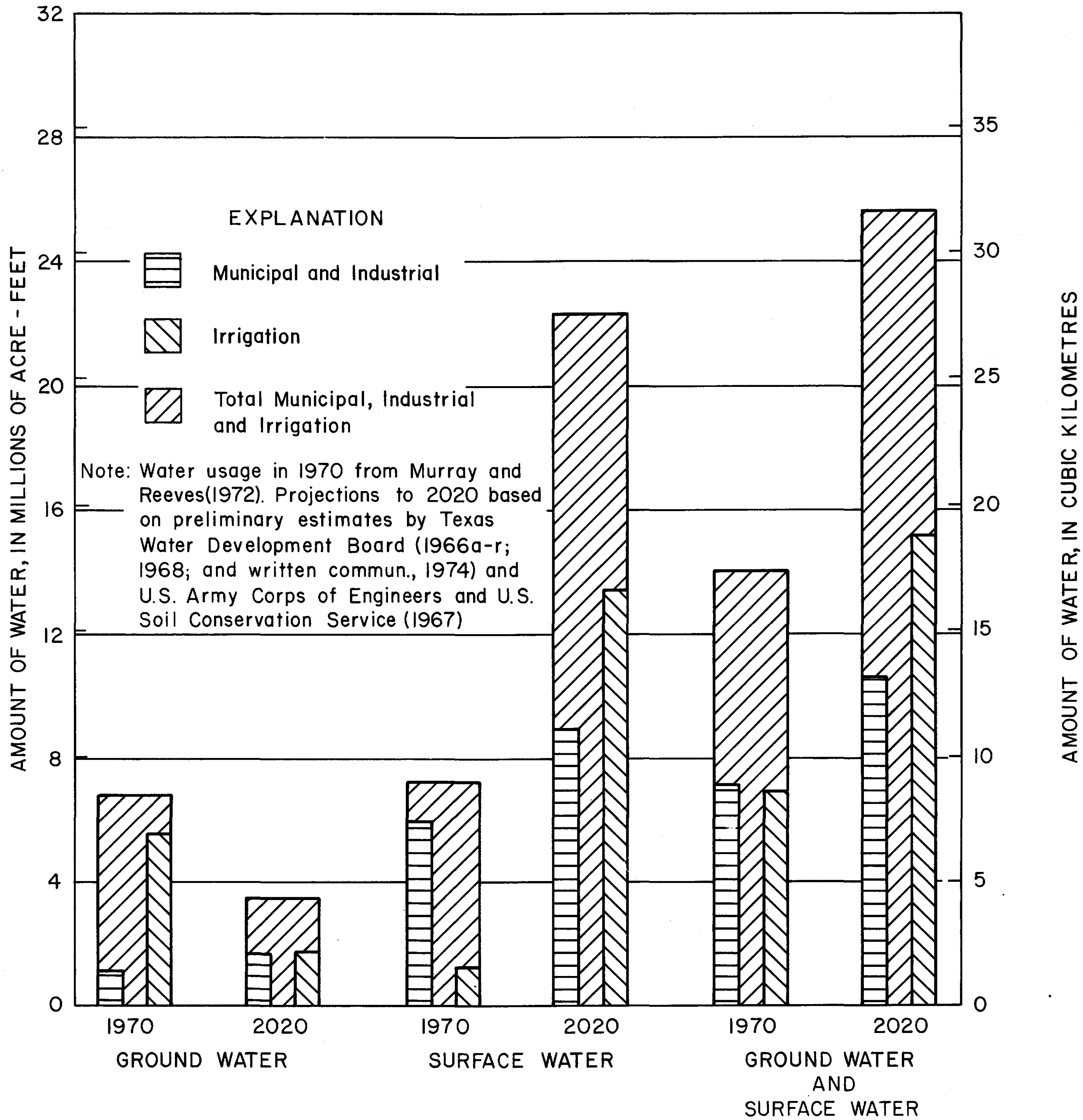

FIGURE 2.—Regional water use for municipal supply, industry, and irrigation in 1970 and requirements projected to 2020.

jected to increase by more than 100 percent. The needs for municipal and industrial supplies are projected to increase by nearly 50 percent (Texas Water Development Board, 1968; and written commun., 1974). All projections are necessarily preliminary, and are subject to revision as additional data become available.

The economic development of some areas of the Texas-Gulf Region may be curtailed by water-supply deficiencies, while elsewhere in the region, large amounts of good-quality water may be surplus to projected needs (pl. 2A). By far the bulk of the total water supply occurs in the eastern part of the region, where projected increases in water requirements are in most places moderate. In contrast, future requirements for water are very large in the western part of the region, where the available supplies are inadequate to meet the demands.

A projected decrease in total ground-water usage is attributed to a reduction in the availability of ground water for irrigation on the High Plains, where the reserves will largely be depleted by 2020. Ground-water requirements are projected to be 3.4 million ac-ft (4.2 km^3) in 2020, or about half of the 1970 ground-water usage of 6.8 million ac-ft (8.4 km^3). Of the 6.8 million ac-ft, 83 percent was used for irrigation, seven-eighths of which was used for irrigation on the High Plains. Ground-water demands for municipal supply and industrial use are projected to increase by nearly 50 percent from almost 1.2 million ac-ft (1.5 km^3) in 1970 to 1.7 million ac-ft (2.1 km^3) in 2020 (Texas Water Development Board, 1968; and written commun., 1974).

Surface-water use is projected to triple from 7.3 million ac-ft (9.0 km^3) in 1970 to 22.3 million ac-ft (27.5 km^3) in 2020. Although municipal and industrial use of surface water will increase by about one-third from 1970 to 2020, irrigation use will increase 10-fold by the end of this 50-year span. Most of this increase for irrigation will be required on the High Plains to replace the projected depletion of the ground-water supply (Texas Water Development Board, 1968; and written commun., 1974). Because of the geographic pattern of projected surpluses and deficiencies, planning and development should be carried out on a regional basis, and all sources of water should be utilized in the most beneficial way. Although the region will require about 26 million ac-ft (32 km^3) of water per year by 2020 for municipal supply, industrial use, and irrigation, the regional supply is ample for these uses, although other needs, such as freshwater inflow to the estuaries, impose an added strain on the supply.

The average annual discharge of surface water to the Gulf of Mexico is 30 million ac-ft (37 km^3); the potential steady-state yield of the ground-water reservoirs is 4.6 million ac-ft (5.7 km^3) per year; and the great reserve of recoverable ground water in storage above a depth of 400 feet (122 m) is about 1.0 billion ac-ft (1,233 km^3). The challenge, therefore, of meeting future water requirements is not so much in coping with a regional shortage, but in planning for regional and conjunctive development of the total resource and in devising the means for overcoming the problems of unequal geographic distribution and demand. The relative scarcity of water as compared to long-term needs on the High Plains and elsewhere in the Texas-Gulf Region have counterparts in adjoining regions, so that most proposals for large-scale transfer of water supplies extend well beyond the region's boundaries. Examples of such proposed transfers are contained in the Texas Water Plan (Texas Water Development Board, 1968) which is currently being updated and refined.

SIGNIFICANCE OF GROUND-WATER RESOURCES IN THE REGIONAL WATER SUPPLY

During the past several decades, ground-water resources have played a sizable role in satisfying the demands for freshwater in the Texas-Gulf Region. Many cities, industries, and irrigators, as well as most rural inhabitants have depended upon this resource because of its accessibility, good quality, and low cost of utilization.

In 1970, ground-water reservoirs supplied about 45 percent of the total freshwater used in the region. In that year, an estimated 7 million ac-ft (8.6 km^3) of freshwater was withdrawn for municipal supply, rural-domestic and livestock supply, industrial use, and irrigation (Murray and Reeves, 1972). This large ground-water use, relative to the use of surface water, contrasts sharply with practices in other Water-Resources Council regions, where the average use of fresh surface water exceeds the use of fresh ground water by about 4 to 1.

Although the ground-water reservoirs provided an estimated 7 million ac-ft (8.6 km^3) on the water used in 1970, about 5 million ac-ft (6 km^3) was used on the High Plains and about 1 million ac-ft (1.2 km^3) was used in the Houston and San Antonio areas. Because of this geographic concentration of ground-water usage, the potential significance of the ground-water supply in the rest of the region is greatly increased. The ground-water reservoirs, excluding the Ogallala aquifer that provided the 5 million ac-ft (6 km^3) used on the High Plains, could provide 4.6 million ac-ft (5.7 km^3) per year, or about 2.3 times the amount used outside the High Plains in 1970.

The unequal hydrologic distribution of the total-water supply in the Texas-Gulf Region is striking. Considering only water having less than 3,000 mg/l dissolved solids, the data summarized in table 2 show that the total regional supply is an estimated 8.6 billion ac-ft (10,600 km^3). Of this amount, 99.6 percent is ground water in storage. Surface water in artificial lakes at capacity and in natural lakes and ponds, and the average amount of water in stream

TABLE 2.—*Distribution of the total regional water supply having less than 3,000 mg/l dissolved solids*

Location	Volume of water (thousands of acre-feet)	Percentage of total water
Ground water		
Above depth of 400 feet	1,975,000	23.08
Below depth of 400 feet	6,545,000	76.49
Total ground water	8,520,000	99.57
Surface water		
Natural and artificial lakes and ponds.	36,000	0.42
Average in stream channels	640	.01
Total surface water	36,640	0.43
Total regional water supply	8,556,640	100

channels at any one time is about 37 million ac-ft (46 km^3), or only 0.4 percent.

Most of the 8.5 billion ac-ft (10,600 km^3) of ground water in storage cannot be recovered feasibly. Nevertheless, a large amount of the water in storage is recoverable and should be considered in plans for water management. It is reassuring to know that this reserve can accommodate overdrafts when necessary, but it is important to remember that this supply of water has been accumulating for generations and that the annual recharge adds only a small increment to the total. The extent to which this princiapl reserve of water can be conserved and managed may be a decisive factor in determining whether or not an adequate supply will be available in the future.

GEOGRAPHIC AND GEOLOGIC DISTRIBUTION OF GROUND-WATER SUPPLIES

Although some water-bearing formations are important sources of water in local areas, only those of regional significance are considered in this report. The geographic distribution of the aquifers, in those areas where they will yield water having less than 3,000 mg/l dissolved solids, is shown on plate 2B. The descriptions of the aquifers apply only to the sections containing water having less than 3,000 mg/l dissolved solids. The stated capacities of wells should not be construed to imply that such yields can be obtained everywhere in the aquifer or that such yields represent the maximum yields possible.

The Hickory aquifer underlies about 5,000 mi^2 (12,950 km^2) of the Edwards Plateau and Llano Uplift of central Texas, where the strata are highly faulted and steeply dipping. The aquifer, which consists principally of sand and sandstone, is more than 400 ft (122 m) thick and extends to maximum depths of almost 5,000 ft (1,520 m). The yields of the larger-capacity wells generally range between 200 and 500 gal/min (13 to 32 l/s), but the yields of a few wells exceed 1,000 gal/min (63 l/s). The aquifer is only slightly developed and is capable of supporting a sizable increase in draft if declines in water levels are acceptable to water planners and users.

The Ellenburger-San Saba aquifer underlies an area of about 4,000 mi^2 (10,360 km^2) and almost completely surrounds the Precambrian core of the Llano Uplift. The aquifer, which consists of more than 1,000 ft (305 m) of limestone and dolomite beds that are characterized by substantial secondary permeability, extends to depths of about 3,000 ft (914 m). A few large springs issue from the aquifer and help sustain the base flow of several streams in the Colorado River basin. Although the yields of large-capacity wells reach 1,000 gal/min (63 l/s), the aquifer is not extensively developed. Additional development will reduce the base flow of some streams in the Colorado River basin.

The Santa Rosa aquifer underlies an area of about 1,000 mi^2 (2,590 km^2) east of the High Plains, but its usefulness as a source of potable water is restricted to parts of a few counties. The aquifer, which is composed of gravel, sand, and finer materials, yields water to wells as deep as 450 ft (137 m). Yields of the larger capacity wells average about 250 gal/min (16 l/s), but some wells yield as much as 1,000 gal/min (63 l/s). The aquifer is capable of sustaining slight to moderate increases in the volume of water pumped.

