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Environmental Protection Technology Series

Ground Water Pollution in the South Central States

National Environmental Research Center

Office of Research and Monitoring

U.S. Environmental Protection Agency

Corvallis, Oregon 97330

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EPA-R2-73-268
June 1973

GROUND WATER POLLUTION

IN THE SOUTH CENTRAL STATES

by

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ABSTRACT

An investigation was conducted to determine the present and potential ground-water pollution problems of Arkansas, Louisiana, New Mexico, Oklahoma, and Texas, to locate problem areas and to suggest research and other methods to prevent or control future pollution and reclaim contaminated areas.

Mineralization due to natural causes is the most influential factor on ground-water quality in the five-state area. Large quantities of saline ground waters are located throughout the region, and some of this returns to the surface as springs over large areas of the Permian Basin. Oil-field activities are overwhelmingly the greatest man-made cause of ground-water pollution in the area. Disposal of oil-field brines combined with hundreds of thousands of improperly completed and plugged oil and gas wells and test holes has polluted a great, though undetermined, amount of ground water throughout the region. Overpumping has resulted in salt water intrusion of inland ground waters, as well as ground waters along the Gulf Coast of Louisiana and Texas. Water well construction in some areas has permitted pollutants from the surface and from other formations to enter fresh water aquifers, and irrigation return flows have increased the mineralization of ground waters in the Pecos and Rio Grande Basins.

CONTENTS

Section		Page

FIGURES

TABLES

SECTION I

CONCLUSIONS

1. Ground water is the major source of water supply for western Texas and Oklahoma and most of New Mexico and is the only source of water in much of this area.

2. Many of the western aquifers are being developed beyond the "safe yield," and water tables are falling rapidly.

3. Because of this critical shortage of water resources in the western half of the project area, any contamination of fresh water has an immediate and long-lasting effect.

4. More ground water in the five-state region is contaminated through natural processes of mineralization than all other sources of pollution. Saline ground water can be found at some depth under almost all of the region. Chlorides are the most widespread contaminant, but sulfates, nitrates, fluorides, and iron are also common natural contaminants.

5. Pollution from oil-field brines is the most serious form of man-made pollution in the five south-central states. Decades of oil production combined with inadequate well construction and minimal limitations on brine disposal methods have grossly polluted the ground-water resources of many areas of the five states--especially in Texas and Oklahoma.

6. Although most or all of the subject states have for many years required plugging and sealing of oil and gas test holes, thousands of such improperly plugged holes blanket the region and provide avenues of pollution from a variety of sources--most notably oil-field brines and natural brines. Until the last few years, very little effort has been made by the states to enforce plugging regulations, and even now these requirements are enforced sparingly by some states in this region. At least some of this reluctance to enforce proper well construction and abandonment is because the state agencies reponsible are more related to petroleum production than to pollution control.

7. Overpumping is a serious cause of salt water intrusion in many sections of the region. Ground waters most seriously affected are located along the Gulf Coast of Texas and Louisiana--especially the Houston and Baton Rouge areas--and along the Pecos River in Texas and New Mexico.

8. Irrigation return flows contribute to mineralization of ground waters in the Pecos and Rio Grande Valleys of New Mexico and Texas because of the close interrelationship of ground and surface waters in this region and the limited water supply.

9. With the increased restrictions on air pollution and waste discharge to surface waters, application of wastes--both solid and liquid--to land is becoming increasingly popular. Care must be exercised in locating, designing, and loading disposal or treatment areas so as to prevent contamination of ground water by known or unknown leachates.

10. Evapotranspiration by native vegetation contributes to increased mineralization of ground waters in the western part of the five-state region--primarily in the Rio Grande and Pecos River Basins.

11. Most large feedlots in the region are located in the Texas and Oklahoma panhandle where water tables are deep and aquifer recharge from the surface is small. It is unlikely that these feedlots are a threat to large areas of ground water but animal wastes can be a local source of contamination, depending on the geology, soil conditions, and depth to the water table.

12. Waste lagoons may or may not be a problem, depending on the geology and soil conditions and type of waste involved. Generally, sewage lagoon pollution is limited to increased nitrate concentrations in the ground water unless these lagoons overlie fractured or cavernous formations. On the other hand, industrial waste lagoons may contain known and unknown chemicals which may be highly toxic and/or highly mobile in ground water.

13. Petroleum products have been found in ground water at several locations and represent a constant hazard because of their widespread use, production, and transportation in the project area.

14. There has been little work done concerning ground water pollution by organics, metals, bacteria and viruses. Consequently, the true pollutional potential of many of man's activities cannot be fully evaluated.

15. The subsurface injection of fluids and other substances poses an existing and potential threat to ground-water quality. Records of such injection are not adequate in some states.

SECTION II

RECOMMENDATIONS

1. Conduct investigations, similar to those reported herein, to identify ground-water pollution problems in all the remaining parts of the United States.

2. In cooperation with the various states, the Environmental Protection Agency should identify, develop, and establish quality control criteria to protect ground-water quality throughout the United States.

3. A comprehensive study is needed of the Pecos and Rio Grande Basins to evaluate water resources, uses and needs, and the effect of these uses and natural salinity on ground and surface water quality and quantity, and to develop a long-range plan of water use within the "safe yield" of both ground and surface water supplies.

4. Sources and locations of significant natural pollution should be identified and isolated, if possible, to protect adjacent fresh water from contamination.

5. Areas of ground-water pollution from oil field brines should be located and mapped. Efforts should be made to assign responsibility for the pollution, extract damages from those responsible, and to rehabilitate the contaminated aquifers.

6. A concentrated effort should be made to locate and plug abandoned oil and gas test holes. Some of the remote sensing techniques may be applicable to this problem.

7. The disposal of wastes below the surface should be a responsibility of the state water pollution control agency.

8. Rules and regulations for completing water wells should be developed and enforced in those states that now have no such regulations for protecting water supplies.

9. Areas where geology, soil conditions, or high water tables, or any combination, are conducive to rapid ground water recharge from the surface should be identified. Surface activities such as feedlots and discharge of wastes to land or unlined lagoons should be restricted.

10. Expand research efforts aimed at solution of the high priority needs with emphasis on those problems most likely to achieve the most valuable impact. For detailed research recommendations, refer to Section VII herein.

11. There is a need for states to maintain detailed records of the subsurface injection of fluids and other materials.

12. Techniques of adequately monitoring the travel of pollutants through the subsurface environment should be developed and applied to safeguard ground-water resources.

SECTION III

INTRODUCTION

About 97 percent of the earth's fluid fresh water is ground water and ground water is used as a water supply by about two-thirds of the people in the United States.1/2/ To preserve this most valuable natural resource, a national program of ground-water quality protection and restoration is a necessity. A major need in developing such a program is a definition of ground-water pollution problems and potential problems and the scope and significance of each. This report is designed to outline the ground-water problems of five south-central states (Arkansas, Louisiana, New Mexico, Oklahoma and Texas), to indicate the extent of the problems and their relative priority to the region, and to suggest possible measures for the renovation of contaminated supplies and the protection of uncontaminated supplies. Four southwestern states were studied in a previous report and the rest of the United States will be covered in subsequent reports.2/

Much ground-water pollution results from natural phenomena that takes place over long periods of time but there is also a great deal of pollution resulting from careless or deliberate acts of man. It is also important to consider that ground water and surface water are hydrologically related and interdependent and that ground water may be polluted by surface water or ground water may pollute surface water. Whatever the cause, ground-water pollution usually takes place slowly. Because ground water movement is very slow, it may take many years to pollute a large volume of ground water. However, once the ground water is polluted, it may also take many years, decades, even centuries, and untold cost to restore the quality of the water after the source of pollution is removed. Therefore, prevention of ground-water pollution is much more desirable than renovation and both require a thorough understanding of the uses of ground water, location of ground-water resources, and real and potential pollution sources.

Use of Ground Water

Ground water supplied about one-fifth of all water used in the United States during 1970. This ratio of ground water to total water use varies widely from one region to another, with the greatest ground-water use being in the central and western states. In the five states of this report, 57 percent of total fresh water used is ground water. Only in Louisiana is there significantly more surface water than ground water used. Table 1 and Figure 1 show the use of water withdrawn from the project area.3/

Table 1. WITHDRAWAL USE OF WATERS IN 1970 (MGD)[3]

	Public Supply	Rural Supply	Industrial*	Irrigation	Total
Arkansas					
Surface Water	95	19	200	230	544
Ground Water	71	64	330	1100	1565
TOTAL	166	83	530	1330	2109
% of Total from Ground Water	42%	77%	62%	82%	74%
Louisiana					
Surface Water	240	11	2900	780	3931
Ground Water	140	78	460	770	1448
TOTAL	380	89	3360	1550	5379
% of Total from Ground Water	36%	87%	14%	49%	28%
New Mexico					
Surface Water	16	33	14	1500	1563
Ground Water	130	29	72	1300	1531
TOTAL	146	62	86	2800	3094
% of Total from Ground Water	89%	46%	84%	46%	49%
Oklahoma					
Surface Water	190	50	95	99	434
Ground Water	72	31	32	720	855
TOTAL	262	81	127	819	1289
% of Total from Ground Water	27%	38%	25%	87%	66%
Texas					
Surface Water	740	52	1200	2500	4492
Ground Water	690	190	480	7800	9160
TOTAL	1430	242	1680	10300	13652
% of Total from Ground Water	48%	78%	29%	75%	67%
GRAND TOTAL	2384	557	5783	16749	25523
% of Grand Total from Ground Water	46%	70%	24%	69%	57%

*Does not include saline water or water used for thermoelectric power.