The Trinity aquifer, which underlies about 20,000 mi^2 (51,800 km^2), constitutes an important ground-water reservoir because of its areal extent and its ability to yield more than 1,000 gal/min (63 l/s) of water to large-capacity wells in some places. The aquifer is composed of interbedded sand, shale, and limestone and reaches a maximum thickness of about 1,200 ft (366 m) at its eastern limit (of water of less than 3,000 mg/l dissolved solids) where it extends to depths of about 3,500 ft (1,060 m). The Trinity aquifer is intensively developed in the Dallas-Fort Worth area where the water is pumped for municipal supply and industrial use.

The Edwards-Trinity (Plateau) aquifer underlies about 15,000 mi^2 (38,200 km^2) of the Edwards Plateau. Freshwater (containing less than 1,000 mg/l dissolved solids) is contained in the sand and sandstone layers of the lower part of the aquifer and in the honeycombed limestone of the upper part. The maximum thickness of the aquifer exceeds 1,000 ft (305 m). Although the yields of wells in most places are relatively small, they may exceed 3,000 gal/min (190 l/s) in places where secondary permeability of the limestone is well developed. Varying degrees of secondary permeability, however, tend to govern the rate of production of individual wells. The base flow of several streams in the Colorado and Nueces River basins is substantially augmented by natural discharge from numerous springs issuing from solution channels in the limestone. The aquifer is not extensively developed and is capable of supporting a sizable increase in pumpage, but additional development will reduce base flows.

The Edwards (Balcones Fault Zone) aquifer occupies a relatively small area of about 2,500 mi^2 (6,470 km^2) along the Balcones Escarpment, which separates the Edwards Plateau from the Gulf Coastal Plain. The aquifer consists of about 500 ft (152 m) of extensively faulted limestone and dolomite. The faulting has greatly facilitated the development of secondary permeability, which in turn has created storage space for large quantities of ground water.

The aquifer is extensively developed in much of its extent for municipal supply, industrial use, and irrigation. Ground-water drafts are particularly heavy at San Antonio, where the aquifer provides the entire water supply for the metropolitan area. The capacities of the wells operated by the city of San Antonio are among the world's largest; some exceptional wells yield more than 16,000 gal/min (1,000 l/s). Springs issuing under artesian pressure from the aquifer largely sustain the low flow of several streams in the Nueces, San Antonio, Guadalupe, and Colorado River basins. Prolonged droughts together with heavy ground-water withdrawals may seriously reduce or even stop some of the springflow.

The Woodbine aquifer underlies about 6,000 mi^2 (15,500 km^2) near the inland extent of the Coastal Plain. It consists of as much as 600 ft (183 m) of sand, sandstone, and shale and extends to maximum depths of about 2,000 ft (610 m). Yields of wells completed in the aquifer approach 700 gal/min (44 l/s) in areas of thick sand accumulations. Although the aquifer is tapped by numerous municipal and industrial wells, it is capable of supporting additional development if water-level declines are acceptable.

The Carrizo-Wilcox aquifer underlies about 30,000 mi^2 (77,700 km^2) near the inland margin of the Coastal Plain and extends across the region in a band from 30 to 80 mi (48 to 129 km) wide. The Carrizo-Wilcox aquifer, which consists of interbedded sand and clay, is one of the most productive aquifers in the region. The maximum thickness of the aquifer is about 3,000 ft (914 m) at its southern (downdip) limits. Yields of wells vary widely, but some large-capacity wells discharge as much as 3,000 gal/min (190 l/s).

In the Carrizo-Wilcox aquifer, water having less than 3,000 mg/l dissolved solids occurs at depths of more than 5,000 ft (1,520 m), which is deeper than in any other aquifer in the region. Artesian pressure is sufficient to cause many of the deep wells to flow. The aquifer is intensively developed by irrigation wells in the Winter Garden area southwest of San Antonio, where the annual ground-water draft exceeds the annual recharge.

The Queen City aquifer, which underlies about 14,000 mi^2 (36,300 km^2) of the Coastal Plain, consists of interbedded sand and clay as much as 500 ft (152 m) thick. The maximum depth of water having less than 3,000 mg/l dissolved solids is about 2,000 ft (610 m). Yields of wells are relatively low, but a few large-capacity wells exceed 400 gal/min (25 l/s). The aquifer is only slightly developed throughout its extent.

The Sparta aquifer underlies about 9,000 mi^2 (23,300 km^2) of the Coastal Plain and mostly overlies the Queen City and Carrizo-Wilcox aquifers. The Sparta consists of as much as 350 ft (107 m) of interbedded sand and clay, and water containing less than 3,000 mg/l dissolved solids extends to depths of more than 2,000 ft (610 m) in places along the southeastern boundary of the aquifer. Large-capacity wells generally yield about 500 gal/min (32 l/s) although the yields of some wells exceed 1,000 gal/min (63 l/s) Except for relatively heavy localized development, the aquifer is only slightly developed throughout most of its extent.

The Gulf Coast aquifer, which includes the Catahoula, Jasper, Evangeline, and Chicot aquifers, underlies about 35,000 mi^2 (90,600 km^2) of the Coastal Plain and extends from the coastline inland for about 90 to 120 mi (145 to 193 km). This aquifer, which is the most extensive of the region's ground-water reservoirs, consists of more than 3,500 ft (1,060 m) of interbedded sand, clay, and gravel. Huge quantities of water are pumped from the aquifer for municipal supply, industrial use, and irrigation. The most intensive and concentrated development is in the Houston area, where large-capacity wells yield from 1,000 to more than 3,000 gal/min (63-189 l/s), and average about 2,000 gal/min (126 l/s). Even though very large quantities of water are being pumped, the Gulf Coast aquifer could support substantial additional development, especially in the area northeast of Houston.

The Ogallala aquifer underlies about 19,000 mi² (49,200 km²) of the High Plains of Texas and New Mexico. It is one of the most intensively developed aquifers in the Nation. Within the Texas-Gulf Region, the Ogallala supplies water to an estimated 50,000 irrigation wells.

The Ogallala consists of as much as 500 ft (152 m) of lenticular beds of gravel, sand, and finer material, and the zone of saturation ranges in thickness from a few feet to more than 250 ft (76 m). The depths to water range from less than 50 ft (15 m) to more than 300 ft (91 m). The yields of irrigation wells range from less than 100 gal/min (6.3 l/s) to more than 1,000 gal/min (63 l/s), depending largely upon the saturated thickness of the aquifer. Large-scale pumping, which greatly exceeds recharge, is drastically depleting the ground-water reserve. Recharge was estimated by Lohman (1972, p. 66) to range from 0.05 to 0.5 in (0.13 to 1.3 cm) per year. In some areas, recharge may exceed 0.5 in (1.3 cm) and perhaps approach 1 in (2.5 cm) (A. W. Wyatt, Texas Water Development Board, oral commun., 1974).

The various alluvial aquifers in the region occupy an aggregate area of about 1,800 mi² (4,660 km²). Although alluvium occurs as flood-plain deposits along the Colorado and Trinity Rivers and other streams, the principal deposits are in the Central Lowland east of the High Plains and along the Brazos River. The Central Lowland aquifers are scattered and isolated terrace and flood-plain deposits that consist of as much as 150 ft (46 m) of gravel, sand, and finer sediments. The yields of large-capacity wells in these deposits range from less than 100 gal/min (6.3 l/s) to more than 1,000 gal/min (63 l/s). The Central Lowland aquifers are not capable of furnishing additional large quantities of water for future development.

The Brazos River alluvial aquifer underlies a flood plain from 1 to 7 mi (1.6 to 11.3 km) wide and follows the long sinuous course of the Brazos River for 350 mi (563 km). The aquifer consists of as much as 100 ft (30.5 m) of gravel, sand, and finer sediments. More than 1,000 irrigation wells tap the aquifer, which yields from 250 to 500 gal/min (16 to 32 l/s) to 50 percent of the wells. The maximum yields exceed 1,000 gal/min (63 l/s). The Brazos River alluvial aquifer is capable of sustaining additional ground-water withdrawals, but the discharge of the Brazos River will be reduced.

The geographic distribution of the aquifers, taking into consideration the overlap that occurs in places, provides coverage of about four-fifths of the Texas-Gulf Region. Only about one-fifth of the region is not underlain by one or more significant ground-water reservoirs, and even these areas are not totally devoid of ground water, but must rely on smaller or less dependable supplies from relatively minor water-bearing formations.

QUALITY OF THE GROUND WATER

In any appraisal of a water resource, the quality of the water must be known before the value of the supply can be judged. A knowledge of the quality of the available water is, therefore, in the same order of importance as a knowledge of the quantity of available water. To cite an obvious example, the oceans contain an estimated 97 percent of the world's total supply of water, but, under present technology and the limits of economic feasibility, it is of little value as a water supply for most uses.

The chemical, physical, biological, and radiological characteristics of water determine its suitability for various uses. Physical problems (turbidity, odor, color, taste, and temperature) and biological problems (bacteria) usually can be alleviated economically, but the removal or neutralization of undesirable chemical constituents can be difficult and expensive.

The type and amount of dissolved constituents in both ground water and surface water are different from place to place, but the chemical quality and physical properties of ground water at any one place generally remain constant. Ground water is also less susceptible than surface water to biological and radiological contamination.

Analyses of water from wells and springs in the Texas-Gulf Region show that there are great differences in the chemical quality of the ground water, both geographically and with depth of occurrence. Such differences are too numerous to depict on a map, but the lowest concentrations of dissolved solids usually occur in the areas of greatest rainfall and least evaporation—in the aquifers of the eastern part of the region where recharge is abundant. The exceptions to this general rule are the occurrences of water with low concentrations of dissolved solids in the limestone aquifers of the central and western parts of the region where recharge is rapid.

Widely ranging levels of salinity are characteristic of the water in storage in the ground-water reservoirs of the region, and this fact, in turn, largely governs the suitability of the water for various uses. For the purpose of this report the degrees of chemical quality, in general terms of total mineralization, are differentiated according to the following classification of Winslow and Kister (1956):

Description	Dissolved solids (mg/l)
Fresh	Less than 1,000
Slightly saline	1,000 to 3,000
Moderately saline	3,000 to 10,000
Very saline	10,000 to 35,000
Brine	More than 35,000

The fresh and slightly saline ground-water supplies have been sufficiently identified in previous ground-water studies (Alexander and others, 1964; Baker and others, 1963a, b; Cronin and others, 1963; Mount and others, 1967; Peckham and others, 1963; and Wood and others, 1963) to permit a delineation of their combined extent (modified from Texas Water Development Board, 1968, figs. II–2 and II–7) in the various ground-water reservoirs of the region (pl. 2B).

Ground water having concentrations of dissolved solids in excess of 3,000 mg/l commonly occurs in the deep subsurface below the slightly saline water and downdip in most of the aquifers of the region. Only the Edwards-Trinity (Plateau), Ogallala, and alluvial aquifers, most of which do not have deep subsurface extensions, contain water that is almost entirely fresh to slightly saline. Largely because of the natural increase in the salinity of ground water with depth, saline water occurs throughout most of the region. The typical range in dissolved solids in water that is being used from the various aquifers is given in table 3.

TABLE 3.—*Typical range of dissolved solids in water used from each aquifer*

Aquifer	Typical range in dissolved solids (mg/l)
Alluvium	500–2,000
Ogallala	400–1,200
Gulf Coast	300–1,000
Sparta	200– 800
Queen City	200– 800
Carrizo-Wilcox	200–1,500
Woodbine	500–1,200
Edwards (Balcones Fault Zone)	300–1,200
Edwards-Trinity (Plateau)	400–1,000
Trinity	500–1.500
Santa Rosa	400–2,500
Ellenburger-San Saba	400–2,000
Hickory	300– 700

QUANTITIES OF GROUND WATER AVAILABLE FOR DEVELOPMENT

Because of the hydrologic relationship of ground-water recharge to precipitation, runoff, and evapotranspiration, potential recharge in the Texas-Gulf Region increases from northwest to southeast and ranges from a miniscule amount on the High Plains to several inches in the Sabine River basin. As a result of this difference in potential recharge, development of the ground-water resources may vary from unavoidable "mining" (pumping in excess of the potential replenishment rate) of ground water in storage in the western part of the region to a plan of limiting withdrawals to the steady-state yield of the aquifers in the eastern part of the region.

The quantities of ground water available for development have been estimated largely on the basis of the amount of natural discharge subject to capture by pumping which is an index of the maximum or near maximum recharge rate from precipitation. The methods used to obtain the data given in this report were: (1) the U.S. Study Commission method, which uses theoretical lines of recharge and discharge and maximum pumping lifts of 400 ft (122 m) to determine the yield of clastic artesian aquifers by increasing natural recharge at the outcrop from increased hydraulic gradients (Alexander and others, 1964; Baker and others, 1963a, b; Cronin and others, 1963; Mount and others, 1967; Peckham and others, 1963; and Wood and others, 1963); (2) the base-flow method for determining recharge to the Edwards-Trinity (Plateau) aquifer, in which recharge approximates base flow of the streams draining the aquifer (Alexander and Patman, 1969; Long, 1958; and Reeves, 1969); (3) the stream inflow-outflow method used for Edwards (Balcones Fault Zone) aquifer, in which recharge is computed on the basis of historical streamflow records (Petitt and George, 1956; and Garza, 1962); and (4) the method of determining the amount of water moving through the aquifers (Ogallala and alluvium) under existing hydraulic gradients (Theis, 1937; Cronin and Wilson, 1967; and Brown and Signor, 1973).

Availability is given also in this report as the amount of water recoverable and partly recoverable from storage. These values have their greatest significance in areas where ground-water mining is unavoidable, as on the High Plains.

The quantities of ground water available for development (table 4) are expressed as the steady-state yield. Under this concept, the yield approximates the maximum perennial replenishment from precipitation. The retention in the aquifer of at least a part of the recharge that would have been released as base flow is inherent in this concept, and development of an aquifer to this extent necessarily results in diminution of surface runoff. The concept also presupposes an idealized pattern of aquifer development whereby construction and spacing of individual wells are suitable for recovering much of the water added to the zone of saturation and for stabilizing water levels.

As shown in table 4, the total steady-state yield of the aquifers of the region is 4.6 million ac-ft (5.7 km³) annually. The largest single yield is 2.5 million ac-ft (3.1 km³) annually from the Gulf Coast aquifer. The quantities of water given as steady-state yields are, at best, only approximations and are to be regarded as preliminary estimates that should be revised and kept current as development progresses and more basic data become available.

It is not suggested that the aquifers should be developed to the indicated extent of the yields in any plan of total water management. As appropriately expressed by Lohman (1972, p. 62), where the framework of prevailing laws and regulations permits the total water resource to be operated for maximum efficiency, water planners, given the knowledge of the combined ground- and surface-water systems and their interrelationship, should then be able to select the most desirable or equitable distribution of available water.

An estimated total of 4.32 billion ac-ft (5,330 km³) of recoverable and partly recoverable water containing less than 3,000 mg/l dissolved solids is stored in the aquifers of the region, and of this amount, about 1.04 billion ac-ft (1,280 km³) of recoverable water, or 24 percent of the total, is estimated to be stored within 400 ft (122 m) of the land surface. The Gulf Coast aquifer, which contains an estimated 450 million ac-ft (555 km³) of recoverable water in the top 400 ft (122 m), has the largest storage capacity of the region's aquifers.

The 400-ft (122-m) depth as used here is an arbitrary level that does not necessarily imply an economic limit of recovery, as economics of pumping can and usually do change for various reasons. Obviously in the case of the Ogallala aquifer, the 5 million ac-ft (6 km³) of water below a depth of 400 ft is economically recoverable. Nevertheless, for the purpose of this report, the available water above a depth of 400 ft (table 4) is considered to be recoverable and implies dewatering (mining) to that depth, which would necessitate pumping lifts in excess of 400 ft. On the other hand, much of the water below 400 ft, especially in those aquifers where freshwater extends to great depths and is in lateral and vertical connection with saltwater, may not be economically recoverable at present costs and may never be practical to recover. Largely for this reason, the volume of water below a depth of 400 ft is referred to in table 4 as partly recoverable.

TABLE 4.—*Quantities of ground water available for development* [1]

Aquifer	Steady-state yield (thousands of acre feet per year)	Recoverable water in storage above depth of 400 ft (thousands of acre-feet)	Partly recoverable water in storage below depth of 400 ft (thousands of acre-feet)
Alluvium	130	5,000	0
Ogallala	90	135,000	5,000
Gulf Coast	2,500	450,000	1,150,000
Sparta	130	20,000	65,000
Queen City	120	70,000	200,000
Carrizo-Wilcox	560	150,000	1,150,000
Woodbine	10	10,000	70,000
Edwards (Balcones Fault Zone).	410	2,000	13,000
Edwards-Trinity (Plateau).	540	70,000	70,000
Trinity	70	100,000	450,000
Santa Rosa	30	8,000	0
Ellenburger-San Saba	20	8,000	12,000
Hickory	40	10,000	100,000
Total (Rounded).	4,650	1,038,000	3,285,000

[1] Steady-state yield and recoverable water in storage from data in Alexander and others (1964), Baker and others (1963a,b), Brown and Signor (1973), Cronin and others (1963), Mount and others (1967), Peckham and others (1963), Petitt and George (1956), Texas Water Development Board (1966a–r), Wood (1956), Wood and others (1963), and other computations by U.S. Geological Survey. Specific yield of 2 percent used in computing recoverable water in storage in Edwards (Balcones Fault Zone), limestone part of Edwards-Trinity (Plateau), and Ellenburger-San Saba aquifers; specific yield of 15 percent used for other aquifers. Ogallala storage as of 1967 after Cronin (1969).

Because of the enormous amount of recoverable water in storage, each aquifer contains a stock of water that can be mined if necessary (as is being done with the Ogallala aquifer on the High Plains), whether the rate of recharge is large or small. The steady-state yield can be augmented for a very long time on a "deferred" basis, whereby the use of the water that is withdrawn from storage may result in a strengthened economy, which is turn can support programs for developing additional sources of supply. (See American Society of Civil Engineers, 1972, p. 21.)

The surpluses and deficiencies in the ground-water supplies in the region result from three factors: (1) the aquifers are not uniformly distributed within the region; (2) the yields of the aquifers are different; and (3) the demands for water vary from one part of the region to another. Indices of areal potential for future development can be established on the basis of the geographical variance in the steady-state yield and the demands projected to 2020. The areas of greatest potential for additional development of ground-water supplies within the Texas-Gulf Region, as shown on plate 2C, are areas of ground-water surpluses where the locally available supplies exceed the projected local demands.

Projected ground-water requirements exceed the available ground-water supply in only three areas—the High Plains, the Dallas-Fort Worth area, and the San Antonio area. The aquifers in these areas are already heavily pumped, and projected withdrawals to satisfy the 2020 demands will result in the initiation or continuance of ground-water mining.

The steady-state supply of ground water exceeds the projected ground-water requirements by different amounts in the rest of the region. Ground-water surpluses of as much as 300,000 ac-ft (0.37 km^3) annually are available in the Sabine and Neches River basins, and the occurrence of highly productive aquifers and relatively low requirements in the Nueces River and Middle Colorado River basins indicate that these areas in the generally water-deficient western part of the region have the potential for additional development (pl. 2C).

In many parts of the region, however, the steady-state supply only slightly exceeds the projected ground-water requirements, and surpluses in these areas are projected to be less than 100,000 ac-ft (0.12 km^3) annually by 2020. In the heavily pumped Houston area, for example, ground-water withdrawals slightly in excess of the projected demand would result in mining of the water in storage in the sand and gravel beds. Water is being mined already from the clay beds by compaction and accompanying land-surface subsidence.

The foregoing discussion of the availability of ground water and of the potential for future development by area does not consider the possible impact of such development. It should be reiterated that full development of ground-water resources to the extent indicated, or even less in some areas, could be detrimental to the adequacy of surface-water supplies by reducing basin runoff. Also, part of the ground-water surpluses in some aquifers augments streamflow that in turn provides recharge to other aquifers.

OPPORTUNITIES FOR MEETING WATER REQUIREMENTS BY GREATER USE OF GROUND-WATER RESERVOIRS

The large ground-water resources of the Texas-Gulf Region, with some notable exceptions, are still in an incipient stage of development. This situation exists despite the fact that development has continued almost unabated for the past half century and that ground water now constitutes the source of about half the water used in the region.

Provisions should be made in programs for meeting future water requirements to develop the available ground-water supply to the most reasonable extent and to use the underground resources, as appropriate, in integrated systems of importing and exporting water, storage, artificial recharge, desalinization, reclamation, and waste disposal.

USE OF GROUND WATER AS THE PRIMARY SOURCE OF WATER SUPPLY

The selection of ground water as the primary source of water supply has generally been based on one or more of the following advantages (Thomas, 1951, p. 223–224):

1. *Accessibility.*—Ground water usually may be reached within a few hundred feet of where it is to be used, and on the same property, whereas surface water may require pipelines and rights-of-way over stretches of several miles.
2. *Availability.*—Ground water may be available for use in areas where the water in streams and lakes has already been appropriated by other users.
3. *Dependability.*—Yield from wells generally fluctuates less than streamflow in alternating wet and dry climatic cycles.
4. *Uniformity in quality.*—Ground water is more uniform in temperature and soluble-mineral load than surface water, and is generally free of turbidity and bacterial pollution.

The use of ground water also has inherent disadvantages, some of which are: (1) a potential for land-surface subsidence in some areas; (2) the absence of recreation facilities associated with surface-water reservoirs; and (3) possible interference with surface-water rights if streamflow is reduced.

Many of the advantages, however, are applicable to ground-water supplies in the Texas-Gulf Region, and in many places the potential for greater utilization of ground-water resources should warrant investigation. In some areas, the ground-water resources can provide for the needs of additional urban development, industrial expansion, and increased irrigation. Consequently, if ground water is utilized as the primary source of water supply, excess surface water in amounts larger than otherwise anticipated, might then become available for export to water-deficient areas. Because most of the eastern part of the region contains such large ground-water resources, much of the proposed development and local use of surface-water supplies might be reconsidered on the basis of regional needs.

CONJUNCTIVE USE OF GROUND WATER AND SURFACE WATER

The problem of meeting demands for water in the future can be solved more efficiently if the resources are developed in accordance with hydrologic principles. One basic principle is that within the dimensions of a region, which include the subsurface, surface, and atmosphere, there is a given amount of water to be managed, regardless of where it may be in storage or in transit at any particular time. The concept of "conjunctive use" means, therefore, in its broadest sense, that ground water, surface water, and atmospheric water are treated as a single resource.

Conjunctive use provides the opportunity to develop the inherent advantages of both surface-water and ground-water reservoirs. The storage capacity of ground-water reservoirs, for example, is far greater than the storage capacity of surface-water reservoirs; and the water stored underground is relatively safe from evaporation and contamination. On the other hand, surface-water supplies are more easily renewed and are usually more desirable for providing large amounts of water to areas of concentrated demand.

The problems of water-resources management would be less difficult if a fully integrated natural and man-made plumbing system for the entire region could be modeled. However, the legal and technological constraints imposed on regional planning cannot be ignored, and the existing facilities cannot be eliminated, because they were not designed as part of a theoretical system. In some places, however, it may be possible to use existing and proposed facilities more efficiently. The following definitions demonstrate the point:

1. Surface-water reservoirs that are constucted for the primary purpose of providing water for artificial recharge of ground-water reservoirs, can be designated as "recharge reservoirs" and could be considered as a proper addition to such primary classifications of surface-water reservoirs as "flood control," "conservation," and "hydroelectric-power generation."

2. Ground-water well fields that are developed for the primary purpose of maintaining conservation storage in surface-water reservoirs, can be designated as "reservoir-maintenance well fields" and could be considered as a proper addition to the primary classification of well fields as "public supply," "industrial use," and "irrigation."