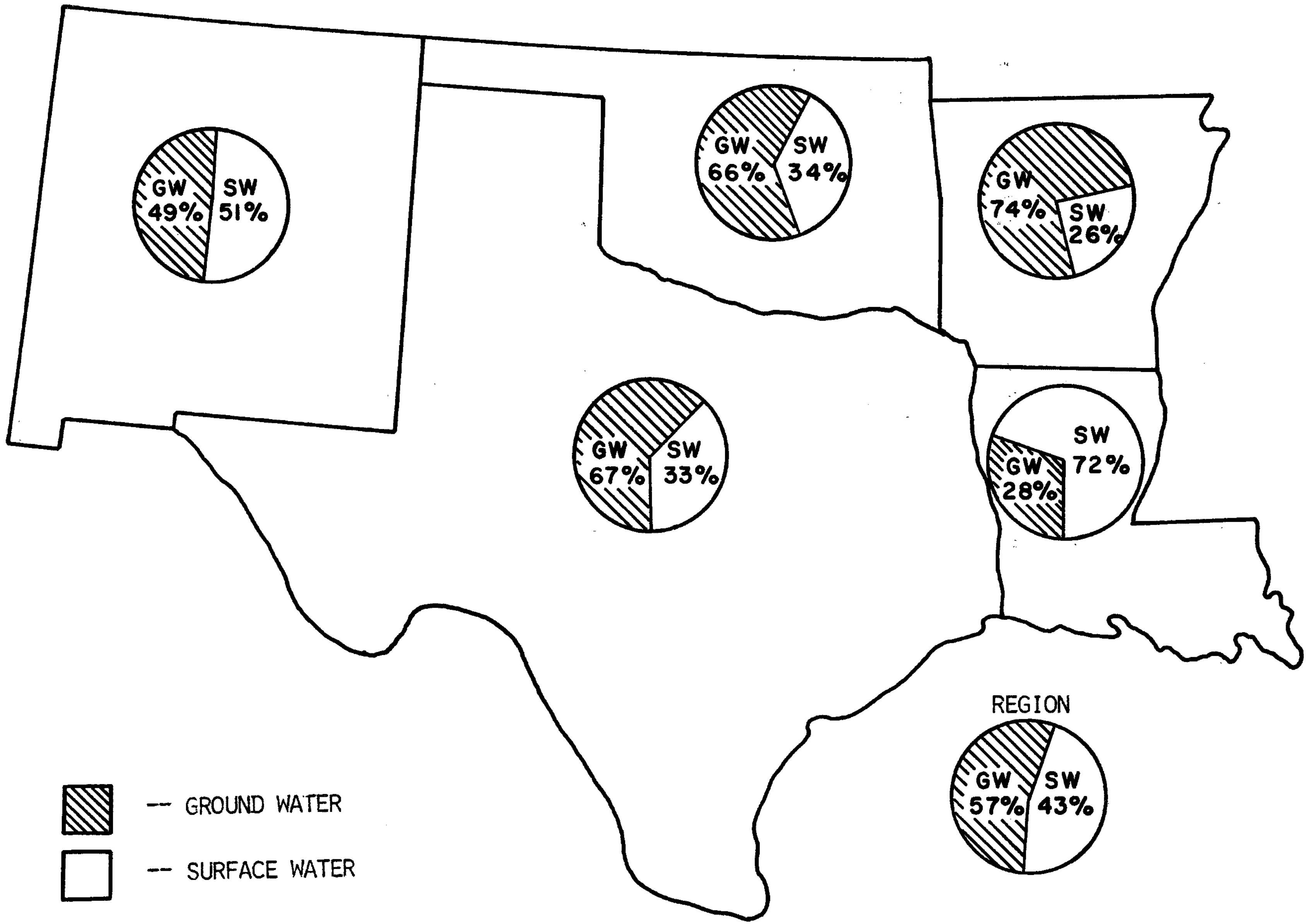


FIGURE 1. COMPARISON OF GROUND-WATER USE TO SURFACE-WATER USE IN 1970 3/

Public Water Supply--includes all water entering public supply systems. The water is used for many different purposes including industrial, domestic, livestock, military and governmental facilities.

In 1970, ground water constituted about 35 percent of the water in public supply systems in the United States. However, in the five states discussed here, ground water accounted for 46 percent of the water withdrawn for public supply. Large cities such as Albuquerque, Amarillo, Baton Rouge, El Paso, Galveston, Lubbock, Midland, and San Antonio relied wholly on ground water; other large cities obtained a significant part of their supply from ground water. Houston, for example, obtained about 75 percent of its supply from wells. A large percentage of the smaller cities and towns have ground-water supplies. In 1962, Texas had 1,326 municipal supplies using ground water, or about 90 percent of all municipalities in the state.

Rural Supplies--provide water for domestic and livestock use on farms, ranches, and residences throughout the United States. Indeed, the development and expansion of the country has been closely related to the availability and development of ground water to meet farm and ranch needs. About 98 percent of the rural domestic use in the project area is ground water. About 70 percent of all rural water used, including that for livestock, is from this resource.

Industrial Supplies--provide water for cooling, processing, washing, sanitizing, etc. The amounts provided for industrial use by public supplies are not included as industrial supplies. It is estimated that 70 percent of all industrial water is used for cooling.

Thermoelectric Power Supplies--provide water for coolers, boilers, and sanitary purposes in fossil and nuclear fueled power plants. Approximately 97 percent is used for cooling to condense steam. Since less than 1 percent is consumed, this use is not included in Figure 1 or Table 1.

Irrigation Supplies--consume more water than any other use in the United States. In 1970, irrigation use in the United States was 140 million acre-feet, of which about 60 percent or 82 million acre-feet were consumed. Figure 2 shows the percentages of ground water and surface water used for irrigation in the project area. In these states, 69 percent of all irrigation use is ground water.

Air Conditioning--use is not well documented since much of the water used for this purpose is taken from supplies used for other purposes. The quantities of water used for air conditioning are included in public and industrial supplies.

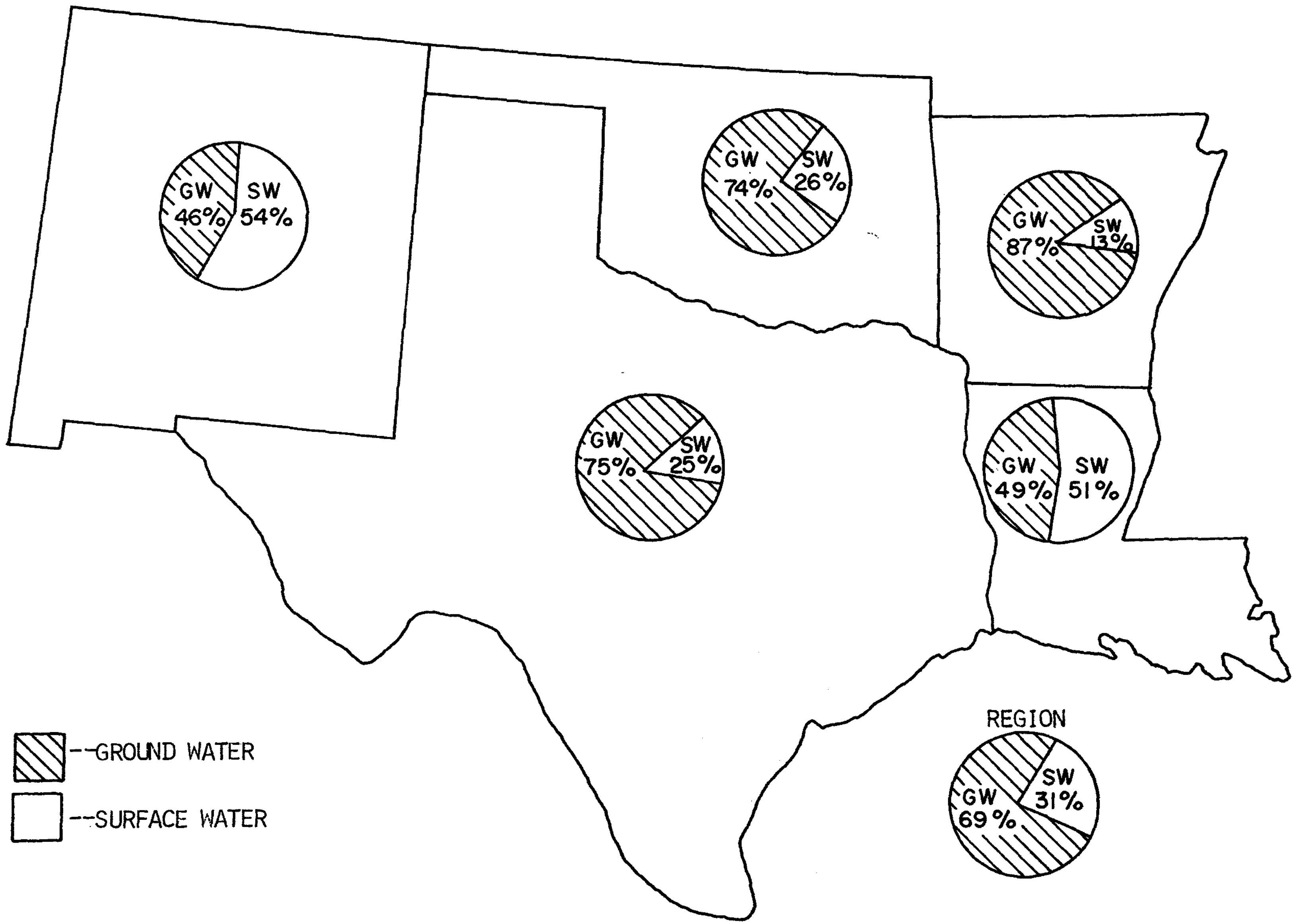


FIGURE 2. COMPARISON OF GROUND-WATER TO SURFACE-WATER IRRIGATION USE IN 1970

Future Use

The future use of water in the United States was projected by the Senate Select Committee on National Water Resources in 1960.4/ Their projections are summarized in Table 2. Usage is expected to double by the year 2000 and although the projection may lack precision, it is certain that there will be a large increase in the use of water and that much of the increase will come from ground water. Several predictions concerning this increase have been reported by McGuiness.5/ Even the most conservative of these involves a threefold increase by 2000 and the least conservative, a tenfold increase. From these predictions, the use of ground water will more than double between 1960 and 1980 and will increase almost five times by the year 2000. Regardless of the accuracy of these predictions, it is certain that ground water will be of increasing importance in coming years, and care must be taken to protect it and develop it for the maximum benefit to all.

Table 2. WATER USE IN CONTERMINOUS UNITED STATES IN BILLION GALLONS PER DAY

	1954		1980		2000	
	With-drawal	Consump-tive Use	With-drawal	Consump-tive Use	With-drawal	Consump-tive Use
Public Supply	16.7	2.1	28.6	3.7	42.2	5.5
Industry (Mfg)	31.9	2.8	101.6	8.7	229.2	20.8
Irrigation	176.1	103.9	167.2	104.5	184.2	126.3
Subtotal	224.7	108.8	297.4	116.9	455.6	152.6
Steam-Electric (Cooling)	74.1	0.4	258.9	1.7	429.4	2.9
TOTAL	298.8	109.2	556.3	118.6	885.0	155.5

SECTION IV

DESCRIPTION OF PROJECT AREA

The project area includes the states of Arkansas, New Mexico, Oklahoma, Louisiana, and Texas. Within this region are vast stretches of desert, high mountain ranges, great agricultural areas, and large swamps along the Gulf Coast. The project area is composed of 560,000 square miles, or about 16 percent of the fifty United States. Water use in this region was over 25 billion gallons per day in 1970, of which 57 percent was taken from ground-water sources.

Physiography

The project area is characterized by the widest variation in physiographic features. From the towering Rocky Mountains in New Mexico, the project area flattens out and descends eastward as it nears the lowland on the Gulf of Mexico.

Using the classification of Thomas who divided the United States into ten ground-water regions, the project area includes parts of six of the basic ground-water regions (Figure 3).6/

1. Western Mountain Ranges
2. Alluvial Basins
3. Colorado Plateaus
4. High Plains
5. Unglaciated Central Region
6. Gulf Coastal Plain

Only a small part of the project area is in the Western Mountain Ranges, the Colorado Plateaus or the Alluvial Basins. However, the Alluvial Basins are very important to New Mexico where the Rio Grande Basin overshadows all other sources of ground water in the state. The Gulf Coastal Plain is the ground-water region that contains the most extensive ground-water reservoirs in the project area.

Once out of the foothills of the Rocky Mountains, the area becomes topographically a series of plains. These plains gradually slope eastward from elevations approaching 6,000 feet in eastern New Mexico to sea level at the Gulf of Mexico.

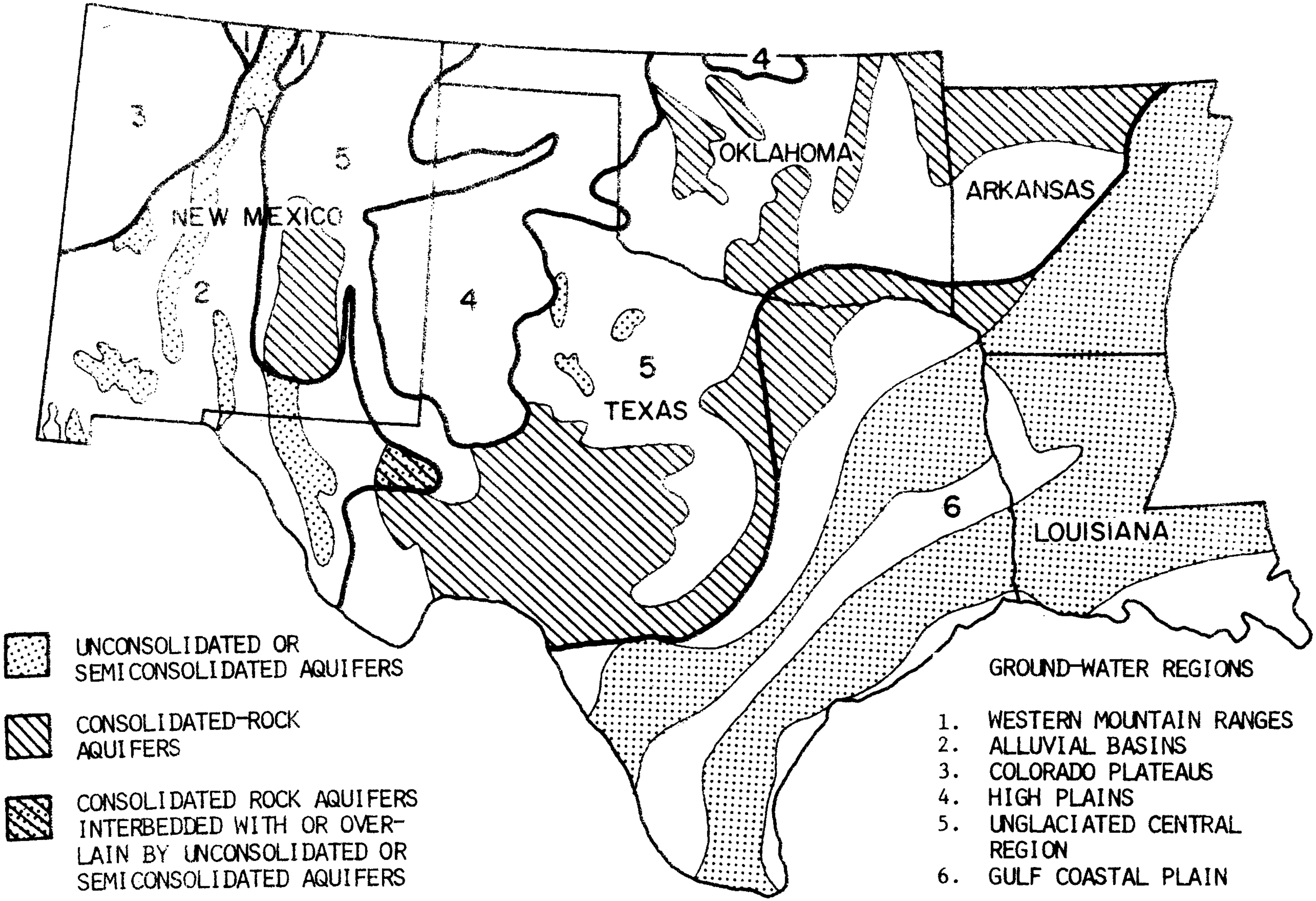


FIGURE 3. GROUND-WATER REGIONS IN THE SOUTH CENTRAL STATES [6/]

The High Plains of eastern New Mexico, the Oklahoma panhandle, and western Texas are relatively flat portions of a physiographic province known as the Great Plains, which stretches north all the way to Canada and covers a vast area of the central United States. Elevations characteristically range between 2,500 and 5,000 feet and are almost completely without erosion.

Just east of the Cap Rock Escarpment, which is the eastern boundary of the High Plains, part of the unglaciated Central Region known as the Osage Plains sweeps from the Edwards Plateau on the south across part of north central Texas and most of Oklahoma. Limestone once formed a continuous cover over all of this area, and the extent of erosion determines the topography of the region. The limestone of the Edwards Plateau on the south is intact although deeply disected and consists mostly of brushy hills and canyons.

To the north, the limestone of the Osage Plains has been eroded away as has much of the underlying rocks. This area is generally characterized by slightly rolling, exposed beds of clay and shale and light timber and scrub brush.

The Gulf Coastal Plain includes almost the southeast half of Texas and Arkansas and all of Louisiana. This region is bounded on the west by the Balcones Escarpment, a fault zone which runs east and then north from Del Rio, Texas, all the way to the Red River. Most of the area is gently rolling with rich-soiled prairies on the west, heavy timber land in east Texas and northwest Louisiana, and level coastal prairie and marshlands along the Gulf of Mexico and the Mississippi River.

Population

The project area includes some of the largest metropolitan areas in the United States, as well as some of the most sparsely populated desert areas. The total population is currently almost 20 million people, as shown in Table 3.

Table 3. POPULATION OF FIVE SOUTH-CENTRAL STATES

	1960	1970
Arkansas	1,786,272	1,886,210
Louisiana	3,257,022	3,564,310
New Mexico	951,023	998,257
Oklahoma	2,328,284	2,498,378
Texas	9,579,677	10,989,123

Climate

The climate of the five-state region is as variable as the elevations within the area. Annual rainfall varies from as low as 8 inches in the deserts of New Mexico and west Texas to as high as 64 inches in the marshlands of Louisiana. The eastern portion is typically humid, the western portion typically dry, and the vast midsection of the area is characterized by alternation of humid and dry conditions.

The study region is at a juncture with two major climatic conditions--warm, moist gulf air masses and relatively cooler and drier air masses from the continental interior. Precipitation occurs when the warm gulf air is forced aloft by relatively cooler air masses from the north such as occurs over the Balcones Escarpment in central Texas.

Except in the mountains of New Mexico, snow is not very common or persistent, but it can be a valuable source of moisture in the High Plains of Texas and New Mexico.

Most of the western part of the study area receives less than 20 inches of annual rainfall. The average annual precipitation is shown in Figure 4.

Limited moisture conditions and high summer temperatures characteristic of much of the study area have a detrimental effect on ground-water quality, especially where natural land drainage is restricted. Temperatures of over 100° F are not uncommon in July and August, and the high evapotranspiration rate results in mineral buildup in the soils and ground water. Average annual pan evaporation, shown in Figure 5, is indicative of the high evapotranspiration rates in the area.

Ground-Water Resources

ARKANSAS

Arkansas is roughly divided into two physiographic divisions. The northwestern higher and more rugged half is part of the Interior Highlands, and the southeastern half is in the Coastal Plain province. Geohydrologically, as well as physiographically, the state is divided sharply into two parts. The northwestern half contains ground-water supplies that are prevailingly small to moderate (though ample for domestic use), and the southeastern half contains larger supplies. Figure 6 shows the approximate productive areas of the most important water-bearing deposits in Arkansas, and Figure 7 shows the approximate yields to be expected from wells.