In the Texas-Gulf Region, conjunctive-use programs might be applicable to the following problems: (1) water shortages during droughts, such as the severe Texas drought of the 1950's and the drought in the Concho River basin duing 1962–71; (2) the overdevelopment of the Carrizo-Wilcox aquifer for irrigation in the Winter Garden area; (3) the ever increasing and hardly sustainable demands that are being imposed upon the Edwards aquifer in the San Antonio area; (4) the declining water levels, land-surface subsidence, and saltwater intrusion that have resulted from pumping some 400 million gallons (0.0015 km^3) of water per day from the Gulf Coast aquifer in the Houston area; and (5) the depletion of water in storage in the Ogallala aquifer of the High Plains to the extent that the economy may suffer.

A prolonged drought imposes a severe strain upon the water resources of a region, because it results in a reduction in the total amount of water available for management. The most immediate effect, however, is the reduction in streamflow and the need to conserve storage in surface-water reservoirs. In some places, the local ground-water resources could be employed to help maintain storage in the reservoirs; in other places, it is realistic to consider piping ground water from other areas. Where ground water and underground space are available, well fields consisting of both recharge and discharge (or dual-purpose) wells could be considered as a possibility for management of excesses and deficiencies in streamflow.

During the drought of the 1950's, surface-water storage in Lake Corpus Christi, which is the source of water for public supply in the area, was greatly reduced. The problem was alleviated by the use of four flowing wells that had been drilled in the Carrizo-Wilcox aquifer in Atascosa County by the Lower Nueces Water Supply District in 1951. The water from these wells was directed into the Nueces River, via the Atascosa River, where it eventually reached and was impounded in Lake Corpus Christi. Although 65 to 75 percent of the water was lost by evaporation, transpiration, and infiltration during the 118-mi (190-km) trip from the wells to the lake, the rate of flow of 10 million gallons (37,800 m^3) per day at the wellheads was sufficient to increase the supply in Lake Corpus Christi.

During the drought of 1962–71 in the Concho River basin, the city of San Angelo, which obtains its municipal supply from Lake Nasworthy, contended with the lack of adequate water in storage by purchasing irrigation rights on the South Concho River, constructing a pipeline to E. V. Spence Reservoir, and drilling wells for ground-water supplies. The wells would have served to ease the critical situation, but the drought ended, and the reservoir filled before the well field was developed.

The important fact in these examples is not that ground water was used or was planned to be used, but that it was used after water shortages had occurred rather than as a planned contingency for drought conditions. The situations in the Winter Garden, San Antonio, and Houston areas provide examples in which heavily pumped subsurface reservoirs could be used advantageously in conjunction with the relatively abundant surface-water resources.

In the Winter Garden area, in Dimmit and Zavala Counties north of Laredo, about 300,000 ac (1,200 km^2) are irrigated by an annual pumpage of about 350,000 ac-ft (0.43 km^3) of ground water from the Carrizo-Wilcox aquifer. The amount of water being pumped greatly exceeds recharge to the aquifer; therefore, the potential problems are declining water levels and possibly economically prohibitive pumping costs.

The solution to the Winter Garden problem as proposed by the Texas Water Plan is to import 200,000 ac-ft (0.25 km^3) of water annually from Amistad Reservoir in the Rio Grande basin. The Water Plan states that this imported water offers the possibility for "conjunctive operation." In addition, the productive capacity of the aquifer can be prolonged by recharging the ground-water reservoir with surface water intercepted within the Nueces River basin.

The Edwards (Balcones Fault Zone) aquifer provides water for public supply, industrial use, and irrigation in an extensive area of south-central Texas. The city of San Antonio, which has a population of about 800,000, depends upon the Edwards for its entire supply. If the demands for water from the Edwards continue to increase, as they are likely to do in this rapidly growing area, the predictable results will be: (1) severe declines in water levels during periods of drought; (2) large reductions in the amount of water available to all users; and (3) reductions in flow, or even periods of no-flow, from the important springs such as those at San Antonio, New Braunfels, and San Marcos.

These problems might be avoided or attenuated by using surface water from the Guadalupe, Nueces, and San Antonio River basins in conjunction with the storage capacity and transmissivity of the Edwards reservoir. Surface-water reservoirs could be constructed on or near the recharge area of the Edwards for the primary purpose of providing recharge to the aquifer.

In the Houston area, about 400 million gallons (0.0015 km^3) of water per day are pumped from the Gulf Coast aquifer for municipal supply, industrial use, and irrigation. Although the potential ground-water recharge is very large, maximum development is limited by the capability of the aquifer to transmit water from areas of recharge to areas of discharge. The Houston area is not short of water, but the sustained heavy pumping in local areas has already resulted in hydrologic and economic problems.

Expanding the use of abundant surface-water supplies or the development of well fields nearer to the recharge areas could be helpful in the Houston area because of the serious problem of land-surface subsidence, which is subjecting the highly developed near-shore areas to progressive inundation by normal tides and to catastrophic flooding by hurricane tides. The lost ground cannot be regained, but subsidence can be arrested by decreasing the pumping and recharging the aquifer.

The problem on the High Plains presents a special situation, where a finite supply of water is being consumed. The water in storage in the Ogallala aquifer has been depleted in recent years at the rate of about 3.5 million ac-ft (4.3 km^3) per year, based on about 3.5 million irrigated acres (14,200 km^2) in 1969 and on an assumed average depletion rate of 1 ac-ft per irrigated acre per year (1,230 m^3 per 4,050 m^2). Surface-water supplies, except from the playa lakes, are practically nonexistent, and recharge to the aquifer is extremely small.

The consequences of depleting the water in storage in the Ogallala can be delayed, however, by modifying the land-use practices and by judicious use of all available water. The amount of water available annually from the playa lakes within the region is estimated (Schwiesow, 1965) at about 2 million ac-ft (2.5 km^3), and the amount of recoverable water remaining in the Ogallala aquifer in 1967 (Cronin, 1969) was calculated to be 140 million ac-ft (173 km^3). If the playa-lake water is used to supplement supplies from the Ogallala, if the water remaining in the Ogallala is used with great care, and if land-use practices can be modified to require less water, the available supplies may last for several more decades.

In the meantime, higher food prices because of worldwide shortages, together with improved technology, may change the cost-benefit ratio so that importation of water will be economically feasible, and the dewatered part of the Ogallala aquifer may be the best reservoir available for storing imported water.

ARTIFICIAL RECHARGE

Although an enormous total amount of water is annually recharged to the aquifers by natural means, it may be desirable for a variety of reasons to increase the amount or rate of recharge in some areas. Artificial recharge may be useful in coping with present or potential problems, but under certain circumstances and in certain areas, the practice is probably necessary in any program to manage the ground-water subsystem in conjunction with and in a manner similar to the management of the surface-water subsystem.

Artificial recharge is best known for its application in alleviating water-supply problems, but the practice has important applications in liquid-waste disposal, secondary oil recovery, maintenance of reservoir pressures, and in arresting land-surface subsidence. As applied to water-supply problems, artificial-recharge programs are designed to: (1) supplement the quantity of available ground water; (2) retard or prevent the depletion of ground-water reservoirs; (3) prolong acceptable ground-water quality by retarding or preventing salt-water encroachment; (4) conserve and dispose of runoff, including floodwaters; (5) store water to reduce costs of pumping and piping; and (6) store water in times of low demand for use during periods of high demand. Although applications relating to liquid-waste disposal and to petroleum-industry operations are currently being practiced in the Texas-Gulf Region, only a few diverse programs relative to water supply are in operation.

The principal area where artificial recharge may be useful is on the High Plains, where progressive depletion of the Ogallala aquifer will require adjustments in irrigation practices. Water supplies can be increased by importing water, but any plan that presupposes an increase in available water must consider the problem of storage facilities, particularly during periods of low use. Adequate storage space is available in the Ogallala if the water can be placed underground by injection wells or by infiltration methods. The method or combination of methods used will be determined by the quality of the recharge water and by the hydraulic characteristics and geochemistry of the aquifer (Brown and Signor, 1973).

Artificial recharge operations and experiments have been conducted on a small scale in several places on the Southern High Plains. Successful recharge by injection wells was achieved by intra-aquifer transfer of Ogallala water (Moulder and Frazer, 1957; Reed, unpub., rept. 1959) and by recharge of water from Lake Meredith (in the Arkansas-White-Red Region) and Lake J. B. Thomas in well fields at Lubbock and in Martin County, Texas, respectively (Brown and Signor, 1973). Although these operations were not carried on long enough to preclude the possibility of failure because of bacterial contamination or slowly occurring chemical changes, the success indicates that there are no insurmountable short-term technical difficulties in recharging high-quality water. However, the pumpback cost of the water, including the expense of the recharge operation, may exceed that which the agricultural users now pay.

The largest available local supply of surface water for artificial recharge on the High Plains is the 2 million ac-ft (2.5 km^3) estimated to be available annually in the playa lakes. Recharge of this water through injection wells, however, has generally been unsuccessful because of clogging of the aquifer by suspended material. The most successful effort in recharging playa-lake water through wells was that of Hauser and Lotspeich (1967), whereby surface treatment of the highly turbid water removed 90 percent or more of the suspended material. Thus far, artificial recharge using playa-lake water has been tried experimentally and is currently being attempted at numerous sites on the High Plains of Texas and New Mexico. (See Broadhurst, 1960; Valliant, 1961; Cronin, 1964; Clyma, 1964; Havens, 1966; Meyer, 1972.)

Artificial recharge by surface spreading, which is ineffective in many places on the High Plains because of the occurrence of layers of low permeability between the land surface and the water table, has been accomplished near Lubbock, Texas, where treated sewage effluent has been used for flood irrigation of 4,000 ac (16.2 km^2) since 1938. After this operation began, the water table in the Ogallala rose from about 120 ft (37 m) below land surface to within a few feet of the surface by 1968 (Brown and Signor, 1973). Artificial recharge by surface spreading has not been attempted elsewhere in the region.

Because of the potential value of artificial recharge in coping with present and future problems, intensive research studies of various aspects of this process are continuing. Such studies will provide information on artificial recharge of the Ogallala aquifer, and the results of these studies may have application in other areas where artificial recharge is contemplated.

Artificial-recharge methods could be used advantageously in segments of two significant aquifers in the southwestern part of the region—in the fully-developed Carrizo-Wilcox aquifer in the heavily irrigated Winter Garden area southwest of San Antonio and in the heavily-pumped Edwards (Balcones Fault Zone) aquifer in the San Antonio area. Imported water is envisioned by the Texas Water Plan (Texas Water Development Board, 1968) to supplement ground water pumped in the Winter Garden area. Excess water available after the growing season could be used to recharge the ground-water reservoir. In addition, the diversion of floodwaters within the Nueces River basin might provide a local source of water for recharging the Carrizo-Wilcox aquifer by surface spreading on its sandy outcrop.

In the San Antonio area, artificial-recharge facilities could include a series of surface-water reservoirs on or near the recharge area of the Edwards (Balcones Fault Zone) aquifer. Such reservoirs could be designed to impound flood waters from the upper Nueces, San Antonio, and Guadalupe River basins for controlled release into the highly permeable aquifer.

In the north-central and west-central parts of the region, pumping from the alluvial aquifers for municipal supply and irrigation has already resulted in water-level declines that will become more serious if demands increase. Imported water envisioned by the Texas Water Plan for this area would sustain agricultural production and would meet the needs for municipal supply. In addition to direct use of the surface water, a program of artificial recharge could be used to store part of the imported water in the ground-water reservoirs, especially when such water is in excess of seasonal needs.

Various applications of artificial recharge in the Houston area and nearby coastal areas of heavy ground-water pumping could be beneficial although reduced pumping and increased surface-water use may be more practical. In this water-rich part of the Coastal Plain, generally adequate supplies of freshwater are available, but the continually expanding and deepening cone of depression in a part of the Gulf Coast aquifer has caused land-surface subsidence and saltwater encroachment.

Repressuring the heavily pumped part of the aquifer by artificial recharge would decrease the rate of subsidence, and if enough water is recharged, subsidence could be halted. Reduced ground-water pumping would have the same effect, however, and would probably be a more feasible method. It is not likely, however, that any measurable recovery in the altitude of the land surface could be effected (Gabrysch, 1972).