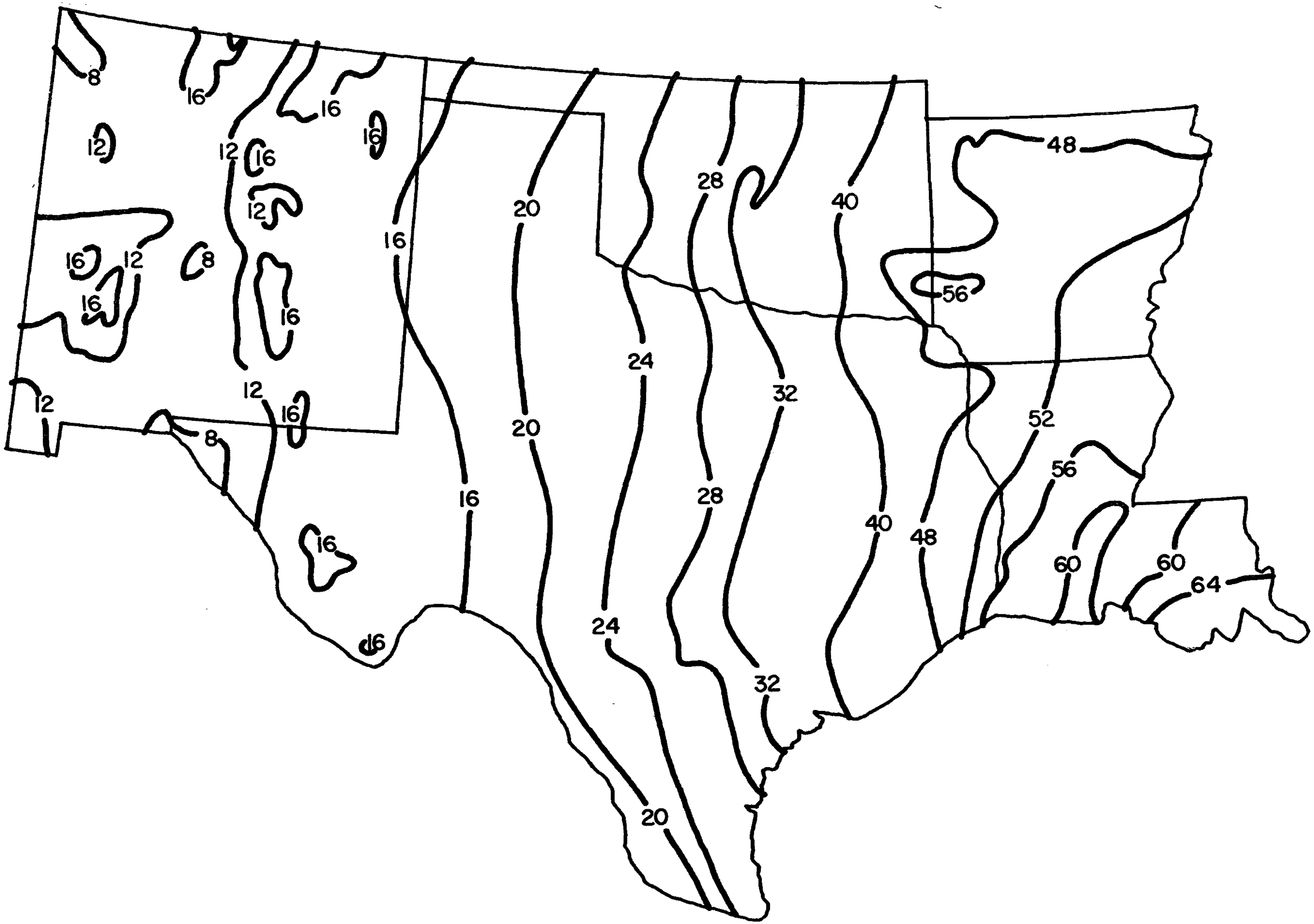


FIGURE 4. AVERAGE ANNUAL PRECIPITATION IN INCHES

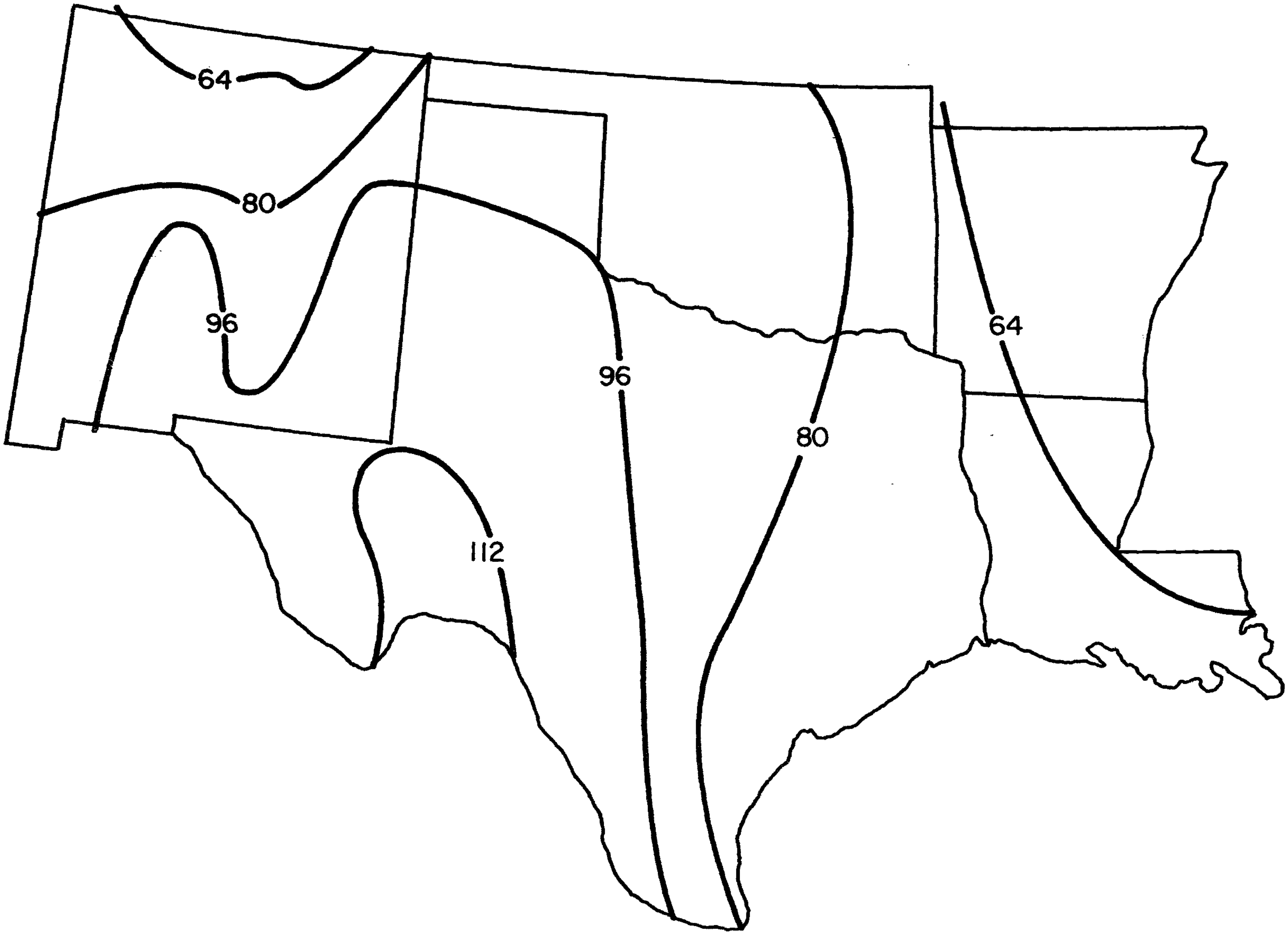


FIGURE 5. AVERAGE ANNUAL PAN EVAPORATION IN INCHES

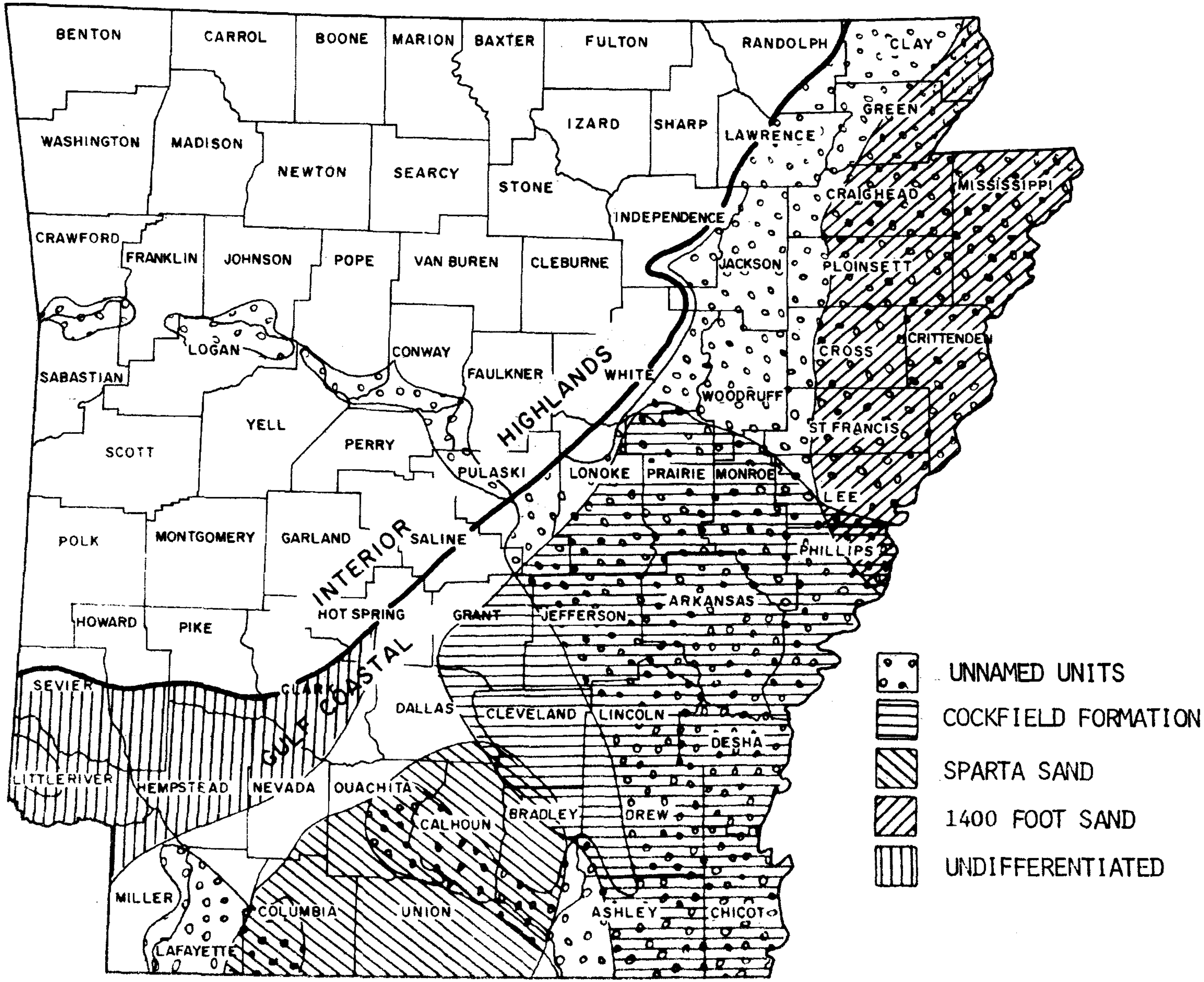


FIGURE 6. MOST IMPORTANT WATER-BEARING DEPOSITS IN ARKANSAS 7/

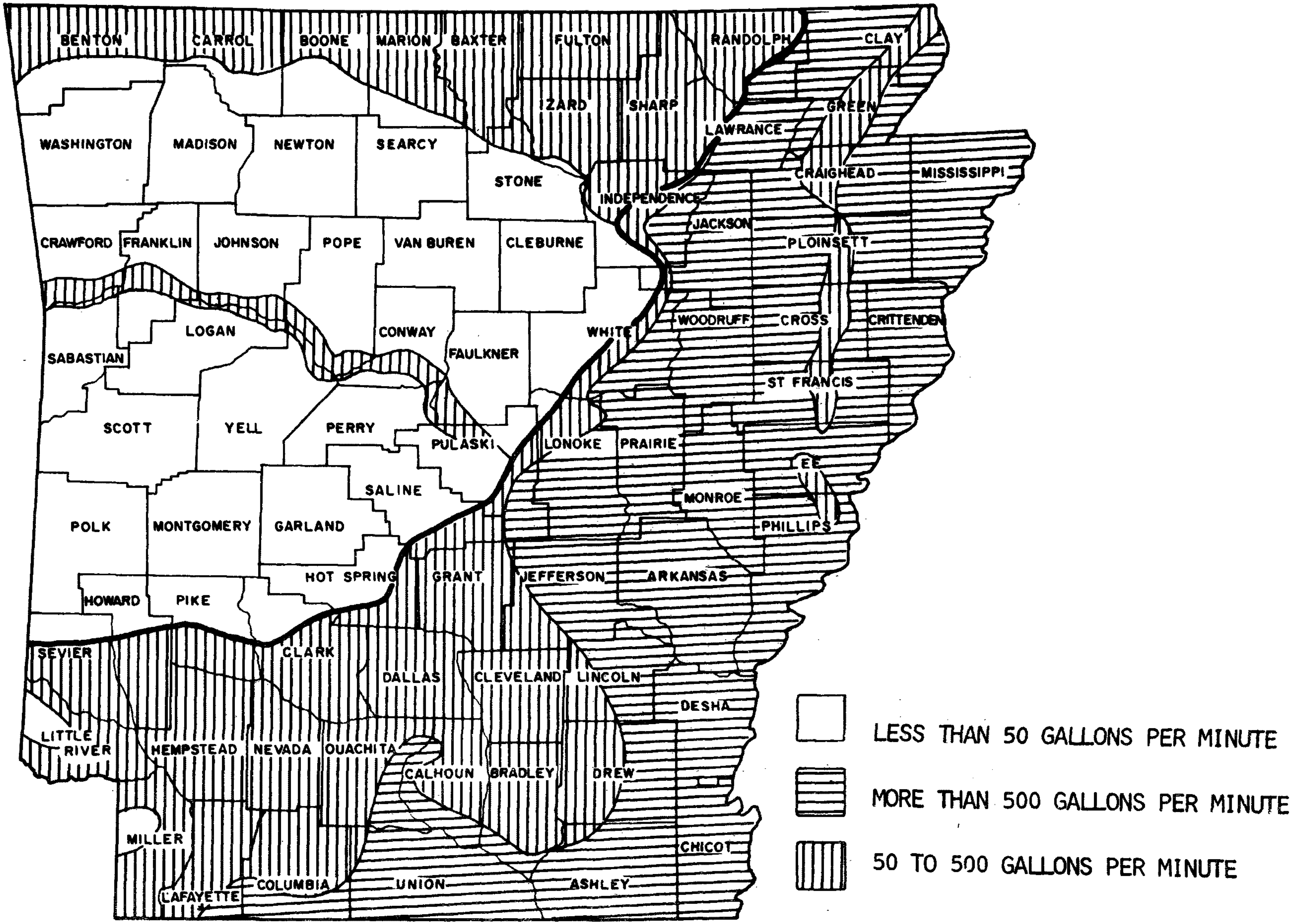


FIGURE 7. APPROXIMATE WELL YIELDS IN ARKANSAS [7/]

Ground water is one of Arkansas' most important assets. The state has few ground-water supply problems, other than those related to unavailability of large supplies in some areas, poor quality of water in substantial areas, and ground-water depletion in the Grand Prairie or extreme eastern region. The general lack of serious water problems has resulted in a corresponding lack of legislation controlling water use. As water use increases and competition develops, the time may come when the state will need to enact more restrictive legislation.

Interior Highlands

The Interior Highlands are located in the northwestern half of the state where ground-water supplies are prevailingly small to moderate.

In most of the Interior Highlands, well yields rarely exceed 50 gpm and are generally less than 25 gpm.7/ Thus, only domestic and stock needs and small municipal needs can be met in most of the region. There are several areas within the highlands where moderate and locally large supplies are available. The most important of these are in the northern tier of counties (the Springfield-Salem Plateaus of the Ozark Plateaus) and the Arkansas River Valley.

Ground water in the Springfield-Salem Plateaus occurs in fractures, many of them solutionally enlarged, and in thick strata of limestone and dolomite. The limestone formations of Ordovician Age are the principal source of ground water in the Salem Plateau area. The Springfield Plateau yields ground water over most of its area and is supplied by the Boone Formation and the Batesville Sandstone. Well yields range from 50 gpm or less up to 500 gpm. 5/

Ground water in the Arkansas Valley occurs in two distinct environments. One includes the unconsolidated alluvial deposits of the Arkansas River and its tributaries and the other includes the consolidated rocks that underlie the entire region.