Artificial recharge might also be used in the Houston area to halt or retard the advancement of saline water toward the freshwater well fields. This might be achieved by injecting freshwater along the interface of fresh and saline water to create and maintain a high-pressure ridge that would function as a barrier to the saline water. Because of the availability of surface water in this area, reduced ground-water pumping would, again, probably be a more feasible method.

Applications of artificial-recharge methods to liquid-waste disposal, secondary oil recovery, and maintenance of reservoir pressures are discussed in a separate section of this report.

SALVAGE OF WATER FOR BENEFICIAL USE

The process of salvaging ground water may be viewed as a means of effecting a prolongation or an increase in supply, and for this reason salvage becomes a factor in aquifer management. Salvage of ground water for beneficial use can be exercised primarily by: (1) reducing consumption of water by evaporation and phreatophytes; (2) practicing conservation; and (3) reclaiming and recycling waste water that has already served some beneficial use.

Consumption of ground water by most phreatophytes generally is conceded to be excessive in relation to the benefit of these plants to man. Although some phreatophytes furnish cover and browse for game, provide erosion control, serve as windbreaks, or have esthetic value, most of them have low economic value. Salvage of ground water by reducing consumptive use by phreatophytes may be accomplished by eradication or by substituting plants of high economic value such as alfalfa.

The most common phreatophytes in the Texas-Gulf Region are saltcedar and mesquite. Cottonwood, willow, baccharis, and other species occur where the accessibility and quality of water are favorable to their existence. The phreatophyte problem is more acute and has received more attention in the semiarid western part of the region, where the phreatophytes are mostly confined to the flood-plain alluvium along stream channels where ground water is within reach of the root systems.

An example of the density, spread, and water consumption of woody phreatophytes in the region is afforded by an intensive study along a reach of the Brazos River and selected tributaries above Possum Kingdom Reservoir (Busby and Schuster, 1973). More than 60 percent of about 100,000 ac (405 km^2) of flood plain in the reach studied was occupied by various phreatophytes. For a part of the area where a succession of aerial photographs was studied, saltcedar showed a progressive invasion of the area and doubled in extent over a period of about 30 years. Mesquite and saltcedar alone in the total area consume approximately 90,000 ac-ft (0.11 km^3) of water annually.

With different land-use practices, a part of this water could be salvaged for greater economic benefits in one form or another. The total amount of ground water that might be salvaged by the control of saltcedar throughout the Brazos River basin has been preliminarily estimated by the Soil Conservation Service to be 625,000 ac-ft (0.77 km^3) annually (Texas Water Development Board, 1968, p. III–30). This amount, when placed in perspective, equals the amount of ground water pumped for all purposes in 1970 in the Houston area. Not all of the 625,000 ac-ft (0.77 km^3), however, would be available for beneficial use, because a part of the potential salvage includes saline water.

Another extensive area of saltcedar growth is along the Colorado River and its tributaries in the west-central part of the region, where dense stands of phreatophytes occupy parts of the flood plain over a distance of approximately 300 river miles (483 km) (Smith and Rechenthin, 1964). A study by Larner and others (1974) in this reach showed that if 1 ac-ft (1,230 m^3) of water per acre (4,047 m^2) could be salvaged through a control program on the flood plain, and 3 ac-ft (3,700 m^3) per acre along the river banks and along the shoreline of Lake J. B. Thomas, a total of at least 10,200 ac-ft (0.01 km^3) of water could be salvaged annually and made available for other uses.

Reduction of consumption of water by phreatophytes in the humid eastern part of the region obviously could salvage a large quantity of ground water, but in this area much of the consumption of water is by dense stands of timber. The relatively high economic value of the timber justifies consumption of the water.

Water-conservation practices, such as reclaiming or recycling water that has already served some beneficial use, are a means of increasing the available ground-water supply by reducing the demand for new water. Reuse allows more service per unit of water withdrawn.

Studies conducted by the Texas Water Development Board to update projected water requirements for agriculture envision a highly efficient use of water from conservation and reclamation practices in the future. For example, application of water per acre on the High Plains of Texas by 1990 is preliminarily projected by the Texas Water Development Board to be about 0.8 ft (0.24 m), whereas the historical average application of water per acre is estimated to be about 1.6 ft (0.49 m) in Texas and about 2.0 ft (0.61 m) in New Mexico (U.S. Bureau of Reclamation, 1973, p. 41). Such a large reduction in use of water would stretch the supply of water in storage in the Ogallala and extend the productive life of the aquifer.

The relative scarcity of water in some areas of the region, coupled with Federal and State laws regulating the quality of waste water before discharge, have spurred many industries to develop techniques that permit multiple use of small amounts of the same water rather than larger amounts of new water that is run only once through the system. Thomas (1951) has shown that some large industries have been able to reduce their demand for new water from underground or surface resrvoirs to as little as 5 or 10 percent of the quantities used in similar industrial operations in other areas.

Barring some breakthrough in weather modification or saline-water conversion, the actual water supply of the region cannot be increased. The supply can be used more effectively, however, by a reduction in unit requirements by all consumers. The result then of conservation, recycling, and reclamation is that more water would be immediately available where it is needed to meet deficiencies or to support economic expansion.

USE OF SALINE AQUIFERS

An evolution in attitudes about saline aquifers has taken place in an accelerating manner and within a relatively short time. The change has been from considering saline aquifers as a nuisance to recognizing them as a potentially valuable resource, not only for their content of usable or treatable water, but also for their potential use for the disposal of liquid waste or for storage of fresh water. The importance of the saline aquifers in the Texas-Gulf Region is enhanced by their nearly ubiquitous areal extent. About 170,000 mi^2 (440,300 km^2) or about 98 percent of the region is underlain by saline aquifers (Winslow and Kister, 1956; Hood and Kister, 1962; and Core Laboratories, 1972).

SALINE AQUIFERS AS SOURCES OF TREATABLE WATER

The demand for desalted water to supplement naturally occurring freshwater did not develop until the beginning of the second half of this century. While the demands for freshwater were steadily increasing over the past several decades, the freshwater supply in some areas was decreasing. Inevitably the requirement to tap sources of saline water became compelling.

Under the Saline Water Act, which was passed by Congress in 1952, provisions were made for the development of practical means for the economical production of water, from saline sources, of a quality suitable for municipal supply, industrial use, irrigation, and other beneficial uses. Since 1952, progress has been made in developing desalination processes, and under four basic classifications—distillation, membrane, crystallization, and chemical—about a dozen processes are currently under study. Some processes are being used commercially while others have progressed only to the pilot-plant stage.

The progress in technology increases the potential value of the saline ground-water resources of the Texas-Gulf Region. Although the supply of saline water in underground reservoirs has never been determined quantitatively, it is accessible almost everywhere. The depth to saline water ranges from a few tens of feet to several thousand feet, and many of the aquifers in the region that yield fresh water also contain saline water in their downdip extensions. Some of these aquifers are capable of yielding from 100 gal/min (6.3 l/s) to more than 5,000 gal/min (315 l/s) of saline water to wells (Winslow and Kister, 1956; Winslow, Hillier, and Turcan, 1968) either by pumping or by normal flow.

In 1965 and 1967, the Office of Saline Water investigated the potential contribution of saline-water conversion to future water supply in several areas of the Texas-Gulf Region. The study in 1965 (Prehn and Sigafoos, 1966) showed that, at a few of the sites, the unit cost of desalted water, including disposal of the effluent, is less than or about the same as the cost of developing the most feasible alternative fresh-water supply. At the remaining sites, the calculated unit cost of desalted water exceeded the cost of developing conventional supplies.

The study in 1967 (Ralph M. Parsons Co., 1968) in several counties in the western part of the region concentrated on the feasibility of producing 2 to 20 million gallons (7.6 to 76 km^3) per day of water for municipal supply and industrial use. The results indicated that saline ground water in a few of these areas can be desalted at reasonable cost to partly fulfill future needs. A major cost factor was the disposal of the effluent resulting from the conversion process.

The studies concluded that the costs of producing desalted water for municipal and industrial use at some sites may be less expensive than or at least economically competitive with alternative sources. The costs of desalting were considered too high for producing irrigation water.

As of January 1, 1972, at least 14 desalting plants, each with a capacity of 25,000 gallons (95 m^3) or more freshwater daily, were operating in the region for production of freshwater for industrial and municipal use (pl. 3A). Most of these plants were owned by industry. The total daily capacity was 5.66 million gallons (21.400 m^3), and the largest single plant capacity was 2.16 million gallons (8,200 m^3) (O'Shaughnessy, 1973).

USE OF SALINE AQUIFERS FOR LIQUID-WASTE DISPOSAL

The urgency being given to programs for reducing stream pollution and pollution of fresh ground-water supplies is stimulating interest in saline aquifers for use in waste disposal. V. E. McKelvey, Director of the U.S. Geological Survey, in a keynote address delivered in Houston, Texas, December 6, 1971, to a Symposium on Underground Waste Management and Environmental Implications (McKelvey, 1972, p. 1) remarked:

> * * * all our growing activities and interest in underground storage and waste management directly involve the increased utilization of what is becoming an extremely important resource—namely, underground space. * * * I believe there is considerable value in thinking about underground space as a natural resource that needs to be appraised in order that we may understand the role it can play in our economy and thus plan for its wise use.

To this end, successful utilization of underground space is predicated upon developing the capability to predict, with reasonable confidence, the consequences of using this resource (Meyer, 1972). "Proper" disposal underground, which here implies a prior knowledge of all interactions within the injected zone, requires that: (1) the fate of the waste is, in general, known and understood; (2) the waste is contained and can be isolated from man's food, water, and activity; and (3) the waste can be recovered if desired or if the need arises (Hill, 1972a, p. 384).

On the other hand, in the absence of technical ability to conduct underground waste disposal in a safe manner, which may be due largely to deficiencies in knowledege of ground-water hydraulics, geology, and geochemistry, placement of liquid wastes in underground reservoirs can create serious and irreparable hazards (Stallman, 1972, p. 6–10; Piper, 1969). In this case, any one or all of the following consequences may occur (Stallman, 1972, p. 6): (1) pollution of groundwater supplies; (2) pollution of surface-water supplies because waste fluids are discharged by upward leakage into streams; (3) changes in permeability caused by thermal, chemical, and mechanical alterations of the rocks (such changes make it difficult to predict future subsurface flow regions); (4) land-surface subsidence and earthquakes; and (5) possible contamination of mineral resources, including fossil fuel.

In the Texas-Gulf Region, emplacement of liquid wastes in subsurface reservoirs is regulated by State agencies. Each application for disposal is handled individually and conditions are evaluated at each proposed disposal site. Because the Texas-Gulf Region is underlain extensively by relatively thick sequences of saline aquifers, the potential of the subsurface strata for liquid-waste disposal is regarded by Hill (1972b, fig. 1) as generally favorable in most of the region.

Numerous liquid-waste disposal wells are in operation throughout the region. Excluding the subsurface disposal of saltwater from the production of oil and gas, 56 municipal and industrial waste-disposal wells were in operation in 1973, and by that year, a cumulative total volume of about 18 billion gallons (0.068 km^3) of liquid wastes, some containing toxic substances, had been injected into saline aquifers (Texas Water Quality Board, written commun., 1973). About 85 percent of the waste-disposal wells are in the heavily industrialized areas of southeast Texas (pl. 3A).

The petroleum industry pioneered the techniques of waste disposal in underground reservoirs. The East Texas Salt Water Disposal Co., operating in the huge East Texas oil field in the northeast part of the region, began the systematic disposal of saltwater in 1942, after an experimental well drilled in 1936 demonstrated the feasibility of returning saltwater to the oil and gas reservoir. By 1972, about 4.5 billion bbl (0.7 km^3) of saltwater had been returned to the underground reservoir. This operation has been successful both in eliminating saltwater pollution of land areas and freshwater sources and in maintaining reservoir pressure to prolong the productive life of the field (East Texas Salt Water Disposal Co., 1958, p. 10).

Spurred by State regulations banning evaporation pits, the oil industry injects the major part of the saltwater produced in the Texas-Gulf Region. The degree of effectiveness achieved by the industry in disposing of these wastes underground will become increasingly more important in terms of using underground space to protect the surface environment.