The principal aquifer in the bedrock of the Arkansas Valley section is the Atoka Formation of Pennsylvanian Age, which consists of shale and sandstone. Wells generally yield less than 50 gpm, but yields of this amount or more are available locally.7/ The most productive rock is not sandstone but hard, fractured shale adjacent to the sandstone beds. The bedrock is important because it underlies a large area.

The most consistently productive aquifer in the Interior Highlands is the alluvium along the Arkansas River. The alluvium is composed of sand, gravel, silt, and clay and grades generally from fine grained at the surface to coarse grained at the base. Yields ranging from 300 to

750 gpm have been obtained from wells tapping the alluvium.8/ Although few large capacity wells have been drilled into the alluvium to date, large supplies could be developed in places by induced infiltration from the river.

Gulf Coastal Plain

The coastal plain is underlain by southward- to southeastward-dipping (and thickening) strata of unconsolidated to slightly compacted and cemented clay, silt, sand, gravel, shale, limestone, and lignite of Cretaceous and Tertiary Ages. Overlying the Cretaceous and Tertiary strata in valleys are flat-lying unconsolidated sediments of Quaternary Age, generally sandy and gravelly in the lower part and finer grained above. There are five major water-bearing units in this area. These include the Cockfield Formation, Sparta Sands, Wilcox Formation ("1400 foot Sand"), Cretaceous undifferentiated deposits, and the Quaternary Alluvium.

The primary ground-water problem in the Gulf Coastal Plain region of Arkansas is one of depletion in the irrigated Grand Prairie area in the Mississippi Alluvial Plain.

The Cockfield Formation of Tertiary Age--consisting chiefly of fine to medium-grained gray sand, in part lignitic, interbedded with light to dark-gray lignitic clay--underlies a large area in east central and southeastern Arkansas. The formation is an important source of water for industrial use in the vicinity of Pine Bluff and for municipal supplies in most of the area in which it occurs. Water from the Cockfield Formation is pumped for irrigation from about 20 or 30 wells in east central Arkansas, chiefly in the Grand Prairie Region, and water of fair to good quality can be obtained at most places. Locally, the upper sand beds yield moderately mineralized water, but less mineralized water is generally available in deeper beds of the formation.

The Sparta Sand of Tertiary Age is an important source of ground water in south central Arkansas, where it is used extensively for industrial and municipal supplies and in the oil fields. This formation consists of massive beds of white to gray, fine to medium-grained sand with beds and lenses of sandy or silty clay and some thin beds of lignite. The Sparta Sand is a high yield aquifer yielding up to 700 gpm in some areas.9/

In northeastern Arkansas there is an important water-bearing deposit of Tertiary Age, known locally at Memphis, Tennessee, as the "1400 foot sand."10/ These sands in Arkansas are part of the Wilcox Formation and occur at a depth of 1900 feet in the east central part of the state.7/

The "1400 foot sands" are composed of a prominent bed of fine to medium sand and forms an artesian aquifer over most of the area. The artesian pressure has been greatly reduced as a result of excessive usage and it is now necessary to use pumps in most of the wells.

In southwestern Arkansas there occurs a general east-trending band of undifferentiated deposits of Cretaceous Age, consisting chiefly of sand or crumbly sandstone overlain and underlain by sandy clay, shale, and marl. Some of these deposits will yield good water in sufficient quantity for domestic and small industrial or municipal supplies but most yields are less than 500 gpm.11/

The Quaternary Alluvium is the most important and highest yielding source of ground water in the coastal plain, and most water is used for irrigation. Deposits of Quaternary Age occur in a large part of the Gulf Coastal Plain in eastern Arkansas and in the valleys of the Saline, Ouachita, Red, and Arkansas Rivers. The upper part of these formations consist of sand and gravel and generally yield large amounts of water to wells.

LOUISIANA

Louisiana, second only to Hawaii in total annual precipitation, is a "water-rich" state with large supplies of ground water and large and occasionally excessive supplies of surface water.12/ More than three-fourths of the state is underlain by fresh-water aquifers capable of yielding moderate to large supplies of ground water, a considerable part of it soft and low in mineral matter. About two-thirds of all ground water pumped in the state is from Quaternary deposits of Pleistocene and Recent Ages which underlie most of Louisiana, as shown in Figure 8.

Water use in Louisiana is greater than in any other southern state excluding Texas. Even though Louisiana has a large water supply, there is a shortage in some streams in dry weather. This shortage leads to deficiencies in supply in inland stretches and to salt-water encroachment in some tidal stretches. Storing the over-abundant flood flow for dry weather use is difficult because of the lack of good reservoir sites in the flat terrain. Although flood-control reservoirs retard flood runoff and provide storage, sedimentation in the reservoirs and streams rapidly reduce storage capacity.

Most of the previous studies on Louisiana ground-water resources have been prepared by the United States Geological Survey in cooperation with the Louisiana Geological Survey and the Louisiana Department of Public Works. In this report the state has been divided into the five geographic areas of Southwestern Louisiana, Baton Rouge Area, Baton Rouge-New Orleans Area, Southeastern Louisiana, and Northern and Central Louisiana.

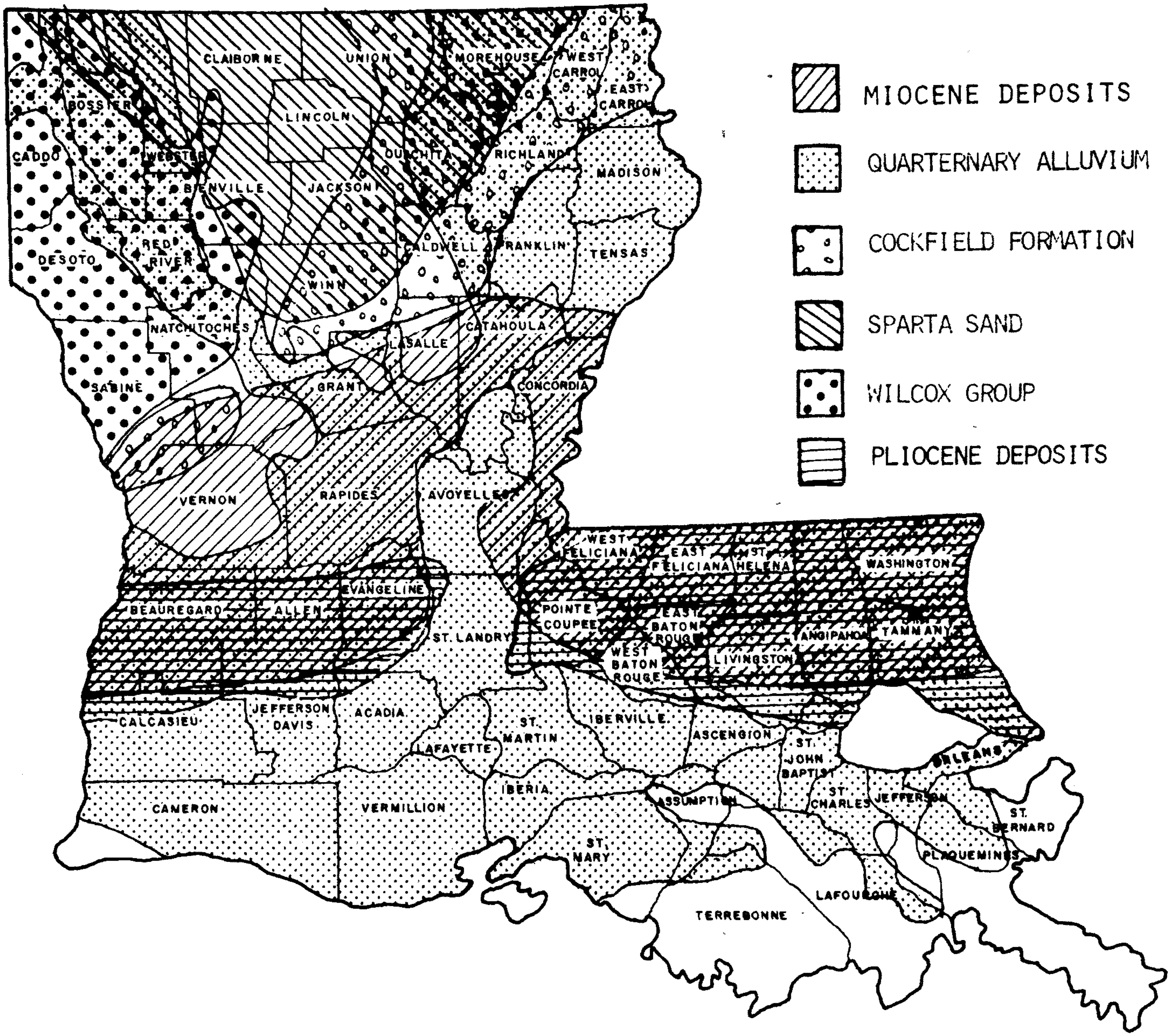


FIGURE 8. MAJOR WATER-BEARING FORMATIONS OF LOUISIANA

Southwestern Louisiana

Southwestern Louisiana is underlain by a thick sequence of southerly and southeasterly dipping interbedded gravels, sands, silts, and clays that have been divided into the Atchafalaya, Chicot, Evangeline, and Jasper Aquifers. The Chicot Aquifer is the principal, most heavily pumped source of fresh water. The Atchafalaya is a source of fresh water only in the extreme eastern part of the area. The Evangeline and Jasper Aquifers contain fresh water only in the northern and central part of the area.

The sands of the Chicot and Atchafalaya Aquifers are hydraulically connected; therefore, in the areas where they overlap they are considered to be a single ground-water reservoir designated as the Chicot reservoir.13/ The Chicot Reservoir underlies most of southwestern Louisiana and extends an unknown distance beneath the Gulf of Mexico and is composed of beds of clay, silt, sand, and gravel of Pleistocene Age. These sediments dip toward the south and southeast and increase in thickness from less than 100 feet in the northern part of the area to more than 7,000 feet beneath the Gulf of Mexico.13/

The geology and climate (heavy rainfall) of southwestern Louisiana combine to form one of the largest sources of fresh ground water in North America. Large quantities of ground water are available for agricultural, municipal, domestic, and industrial purposes with over three-fourths of all ground-water pumpage being used for rice irrigation. However, with the decline of water levels, salt-water encroachment is a local problem or potential problem in coastal streams during dry weather periods. Thus far, major pollution has been limited to an area along the Vermilion River.

Heavy ground-water pumpage in southwestern Louisiana, and in the Lake Charles industrial area in particular, has caused a reversal in the piezometric gradient south of the areas of heavy pumpage. This has allowed salty water in the southern part of the reservoir to move slowly northward.

The Evangeline and Jasper Reservoirs consist of unconsolidated fine to medium-grained sand of Pliocene Age. The volume of water pumped from these reservoirs is relatively small compared with the total pumpage in southwestern Louisiana.

Baton Rouge Area

The Baton Rouge area is underlain by a complex sequence of continental and marine sediments. Pumpage is from the alluvium and from the older artesian aquifers known for their general depths as the "400-foot," "600-foot," "800-foot," "1,000-foot," "1,200-foot," "1,500-foot," "1,700-foot," "2,000-foot," "2,400-foot," and "2,800-foot" sands.

Alluvial deposits of Recent and Pleistocene Ages are limited to the floodplain of the Mississippi River near Baton Rouge. These deposits consist of approximately 80 percent water-bearing sands and gravels and 20 percent silt and clay.14/ In the floodplain, the deposits range in thickness from 250 feet in northern West Baton Rouge Parish to 600 feet in the south-central part of the area.

Most water for public and industrial use is pumped from artesian aquifers in the area which vary in thickness, grain size and depth.

The shallow sands--the "400-foot" and "600-foot"--were formerly the most heavily pumped, and water levels were drawn rather low. In recent years, withdrawals have been reduced and the water levels have recovered substantially. The quality of the water is fairly good, but encroachment of brackish water has been detected in one area of the "600-foot" sand.

Water levels in deeper sands are declining as they are pumped more heavily to meet demands. Salt water is encroaching toward Baton Rouge in the artesian aquifers and poses a real or potential threat to fresh ground-water supplies. Large scale faulting across the southern Baton Route area acts somewhat as a hydraulic barrier to the northward movement of salt water in the deeper aquifers. However, salty water has been found north of the fault zone in the "1,000-foot," "1,500-foot," and "2,000-foot" sands, as well as the "600-foot" sand.40/

Baton Rouge-New Orleans Area

The Baton Rouge-New Orleans area is that area south of Baton Rouge down to and including New Orleans. It is a part of the upper deltaic plain of the Mississippi River.

Aquifers that contain fresh water are largely limited to the upper 800 feet of sediments. Deposits making up the deltaic complex are of Pleistocene and Recent Ages. Except for local problems, fresh ground water in at least moderate quantities can be obtained throughout the area. However, at many places careful development is necessary to minimize upward or lateral movement of salt water into the fresh water. The main water-bearing deposits are the "700-foot" sand which supplies most of the New Orleans area and the Mississippi River alluvium.

Water in the New Orleans area grades from fresh to salty in a north to south direction, but salt-water encroachment caused by declining water levels is not deemed serious, provided the current distribution of the pumping is maintained. Wells yielding 1,000 gpm or more can be constructed almost anywhere.15/

Relatively large amounts of water are available locally from shallow wells that tap the alluvial deposits of the Mississippi River. However, in some areas, continuous pumpage would result in salt-water encroachment from brackish water in the basal part of the aquifer.

Southeastern Louisiana

Southeastern Louisiana is one of the most promising areas for future development in the state. Enormous quantities of soft, fresh water are available from sands of Quaternary and Tertiary Ages which extend to depths exceeding 3,500 feet in some places. Water is available by flowing artesian wells in large parts of the area, but some of the shallow water is corrosive.

Northern and Central Louisiana

Northern and central Louisiana are underlain by a series of deposits yielding from small to large amounts of ground water. Three of the more important water-bearing formations are the Sparta Sand of the Claiborne group, the Wilcox group, and the Quaternary Alluvium of the Red River.

The Sparta Sand, which is the most important aquifer in north central Louisiana, ranges in thickness from about 500 to 900 feet where it contains fresh water.12/ Ground water in the Sparta Sand is unconfined in its sandy outcrop areas, and is under artesian conditions where the sands are overlain by impermeable material. Water quality varies depending on whether it is found in the outcrop area or under artesian conditions. Pumping from the Sparta has caused water levels to decline at Hodge in Jackson Parish, Monroe in Ouachita Parish, and Bastrop in Morehouse Parish. Pumping in these areas may eventually cause salt water to encroach from down-dip to the east.

Sands of the Wilcox group yield fresh water in northwestern Louisiana. This aquifer is composed of a heterogenous sequence of beds of lignitic sand, silty sand, sandy and silty clay, and clay. These fine grained deposits form a deltaic sequence that thickens rapidly southward. Artesian conditions prevail in much of the Wilcox Sands; however, only a few wells have flowing water. Yields from wells tapping the Wilcox Sands are generally small, but larger yields are sometimes found locally.

Alluvial deposits in the Red River Valley constitute a relatively undeveloped but potentially important aquifer in northwestern and central Louisiana. The alluvium consists of an upper unit of clay and silt with sand and gravel making up the lower half of the deposits. Ground water in the Red River Valley generally is under artesian conditions. Other than for stock and irrigation supplies, the water is used very little but there is great potential for additional irrigation.

NEW MEXICO

The Major ground-water producing areas of New Mexico are located in alluvial deposits of the Rio Grande Valley which transverse the state from north to south and in the High Plains and Pecos Valley of extreme eastern New Mexico. Less productive aquifers are scattered throughout the state and many of these are of major local importance even though their overall development is comparatively minor.

Being an area of semi-arid climate, New Mexico relies on ground water to supply about one-half of its large and growing water needs. Irrigation is a major user and in 1970 accounted for almost 85 percent of the total ground water used in New Mexico.3/ Heavy pumping combined with low rainfall and limited recharge of most of the aquifers has resulted in ground-water mining.

Ground-water mining also has a profound effect on surface water supplies in New Mexico because of the close hydraulic association between ground and surface water along major developed streams. New Mexico was one of the earliest states to recognize this interconnection in the adoption and administration of legislation pertaining to water rights.

The U.S. Geological Survey and the New Mexico State Engineer's office have conducted extensive studies concerning both the quantity and quality of ground water and their reports are the primary source of this summary on New Mexico. The New Mexico Bureau of Mines and Mineral Resources, University of New Mexico, New Mexico Geological Society and the Pecos River Commission have also contributed significant studies of the ground-water resources of New Mexico in terms of eight major areas: High Plains, Rio Grande Valley, Canadian and Cimarron River Basins, Pecos River Basin, basins in central and south central New Mexico, basins in southwestern New Mexico, Gila and San Francisco River Basins, and Colorado Plateaus. These areas are shown in Figure 9 and relative water yields are shown in Figure 10.

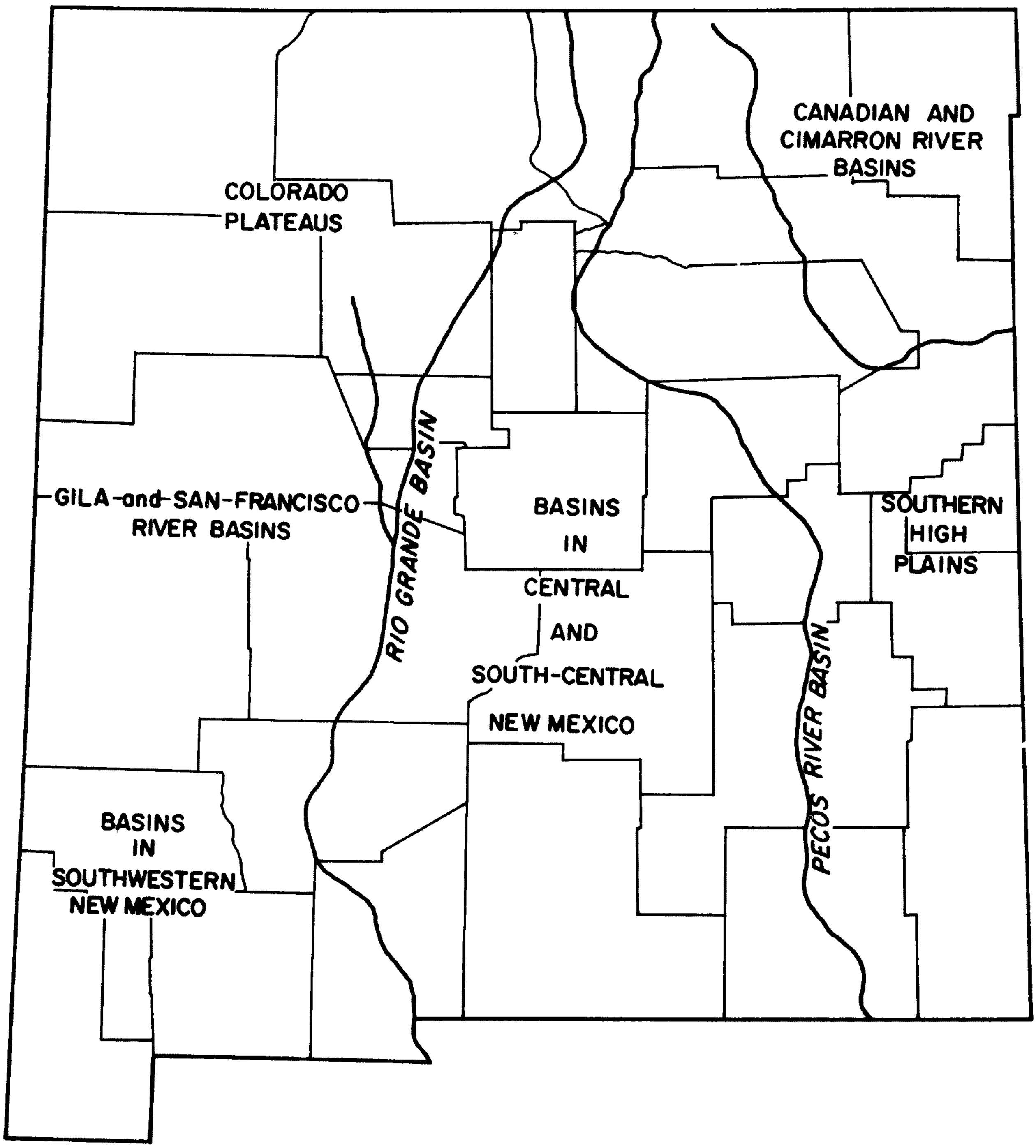


FIGURE 9. EIGHT MAJOR GROUND-WATER AREAS IN NEW MEXICO

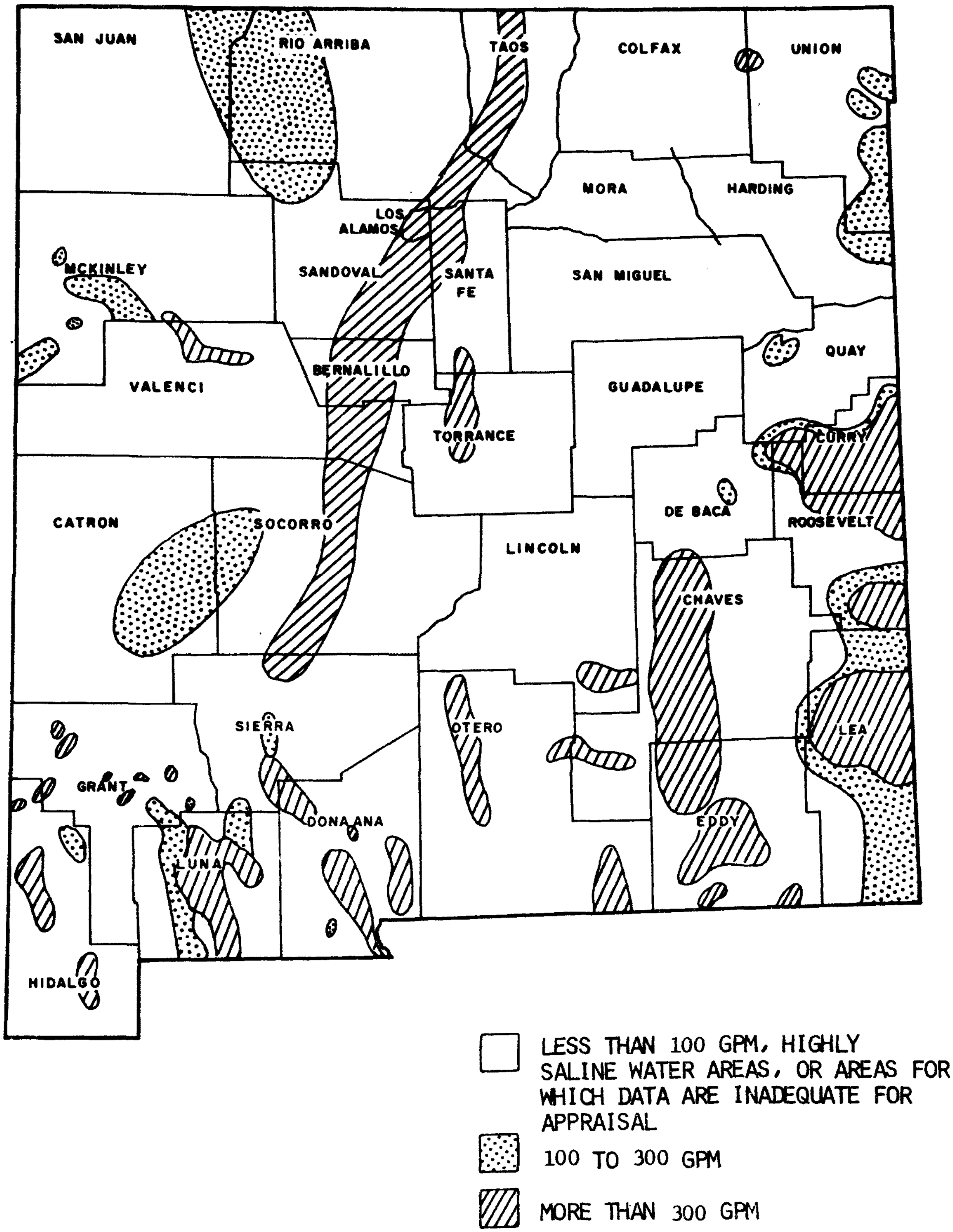


FIGURE 10. RELATIVE WATER YIELDS OF NEW MEXICO AQUIFERS [16]

High Plains

The sand and gravel aquifers in the High Plains of New Mexico are the western part of the massive series of aquifers which underlie much of northwest Texas and parts of several states all the way to South Dakota. The High Plains in New Mexico is an area of heavy pumping and ground-water mining. Most water is from the Ogallala Aquifer, although along the edges of the Plains and in basins excavated into the plains, such as the Portales Valley, alluvium of Quaternary Age also yields heavy pumping.