USE OF SALINE AQUIFERS FOR FRESHWATER STORAGE

The proposed use of saline aquifers for storing freshwater has promise, under certain conditions, as a method of water management. Basically the process involves artificial recharge, where freshwater is emplaced in saline aquifers for later retrieval.

The utilization of saline aquifers for this purpose has been hindered, until recently, by the lack of a sound basis for predicting possible quality attenuation of the freshwater from repetitive cycles of injection and withdrawal. Mathematical and laboratory models constructed a few years ago showed conclusively that the efficiency of the process—ratio of freshwater recovered to freshwater injected—exceeded 90 percent and improved with the number of cycles of injection and withdrawal (Kimbler and others, 1973, p. 203). Kimbler and others (1973, p. 198) state that potentially, there is an overwhelming economic advantage in using underground-storage space as compared to the construction and use of surface space.

Freshwater was injected and retrieved through a well open to a saline aquifer in 1971 and 1972 by the U.S. Geological Survey at Norfolk, Virginia, in cooperation with the city of Norfolk. The purpose of this experiment was to determine if it would be feasible to use surface water that is surplus to immediate needs, process it in existing treatment plants, and store it underground in saline aquifers. The freshwater would be retrieved when peak demands place severe strains on the water systems.

The results of the study showed that although the permeability of the aquifer was reduced by clay dispersion, chemical treatment of the aquifer could overcome this problem, and that a well field could be constructed and operated economically (Brown and Silvey, 1973, p. 405).

This process could be useful in the flat coastal and estuarial area of the Texas-Gulf Region where the ground water is saline, such as the Galveston area and the Beaumont-Orange area. Old well fields in these areas that are no longer used because of saltwater encroachment might be used for storage and retrieval of highly treated fresh surface water.

Saline aquifers used for injection of toxic wastes would not be usable for freshwater storage at the same locations and depths. Disposal of such wastes generally would be in deeper zones that are not likely to be used as reservoirs for freshwater storage.

PROBLEMS ASSOCIATED WITH GROUND-WATER DEVELOPMENT

Ground-water problems usually result from developing the resources with inadequate knowledge of the geologic and hydrologic framework of the reservoirs. Solution of some of the problems will require the physical means of coordinating surface-water and ground-water storage and use and the removal of legal and economic constraints that prevent the required coordination. Development of ground-water reservoirs in conjunction with surface-water supplies may provide solutions to some problems, mitigate the harmful effects of others, and in some instances prevent their occurrence.

The following discussion of four typical problems of varying degrees of concern in the Texas-Gulf Region indicate the kind of difficulties that may be anticipated where conjunctive planning and development practices are lacking.

DECLINING WATER LEVELS

Declining water levels are inevitable until a steady-state gradient is established. Depending upon the hydraulic characteristics of the aquifer and the rates of recharge and pumping, the declines may be small and temporary or they may be severe and continual.

Severe water-level declines result from two basically different conditions: (1) sustained pumping in excess of captured discharge; or (2) water being withdrawn at a rate greater than the rate of flow through the aquifer at the existing gradient, even though potential recharge in the area may be more than adequate. Examples of these two conditions in the Texas-Gulf Region are the declining water levels on the High Plains, where pumpage exceeds captured discharge from the Ogallala aquifer, and the declining water levels in the Houston area, where potential recharge is adequate but where changing withdrawal rates have not permitted the gradient to stabilize, or enough time has not elapsed at any withdrawal rate for the gradient to adjust throughout the aquifer.

The most serious water-level declines in the region are occurring on the High Plains of Texas and New Mexico, where ground water is being mined from the Ogallala aquifer. The water-level decline in the aquifer represents a decline in the altitude of the water table rather than a decline in pressure, because all of the ground water is being taken from storage by dewatering the reservoir.

The decline of the water table in the Ogallala began shortly after irrigation reached a substantial state of development in the 1930's, and the decline has continued at a rapid rate ever since. The rate of depletion of the reservoir from the middle 1930's to 1973 averaged about 2.5 ft (0.76 m) per year at a site near Plainview, Texas, (fig. 3) and averaged about 1.5 ft (0.46 m) per year at a site in Roosevelt County near Portales, New Mexico. Since 1941 the rates of depletion have increased sharply and the yields of wells have decreased (Cronin, 1964). Conservation measures, in advance of long-range plans for possibly importing water into the area, are already being applied to slow the rate of depletion, but imported water probably will not be available soon enough to prevent large reductions in the irrigated acreage.

The water-level declines in the Houston area, unlike the declines on the High Plains, represent diminishing artesian pressure and not dewatering of the aquifer. In a sense, the artesian head is being mined, as expressed by Lohman (1972, p. 67). Most of the water is being pumped from a part of the Gulf Coast aquifer (Evangeline and Chicot aquifers) where the ground water is under artesian conditions. Although the aquifer is saturated at the outcrop, and is even rejecting potential recharge, the transmissivity of the aquifer is not sufficient at existing gradients to convey the water to the wells rapidly enough to stabilize water levels. Most of the water pumped is coming from and through the clays in the area of the cone of depression.

Although there is no water shortage, the water-level declines at Houston have created serious problems. A representative well in a heavily industrialized part of the Houston area shows that the rate of decline averaged about 8 ft (2.4 m) per year from 1939 to 1973. During this period, depths to water in the well increased from about 90 to 370 ft (27 to 113 m) below land surface (fig. 3). The declines of water levels in other places, especially in the less heavily industrialized sector of the city, have been slightly less severe.

The problems of water-level declines commonly afflict areas where pumping of very large amounts of ground water is concentrated within small areas. The problem may develop inauspiciously at first, but

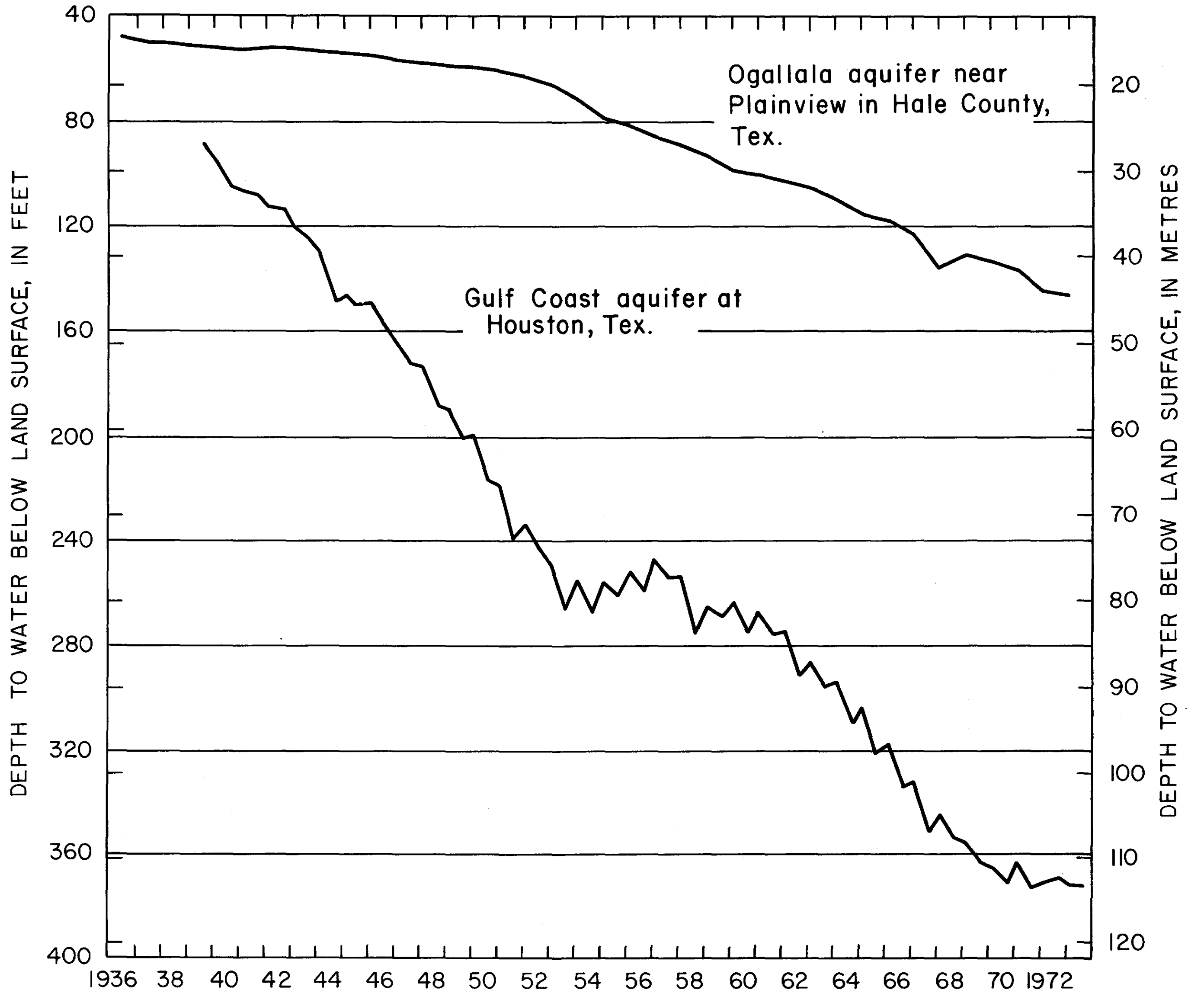

FIGURE 3.—Hydrographs showing water-level declines in the Ogallala aquifer near Plainview, Texas, and in the Gulf Coast aquifer at Houston, Texas.

later becomes significant, even when water supplies are adequate, because the difficulties may include prohibitive pumping costs, saltwater intrusion, and land-surface subsidence.

Distributing the pumping over a comparatively larger area, particularly over an area that includes the principal region of recharge or area of more rapid recharge, would mitigate the problem considerably. In addition to well-field dispersion, a water-management program of conjunctively utilizing ground water and surface water might be beneficial.

DEPLETION OF STREAMFLOW

Ground water and surface water are so interrelater that in most places the withdrawal of ground water will modify the natural regimen of streamflow. In any area where there is hydraulic continuity between the surface-water sources and the ground-water reservoirs, pumping from wells will result in depletion of streamflow; and the surface water that is diverted or intercepted may be required by or belong to downstream users.

The interrelationship of ground water and surface water in the San Antonio area serves to illustrate how ground-water development affects the streamflow. The Edwards (Balcones Fault Zone) aquifer, which is heavily tapped by wells, receives recharge from the streams that flow across the outcrops. Water that is recharged from the streamflow moves rapidly through the cavernous, fractured, and honeycombed framework of the aquifer and then discharges in large springs that sustain the flow of the Frio, San Antonio, Guadalupe, and San Marcos Rivers. The rate of springflow changes rapidly in response to changes in the volume of water in storage in the aquifer, and the volume of water in storage changes rapidly in response to rainfall and pumping rates. Flow of Comal Springs in Comal County, the largest of the springs, fluctuates chiefly from precipitation trends and from changes in pumping rates in San Antonio and Bexar County (Garza, 1962, p. 20).

A continued increase in ground-water development in the San Antonio area, without provisions for increasing the recharge, could result in a reduction of ground water in storage to a degree that could eliminate the flow of the springs, at least part of the time. Cessation of the springflow would substantially reduce the downstream surface-water supply and destroy one of the major esthetic values of the area.

Depletion of streamflow as a result of ground-water development is more subtle elsewhere in the region, and has been detected (or suspected) largely by inference. One such area is on the Gulf Coastal Plain between Houston and Corpus Christi. Heavy ground-water drafts for rice irrigation have caused a gradual lowering of the water table until it is below the stream level of the Lavaca and Navidad Rivers in some places. Although a complete loss of the base flow of the rivers seems remote, a reduction in streamflow probably has occurred (Baker and Follett, 1973, p. 41).

SALTWATER INTRUSION

The movement of poor-quality water into freshwater supplies can be as serious a problem as that of ground-water depletion. A deterioration of water quality may necessitate abandoning wells while there are ample supplies of water in the reservoir. A drawn-down reservoir may fill again by natural processes if pumping is reduced, but dissolved contaminants may be difficult or impossible to remove. Because natural dilution is a slow process, the effects of deterioration of ground-water quality may be long-lasting.

Saltwater intrusion into fresh ground water is the principal cause of ground-water deterioration in the Texas-Gulf Region. This problem is not only currently troublesome, but poses the greatest threat to future ground-water development in some parts of the region. The problem manifests itself to a far greater degree in the coastal areas than elsewhere in the region, and is most acute in southeast Texas from Houston to Orange. In this area, fresh ground water is in sharp contact with saltwater, which may be positioned above, below, or seaward of the freshwater.

Intrusion of saltwater in the Houston-Galveston area is occurring along several fronts in two different zones (Evangeline and Chicot aquifers) in the Gulf Coast aquifer. Regional depressions in the potentiometric surface in the Evangeline aquifer imply that the interface of the fresh and saline water in Harris County is transient and that the saltwater front is moving updip toward the centers of pumping. In the Chicot aquifer, the saltwater front in Galveston County has already invaded the city of Galveston's "old" well field by either lateral or upward movement of the water (Petitt and Winslow, 1955, p. 81). Farther inland, saltwater contamination is occurring in shallow wells in the Chicot aquifer along the Houston Ship Channel, presumably from the intrusion of saline water in the channel.

In the Beaumont-Port Arthur-Orange area, heavy pumping of ground water initiated the deterioration of ground-water quality prior to 1939, and the deterioration is continuing. The pattern of saltwater intrusion, at least in Orange County, indicates that the saltwater front in the Chicot aquifer is advancing laterally toward the center of pumping (Gabrysch and McAdoo, 1972, p. 10).

These examples show that the problems of saltwater intrusion result from development of the water resources. With foresight, the problems might have been prevented or reduced in severity. For example, the creation of pressure ridges, by artificial recharge, during the early stages of development would have provided barriers to saltwater intrusion and would have protected the freshwater supply. Ground-water quality, as well as quantity, must be managed if the supply is to remain suitable, as well as available, for its intended use.

SUBSIDENCE OF THE LAND SURFACE

Conclusive evidence from studies in the Houston area (Winslow and Doyel, 1954; Winslow and Wood, 1959; and Gabrysch, 1969) shows that a decrease in artesian pressure resulting from large withdrawals of ground water creates stresses in the aquifer that cause water to move slowly out of the water-saturated clays and into the interbedded sands. The clays, which are highly compressible, become increasingly compacted, and this in turn results in subsidence of the land surface.

The areas of major subsidence in the Texas-Gulf Region are centered in and around Houston, but subsidence is either known or suspected in other coastal areas of heavy pumping from Louisiana to possibly Kingsville, south of Corpus Christi.

In Houston, the increasing draft of ground water which causes the progressive lowering of artesian pressures is enlarging the subsidence bowl in depth and lateral extent. Between 1943 and 1973, the land surface subsided a maximum of about 7.5 ft (2.3 m) near the Houston Ship Channel, while in parts of eight counties in southeast Texas, subsidence was at least 0.5 ft (0.15 m) (fig. 4). Subsidence prior to 1943 in the area of the Houston Ship Channel was about 2 ft (0.6 m), which added to the 7.5 ft (2.3 m) that occurred between 1943 and 1973 makes a total of 9.5 ft (2.9 m) of subsidence in that area (Gabrysch and Bonnet, 1974). Subsidence will continue if the decline in artesian pressures continues, and even if the pressure could be maintained at its present level, the land surface would nevertheless subside a few additional feet near the center of the cone of depression.

Some of the effects of subsidence in Houston and surrounding areas are severe. Some buildings have been cracked, roadways have been damaged, well casings and pipelines have been damaged, and waterlogging has increased the cost of construction and repairs. Some waterfront properties are now flooded by normal high tides and are subject to inundation and destruction by hurricane tides. Efforts to minimize the subsidence problem will necessitate a decrease in the rate of artesian-pressure decline, which can be accomplished only by reducing the ground-water draft or by recharging the aquifers.

Subsidence in the other coastal areas is much less severe. In the urbanized Beaumont-Port Arthur-Orange area, subsidence has been generally less than 0.5 ft (0.15 m) between 1918 and 1973, but it is expected to continue if there is a continued decline in water levels. In rural areas between Houston and Corpus Christi, the land surface is subsiding from large ground-water withdrawals for rice irrigation. In Jackson County, land-surface subsidence to 1972 has been as much as 1 ft (0.3 m), and is expected to continue at annual rates estimated to range from 0.012 to 0.026 ft (0.004 to 0.008 m) (Baker and Follett, 1973, p. 32, 34). In these rural areas, the subsidence is fairly well distributed, which minimizes the undesirable effects. Changes in the land slope, however, will affect the drainage patterns and stream gradients to some extent.

POTENTIAL FOR OBTAINING ELECTRICAL ENERGY AND FRESHWATER FROM THE GEOPRESSURED RESERVOIRS

Studies by Jones (1969) and others and information obtained from drilling operations for oil and gas have shown that thousands of square miles of the Coastal Plain are underlain, at depths of 6,000 to 20,000 ft (1,800 to 6,100 m), by ground-water reservoirs containing zones of extremely high pressures and temperatures that have been termed "geopressured reservoirs" (Dickinson, 1953).

Geopressured reservoirs occur in the Texas-Gulf Region in part of the Coastal Plain in an area that extends from near the edge of the continental shelf to 50 to 150 mi (80 to 240 km) inland from the coastline (pl. 3B). Within this area, the principal ground-water reservoirs that are geopressured are the downdip extensions of the Carrizo-Wilcox aquifer and the Gulf Coast aquifer. Geopressured reservoirs may underlie other areas in the Texas-Gulf Region, but their presence is mostly a matter of speculation at this time.

The most significant aspects of these geopressured reservoirs are the relatively low salinity of the water, the unusually high temperature and water pressure, and the content of natural gas in solution in the water. Below depths of several thousands of feet, a progressive freshening of the ground water with depth in the geopressured reservoirs is typical. The dissolved-solids content commonly decreases vertically downward from more than 100,000 mg/l to less than 10,000 mg/l, and is less than 5,000 mg/l in some places. In some areas at depths greater than 6,000 ft (1,800 m), the water is reported to contain less than 1,000 mg/l dissolved solids, while highly saline water occurs both above and below the freshwater (Jones, 1969, oral commun., 1974).

Abnormally high geothermal gradients and water pressures accompany the relatively low salinities. Drainage restrictions imposed on the water-bearing deposits by growth faults (faults that have been more or less continuously active) and chemical changes are probably responsible for the high pressures and temperatures in the geopressured reservoirs.

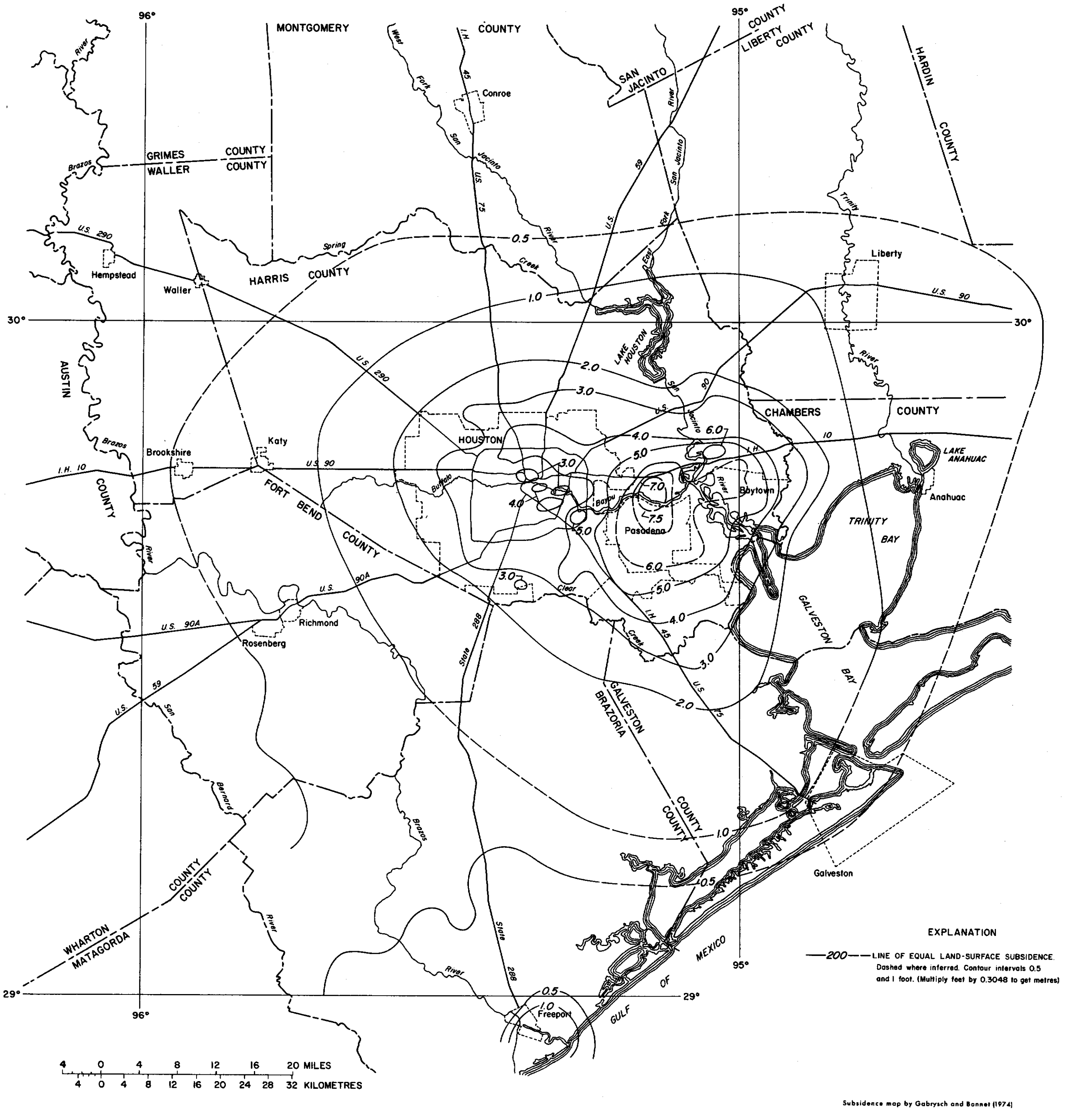

FIGURE 4.—Map showing land-surface subsidence in the Houston area, 1943–73.