As with much of New Mexico, the major water resource problem in the High Plains is the lack of natural ground-water recharge. Average annual rainfall is less than 20 inches and there is no surface runoff to perennial streams. Essentially, the only recharge to the ground water is seepage from undrained depressions and arroyos during infrequent periods of flooding and infiltration of precipitation into dune sand such as that in the Portales Valley.

The Ogallala is heavily developed all the way from southern Quay County to southern Lea County with the thickest and most productive area being in northern Lea County. Individual wells yield up to 1,600 gpm but water levels are declining and pumping lifts are as much as 400 feet.17/

The Ogallala is thinner in southern Lea County where much of the water is obtained from Quaternary sediments which overlie it in the east and replace it in the west.

These Quaternary deposits are also an important ground-water source in the Portales Valley where they lie in a broad shallow valley cut into and through the Ogallala Formation in northern Roosevelt and eastern De Baca counties. Individual wells yield from 300 to 1,000 gpm, but water levels have been declining at almost three feet per year since 1950.16/

Although the overwhelming majority of water in the High Plains of New Mexico is obtained from alluvium formations, the Santa Rosa and Chinle Sandstones of Roosevelt, Chaves, Eddy, and Lea Counties do yield small but important supplies for domestic and stock use.

Rio Grande Valley

The valley of the Rio Grande is an alluvial trough that stretches from Colorado's San Luis Valley on the north across New Mexico to El Paso, Texas on the south. This trough is up to 30 miles wide in some locations and is known to reach depths of 6,000 feet near Albuquerque.18/

This alluvium produces large yields of water and beneath the river's floodplain the water table is only a few feet below the surface but is more than 1,000 feet deep along the margin of the trough.16/ Although the Rio Grande Valley contains usable ground water to great depths, the hydraulic interrelationship with the surface water would result in hydrologic and legal problems if uncontrolled development of the ground-water reservoir were permitted. Reduction of the ground-water table would reduce the flow in the river where the surface waters are already fully appropriated.

Canadian and Cimarron River Basins

The Canadian and Cimarron River Basins in northeastern New Mexico overlie meager ground-water supplies. The only moderately productive areas are the Ogallala north of the Canadian River, an area of Mesozoic rocks near Tucumcari, and a small alluvial aquifer in Union County. The most common sources of ground water are the sandstone formations and one of the most productive is the Entrada Sandstone which provides water for the city of Tucumcari.

Pecos River Basin

The Pecos River heads in the mountains east of Santa Fe and flows south-southeast into Texas south of Carlsbad, New Mexico. In the northern part of the basin, the river has cut through the Ogallala Formation and into rock, mostly sandstone and shale of low permeability. Ground-water supplies in the area are meager although domestic supplies are available from limestone fractures in the mountain region and from the Abo Sandstone farther south. From the northern part of De Baca County on southward, alluvial fill is a productive source of ground water. Of more importance to the basin as a whole are the underlying limestone formations which constitute the artesian aquifers of the Roswell and Carlsbad area. With the heavy development for irrigation the artesian pressure has declined until most wells in the area must now be pumped. Nevertheless, wells of a few thousand gallons per minute are common near Roswell.

The San Andres Limestone in the vicinity of Santa Rosa contains large supplies of ground water and discharges a considerable amount to the Pecos River south of Santa Rosa. Much of this discharge is water which has disappeared into the stream bed north of Santa Rosa. Ground water in the Pecos Valley is more an essential part of the hydrologic system than in most stream valleys. Soluble rock formations are found almost everywhere beneath the land surface resulting in subsurface erosion and surface sinks. These are evidenced in losses and gains of flow at a number of locations along the river.

Basins in Central and South Central New Mexico

The principal basins between the Rio Grande and Pecos include the Estancia Valley, the Tularosa Basin, and the Jornada del Muerto.

The Estancia Valley is located in Torrance and southern Santa Fe counties and has no surface water outlets. Precipitation either infiltrates into the subsurface, evaporates from saline lakes, or transpires from vegetation. The major source of water in this area is the alluvium; but the Madera Limestone in the west, the Glorieta Sandstone in the north, and the Yeso Formation in the southern and northeastern parts of the valley also yield considerable water. Generally, the water in this valley is limited and of poor quality.

Ground water in the Tularosa Basin aquifer and vicinity is of the poorest quality in New Mexico. The Tularosa is a large alluvial basin with no surface outlet and a large supply of saline ground water but very little fresh water. There are a few scattered locations around the edges of the basin where fresh water is available but only two of these are principal water sources. One consists of a long narrow area around Tularosa and Alamogordo; the other more productive area is in the extreme southwestern part of the basin. Nevertheless, fresh water is very scarce in the Tularosa Basin and current supplies are being depleted.19/

The Jornado del Muerto is a large alluvial basin between the Tularosa Basin and the Rio Grande. Ground water in sufficient quantity for watering stock can be found almost everywhere in the basin fill at depths ranging from 30 feet to about 400 feet. However, most of the ground water is not of sufficiently good chemical quality for human consumption. In rare locations, sufficient water for irrigation has been developed from the Dakota Sandstone and the underlying San Andres Formation but this water is not potable. The few known sources of potable water in the Jornado del Muerto are around the edges of the basin in alluvial-fan deposits.16/

Basins in Southwestern New Mexico

Southwestern New Mexico is an area of extensive alluvium deposits throughout a number of scattered intermountain valleys. The principal basins include the Mimbres Valley; the Animas Valley; the Playas, Hachita, and Lordsburg Valleys; the San Augustin Plains; and the Gila and San Francisco River Basins. With the exception of the San Augustin Plains and the Gila and San Francisco River Basins, all these basins have similar characteristics. The Mimbres Valley has the longest history of gound-water development and large capacity wells in the alluvium commonly yield from 500 to 1,000 gpm of fair quality water.5/ Water levels are declining because most of the water being pumped is taken from storage. When the water levels reach a point where pumping is too expensive for irrigation, sufficient ground water will remain for domestic, stock, municipal, and other uses where pumping costs are a secondary consideration.

The San Augustin Plains is a large, almost uninhabited basin with no external surface drainage and there is no irrigation development. Much of the ground water is saline, but there may be areas of good water around the edge of the surrounding mountains.

The Gila and San Francisco River Basins contain extensive ground-water supplies in alluvial deposits. Ground water is extensively developed for irrigation along the Gila, and well yields are as high as 2,500 gpm.5/ Water levels have not declined significantly because of the shallow pumping depths and rapid recharge during periods of high river flows. Ground water along the San Francisco River Basin has experienced very little development and there is additional irrigable land along both the San Francisco and Gila.

Colorado Plateaus

The Colorado Plateaus area is roughly the northwest quarter of the state, west of the Rio Grande Valley. Most of the area drains to the Colorado and San Juan Rivers. Generally, ground-water supplies are small and scattered and commonly at considerable depth or of poor quality, or both.

Despite the scarcity of ground water, the San Juan River Basin has the largest remaining water supply available to New Mexico. However, this supply is not expected to be adequate for increasing needs resulting from the population increase and the expanding oil and gas industry.

The area of heaviest pumping is in the vicinity of Gallup where coal and uranium mining and associated industrial growth have created a relatively heavy demand on sparse water supplies. Water is obtained primarily from fine-grained sandstone, alluvium, and basalt. Well yields range from 1 to 250 gpm but most yield less than 50 gpm.20/

The Rio Puerco and Rio San Jose drain the southeastern and eastern parts of the Colorado Plateaus in New Mexico. The San Jose Basin contains the heavily developed Grants-Bluewater irrigation area, as well as a large proportion of the nation's uranium reserves. The most productive aquifer in the Rio Puerco-Rio San Jose area is the San Andres Limestone with smaller ground-water supplies coming from alluvium, basalt, and fine-grained sandstone. Well yields range from 10 to 2,800 gpm.5/ Beginning in 1951, water used for uranium mining and milling in the Grants-Bluewater area increased with a corresponding decrease in irrigation pumpage so that the total withdrawal has remained rather constant. The maximum development has been reached and water levels are continuing to decline.

OKLAHOMA

Ground water is not as abundant in Oklahoma as it is in some other states, but it is an important factor in the State's economy and is capable of greater development. Ground water is Oklahoma's most valuable mineral resource and supplies approximately 87 percent of the irrigation water used in the state.21/ Various ground-water reservoirs throughout the state are estimated to contain over 300 million acre-feet of water. Approximately 300 towns and cities obtain their municipal supplies from wells and springs. In fact, over half the people in the state rely on ground-water sources for drinking water and household supplies.

Ground water is available over most of Oklahoma in sufficient quantity for domestic supplies; however, in some parts of the state, the water is too high in chlorides or sulfates for most uses. In some areas where ground water may be of better quality than surface water, industries and commercial users have developed private supplies for their own needs. The major aquifers used in Oklahoma are shown in Figure 11.

High Plains Area

The High Plains covers all but a small fraction of the three panhandle counties and extends a short distance into adjacent counties of northwestern Oklahoma. The area is underlain by deposits of sand, gravel, and minor amounts of clay and these sediments in some areas are capped by a limy rock called caliche.

The deposits of the High Plains are composed primarily of the Ogallala Formation, the most important aquifer in the state. This is probably the best aquifer in Oklahoma because of its area, thickness and high permeability, despite the fact that it is only partially saturated with water. Because of low annual precipitation and high evaporation in this area, insufficient water reaches the Ogallala to keep it sufficiently recharged to offset pumping losses.