A typical increase in the geothermal gradient in a well pentrating a geopressured reservoir in south Texas is shown on figure 5. Geothermal gradients within the reservoirs are as much as 3.4°C (6.2°F) per 100 ft (30.5 m) (Jones, 1969). Minimum temperatures of water in the geopressured reservoirs generally range between 80° and 120°C (176°–248°F) near the tops of the reservoirs; maximum temperatures are a matter of speculation because the reservoirs may be geopressured to the zone of metamorphism or to the ultimate depth at which fluids are free to move (Jones, 1970). The highest temperature recorded in the Texas-Gulf Region was 273.6°C (525°F) at a depth of 19,222 ft (5,859 m)

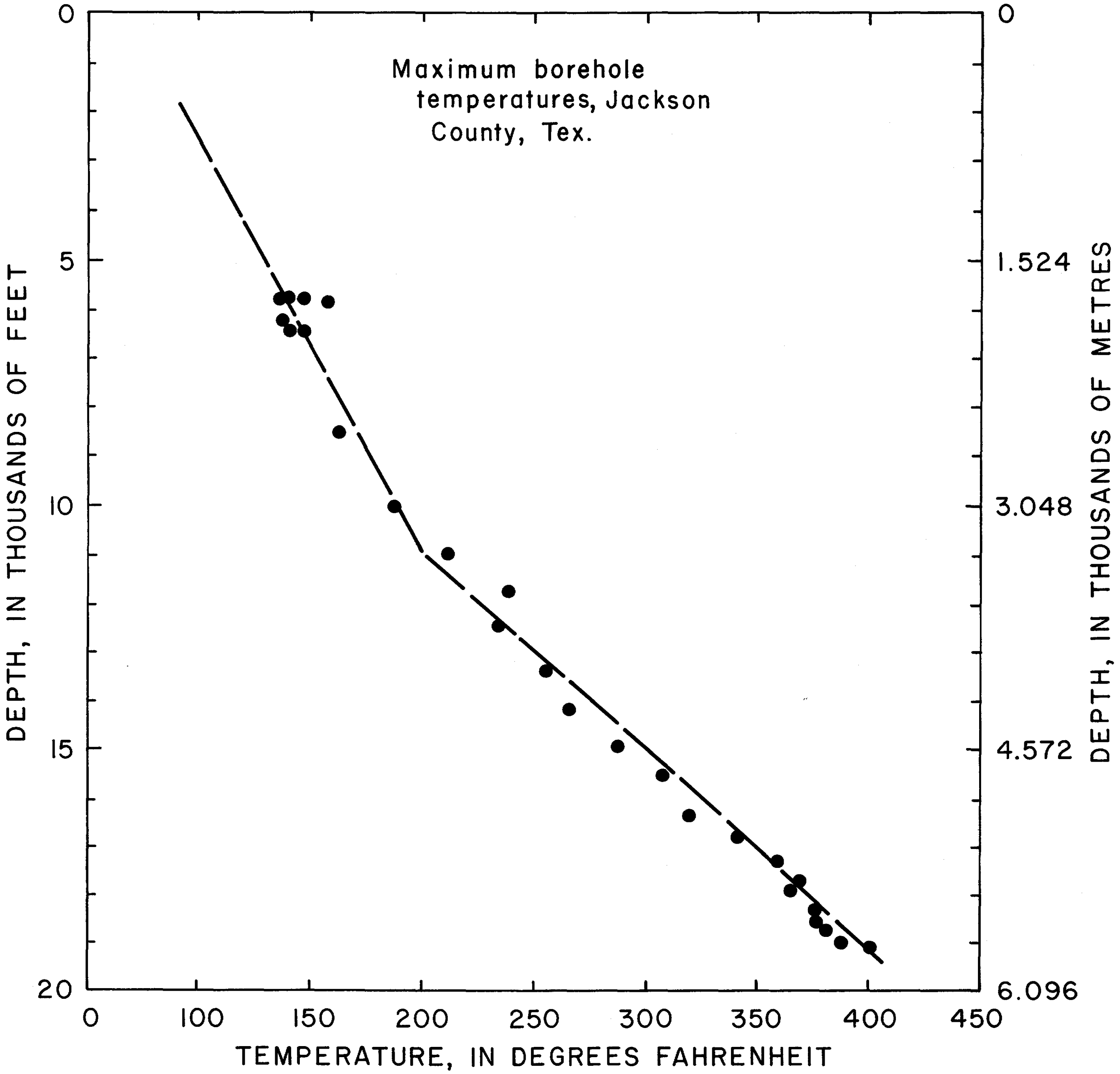

FIGURE 5.—Graph showing thermal gradient in the geopressured zone.

in a well in Matagorda County between Houston and Corpus Christi (Hough and Couvillion, 1966).

Water pressures in wells tapping the geopressured reservoirs range from a few hundred to as much as 500 atmospheres (7,350 pounds per square inch or 517 kilograms per square centimetre) or more at the land surface (Stuart, 1970). This is equivalent to static heads of more than 15,000 ft (4,570 m) above land surface.

The geopressured aquifers may be potentially important for the generation of electrical power and the production of freshwater by desalting. Electrical power might be generated by exploiting the three forms of energy inherent in the water: geohydraulic energy from high-pressured flow at the surface, thermal energy from the heat content of the water, and natural gas in solution in the water. However, research is needed in geothermal-power production and generation equipment as well as detailed studies of the geopressured reservoirs before the economic feasibility can be evaluated and any development of the resource can take place within the region.

CONSTRAINTS ASSOCIATED WITH THE DEVELOPMENT OF GROUND-WATER RESOURCES

WATER RIGHTS

The two major doctrines of water law in the United States—the common-law doctrine of riparian rights and the doctrine of prior appropriation—are observed in the Texas-Gulf Region. These doctrines, which evolved in respect to surface water but have subsequently been extended to ground water by case law or by statute, are based on the conflicting but fundamental principles of private versus public ownership of the water.

In Texas and Louisiana, which adhere to the common-law doctrine, ground waters are private and are not subject to appropriation by the State. The waters are subject to capture and use by the owners of the surface rights, their agents, or assignees. Louisiana exercises no regulation in any form, and Texas exercises no regulation except as provided by the establishment of ground-water conservation districts, which are local and completely autonomous after establishment. New Mexico invokes the doctrine of prior appropriation. Under this concept, the ground waters are public and subject to appropriation in accordance with the law.

The adherence to one or the other of these water laws and regulations was basically influenced by the climatic environment of the State. In the arid to semiarid parts of the West, the dependence of agriculture and other businesses upon the limited supply gave water a high value, and led to the necessity of imposing appropriate constraints on water development. Conversely, in the humid or subhumid East, the needs of most water users were readily satisfied within a legal framework of little or no constraint. Despite the fact that Texas has both climatic environments, the one doctrine of common-law rights applies Statewide to the ground-water resources.

To cope with excessive competition for limited supplies of ground water in the semiarid parts of Texas, or to resolve other ground-water controversies, the State currently resorts to limited regulation of ground-water use in some areas. It authorizes groups of water users to form underground-water conservation districts for the regulation of well spacing and production and for the preservation, protection, recharging, and prevention of waste of the ground water from an aquifer.

Under Texas law, an aquifer that is proposed to be regulated must have ascertainable boundaries and must be capable of yielding at least 150,000 gallons (568 m^3) per day to a well. Wells producing less than 100,000 gallons (378 m^3) per day are not regulated, so far as withdrawal is concerned. The act creating the underground water districts was amended in 1973 (House Bill 935) primarily to allow for the control of land-surface subsidence caused by withdrawal of ground water.

By 1974, two underground-water conservation districts were operating in the Texas part of the Texas-Gulf Region, one to regulate development of a major part of the Ogallala aquifer on the High Plains and the other to regulate development of the Edwards (Balcones Fault Zone) aquifer in the San Antonio area.

In New Mexico, the doctrine of prior appropriation allows the State's waters to be appropriated for beneficial use within the State. Although the ground water is public, no permit or license to appropriate ground water is required except in designated or declared basins. The declaration of an area by the State Engineer as an "underground water basin" thus enables the State to control orderly development of ground water in order to protect prior water rights—for example, to protect senior ground-water rights in areas of overdraft. By 1974, two underground-water basins had been declared by the State in the New Mexico part of the Texas-Gulf Region and were operating to control development of the Ogallala aquifer on the High Plains.

TECHNOLOGICAL PROBLEMS

Various deficiencies in scientific knowledge, procedures, and equipment, or in many instances failure to use present technological capabilities, continue to impede progress in utilizing the ground-water reservoirs to their full potential. Advances have been made, especially within the past 2 decades, in water-related research, but the increasing requirements for water and the complex problems that are caused by fulfilling these needs reveal the desirability of continued technological improvement.

Innovative methods and techniques of combating the problems related to full use of both the freshwater and saline-water resources should be developed and perfected. The lack of adequate funding, however, probably constitutes the basic constraint to technological advancement.

One field of research that has experienced technological problems for years is that of artificial recharge, especially recharge by wells. Laboratory research and experimental efforts have shown that the process is complicated by problems ranging from the quality of the recharge water to permeability reductions in the aquifer. Scientific progress may eventually solve these problems, but until they are resolved, the benefits to be derived from artificial recharge will necessarily be delayed.

Technological and economic problems in desalinization continue to restrict this process from being used to good advantage where freshwater is scarce. Research is continuing, and improvements are being made both in procedure and equipment; but until significant technological advancements are achieved, the economic feasibility of the process prevents widespread use of the large supplies of saline water.

NEEDS FOR ADDITIONAL INFORMATION ON GROUND-WATER RESOURCES

To preserve the economy of the Texas-Gulf Region and to provide for future water demands, it will be necessary to conduct water-resources investigations that yield information geared to present and anticipated water development.

A full presentation of the deficiencies in information is beyond the scope of this report, but some of the most important needs, as they apply to the Texas-Gulf Region, are as follows:

1. *Evaluation of aquifers and aquifer systems employing digital or electric-analog models.*—Such models would be used to analyze the effects of future conditions of pumping and would serve as tools for gathering the information needed to formulate long-term plans for ground-water management. In addition to these applications, the use of highly sophisticated models, as stated by Moore (1971), could optimize management objectives within specified physical, economic, and social constraints, which makes it possible to integrate use of ground water into water-resource planning with a high degree of certainty. The effectiveness of models in local areas has already been demonstrated. (See Wood and Gabrysch, 1965; Jorgensen, 1974).
2. *Determination of the amount of natural discharge from the aquifers that is subject to capture.*—Computations of long-term availability of ground water are generally being made with inexact knowledge of the rate of discharge. In some areas, the rates of withdrawal should be no more than the rates of natural discharge subject to capture. As an approach to this problem, such studies should relate the base flow of streams that drain the recharge areas of the aquifers to fluctuations of water levels in shallow wells. These studies will require a more detailed knowledge of aquifer coefficients in the recharge areas and a better understanding of the movement of water in these areas.
3. *Information on diffusion and dispersion in relation to transport of pollutants from surface disposal of wastes.*—This is an in-increasingly important field of study as development increases and wastes are discharged onto the land surface or into surface-water bodies from which the pollutants can enter the ground-water subsystem. A good example is the study of the subsurface effects of sewage disposal by septic tanks. Such studies will provide a basis for effective water-quality management.
4. *Determination of potential contamination and other problems associated with underground storage of water.*—Liquid wastes in unprecedented quantities are being injected into saline aquifers because of stringent controls on disposal to streams. Knowledge is required regarding the geologic, geochemical, and hydrologic factors related to injection processes; waste mobility; quality attenuation; and degree of containment.
5. *Intensified research and testing to determine the potential of the geopressured reservoirs to produce electrical energy.*—Regional studies of the geopressured aquifers will permit an appraisal of the extent and magnitude of the geothermal energy that might be developed, and will identify possible detrimental effects of development. The geologic properties of the aquifer materials, especially the clays, need to be determined for predicting land-surface subsidence; observation wells need to be drilled; and possibly a prototype production well could be designed and drilled.
6. *Additional information on saltwater encroachment in the Gulf Coastal Plain.*—Studies of saltwater encroachment will be necessary before measures can be taken to protect fresh ground-water supplies in the heavily industrialized and populated cen-

ers along the Gulf Coast. To map accurately the saltwater fronts and to monitor their advancement toward centers of pumping, a network of properly located observation wells of various depths should be established.

7. *Additional information on land-surface subsidence along the Gulf Coast.*—Additional research on the mechanics of land-surface subsidence must be made to allow more accurate predictions of future subsidence. Significant technological progress has already been made through studies in the Houston area, but this research needs to be refined and expanded to accommodate different geologic and hydrologic conditions in other areas of known or suspected subsidence.
8. *Development of techniques for artificial recharge.*—The importance of this field of research should be emphasized because its potential for application in the Texas-Gulf Region is widespread. It is possible that many problems relating to overdraft of ground-water supplies, such as saltwater encroachment, land-surface subsidence, underground storage of surplus freshwater, and disposal of liquid wastes could be reduced by development of practical and economical methods of artificial recharge. Research, with an interdisciplinary approach, directed toward descriptions of the geologic environment, hydraulics, geochemistry, bacteriology, engineering details for an entire management scheme, and economics of the recharge system would have the potential for answering many questions.
9. *Determination of the amount of water in storage in the ground-water reservoirs, especially the Edwards (Balcones Fault Zone) aquifer.*—Complete and accurate appraisals of the quantity of water in storage in ground-water reservoirs are needed by water planners concerned with eventual conjunctive management of the ground-water supply with water from other sources.
10. *Studies of the relationship of ground water and surface water to determine the effects of aquifer development on surface flow.*—Water planners are becoming increasingly aware of the significance of the relationship between ground water and surface water, and the extent to which one affects the other must be determined. A water plan that presupposes total development of the ground-water resources in a manner that captures all discharge should include reassessment of the surface-water resources in terms of possible reductions in streamflow.

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