The Ogallala is as much as several hundred feet thick. In Oklahoma alone, it contains more than 100 million acre-feet of available water and supplies most of the water requirements of the panhandle. Ground water

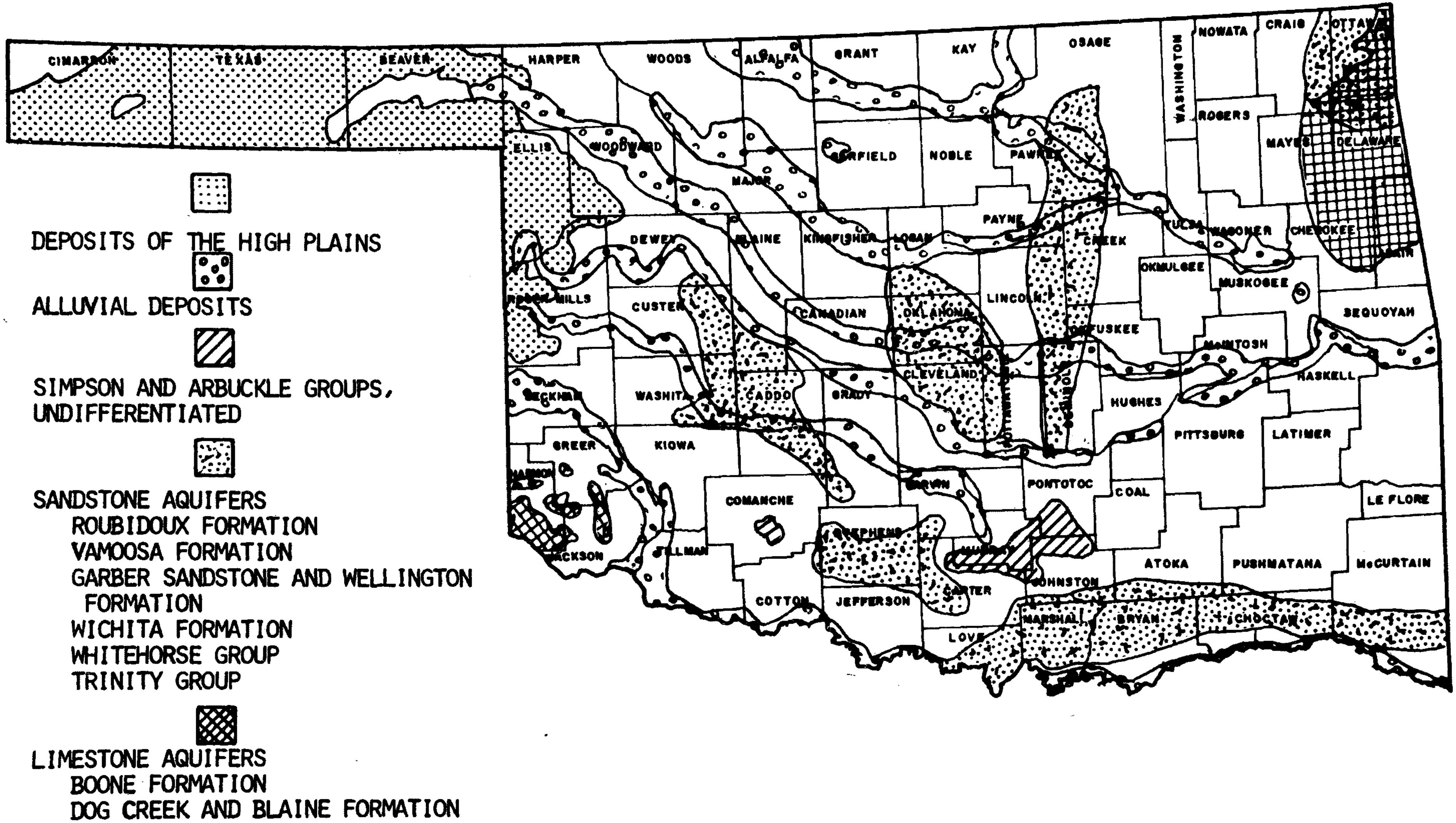


FIGURE 11. PRINCIPAL WATER-BEARING FORMATIONS OF OKLAHOMA [6/]

from the Ogallala is used to irrigate about 135,000 acres, for the industrial needs of the Keyes helium plant and the natural gas industry in the panhandle and for all public and domestic supplies in the area.26/

Wells in the thickest and most permeable sections of these deposits yield as much as 1,000 gallons per minute, and yields of several hundred gallons per minute are common throughout large areas.

Western Oklahoma Area

This area includes the western half of Oklahoma, excluding the High Plains area. It is composed of the following formations: Rush Springs Sandstone, Garber Sandstone and Wellington Formation, Blaine Gypsum and Dog Creek Shale, and Wichita Formation.

The Rush Springs Sandstone underlies an area of about 1,840 square miles in west central Oklahoma. The topography is characterized by rolling plains interrupted in places by sand dunes or deeply eroded stream valleys. The formation is composed of fine-grained, cross-bedded to even-bedded sandstone. It is the principal aquifer in this area and yields moderate to large supplies for most domestic, municipal, irrigation, and industrial uses. The maximum reported yield is about 1,000 gallons per minute and common yields to irrigation wells are about 400 gallons per minute.23/

The Garber Sandstone and Wellington Formation outcrop across the eastern two-thirds of Cleveland and Oklahoma Counties in a north trending belt 6 to 20 miles wide. The area of outcrop is characterized by rolling, steep-sided hills that are forested with scrub oak and other small, slow-growing deciduous trees. It consists of lenticular beds of massive-appearing, cross-bedded sandstone irregularly interbedded with shale which is, in part, sandy to silty. The sandstone layers are fine to very fine grained and loosely cemented. The two formations as a unit have a total thickness of 800 to 1,000 feet.24/

The Dog Creek Shale and Blaine Formation in Harmon and part of Jackson and Greer Counties constitute the most important aquifer in these counties. The aquifer consists principally of interbedded shale, gypsum, anhydrite, dolomite, and limestone. Solution cavities containing large quantities of water may yield some water high in calcium sulfate. The pattern of fresh water is erratic, so a "dry" well may be drilled within 100 feet of a well of high yield. Yields from wells tapping this formation range from less than 10 to 2,000 gallons per minute.

The Wichita Formation of Permian age consists of fine-grained sandstone and red shale, similar to the rocks of the Garber and Wellington Formations and of roughly equivalent age. This formation supplies water principally for industrial and municipal use in western Garvin, all of Carter, and southern Stephens Counties. West of Ardmore, fresh water has been reported to depths of as much as 900 feet and wells yield as much as 250 gallons per minute. Yields of more than 100 gallons per minute are common in other areas. The quality is suitable for municipal and industrial purposes at many places.

Eastern Oklahoma Area

The Eastern Oklahoma Area is composed of the following aquifers: Nelagony-Vamoosa, Boone Formation, Simpson and Arbuckle Group; Trinity Sandstone, Roubidoux Sandstone, Washita and Kiamichi Group, Goodland Limestone, Woodbine Formation, Tokio Formation, Ozan and Brownstown Formations.

The Vamoosa Formation crops out in a north-south band approximately 20 miles wide extending from Seminole to Osage County and is an important aquifer in that and nearby areas. The formation consists of 250 to 600 feet of interbedded sandstone, shale, and conglomerate. It supplies water for municipal and industrial uses along its outcrop and for several miles downdip to the west. The best wells seem to be in the Seminole area where wells produce about 150 gallons per minute.25/ Elsewhere, yields range from a few gallons per minute to 100 gallons per minute.

The Boone Formation of early and late Mississippian age consists primarily of limestone and cherty limestone and is an important aquifer over a large part of the Ozark area of northeastern Oklahoma. It averages about 300 feet in thickness and contains numerous fracture and solution openings. The Boone forms a sizable ground-water reservoir and is the source for many springs in that area. Springs issuing from the Boone play an important part in maintaining the year-round flow of streams such as Spavinaw Creek in northern Delaware County. Spring flow from the Boone in Ottawa County has been estimated at 14 million gallons per day.

In the Arbuckle Mountain region several sandstones of the Simpson group of Middle Ordovician Age supply potable water in the outcrop area and for a short distance downdip. A sandstone of equivalent age crops out in Cherokee and Adair Counties in the Ozark part of northeastern Oklahoma and supplies water locally to domestic and farm wells. Little information is available on the sandstone of the Simpson, but apparently they contain highly mineralized water at short distances downdip from the outcrop.

Beneath the Simpson group in south central Oklahoma is the Arbuckle group of late Cambrian and Early Ordovician Ages. This group is composed of a thick section of limestone and dolomite beds which have been tilted, folded, and broken by faults. In and near the outcrop south of Ada, fresh water occurs in solution openings to depths of more than 2,500 feet, and yields of 2,000 gallons per minute are reported from well tests.28/ The aquifer supplies water for municipal, industrial, and irrigation purposes in the Arbuckle Mountains area. In the outcrop, water is somewhat hard but contains only a moderate amount of dissolved solids. At varying distances from the outcrop area, water in the Arbuckle is highly mineralized.

The Trinity group is the basal division of the Cretaceous rocks in McCurtain County, Oklahoma. The group is divided into three formations which, in ascending order, are the Holly Creek Formation, the DeQueen Limestone, and the Paluxy Sand. The Holly Creek is composed of a series of red clays, thin sand beds, and gravel lenses. It yields potable water to farm wells in east central McCurtain County. The DeQueen Limestone consists of varicolored calcareous clays and pinkish-gray limestones and marls in beds generally less than a foot thick. Downdip beneath younger rocks it contains gypsum and anhydrite beds. The DeQueen yields little ground water in McCurtain County.

The Paluxy Sand is composed of white and yellow sands, some iron-cemented sandstones, conglomerates, and red, yellow, purple, or blue clays, and a few limestone lenses. The Paluxy, the most important aquifer in McCurtain County, is the source of municipal supply at Valliant, Millerton, and Garvin and supplies water to farmsteads throughout its outcrop area.

The Trinity group ranges from a featheredge up to about 2,200 feet. Water is pumped for municipal and industrial use throughout the productive belt and is beginning to be pumped for irrigation. Properly constructed wells penetrating the most permeable deposits yield 450 gallons per minute or more, and natural flowing wells are possible on low ground in lightly pumped areas. The quality of the water varies greatly from place to place. In some places, fresh water extends to a depth of 800 feet, but locally elsewhere salt water is found at a shallow depth.

The Roubidoux Formation consists of about 150 feet of dolomite and interbedded sandstone. It is an aquifer of substantial importance in a sizable area of Ottawa, northern Delaware, and eastern Craig Counties in northeastern Oklahoma. It yields water to wells 800 to more than 1,000 feet deep in the northeast corner of Oklahoma. Although some wells produce as much as 600 gallons per minute, the aquifer has been overdeveloped locally and water levels have declined several hundred feet since the first wells were drilled more than 50 years ago.27/ The water is moderately hard but low in dissolved solids. The Roubidoux is used for both public and industrial supplies.

The Washita Group, including the Kiamichi Formation in southern McCurtain County, crops out as an east-west belt that is only about half a mile wide at the Arkansas State line and widens irregularly westward. Logs of wells near the outcrop show that the formation thins from about 200 feet on the western side of the county to less than 70 feet on the eastern side. Only the Kiamichi, which is 20 feet thick, is present on the south side of Little River at the Arkansas State line. It is composed of gray fossiliferous limestones and calcareous dark-blue shale; thins eastward and contains relatively small amounts of poor quality water in solution openings and cracks in the limestone.

The outcrop of the Goodland Limestone crosses the McCurtain County line from Arkansas just north of Cerrogordo and extends westward across McCurtain County in a narrow strip one-eighth to one-half mile wide. Along most of its length the outcrop is immediately south of Little River, and the sinuous outcrop pattern follows the river and its tributaries. It is thin-bedded dense limestone at the top with soft chalky and massive limestone in lower parts. The entire formation is fossiliferous and does not yield much water. The presence of many solution pits, openings, and enlarged fractures in the outcrop of the Goodland Limestone shows that the formation is susceptible to solution by water. However, records show that few wells tap ground water in this formation and these yield water of poor quality.

The Woodbine Formation crops out across the middle of the southern half of McCurtain County. It ranges in thickness from a featheredge at the outcrop to more than 355 feet in the subsurface in the southeastern part of the county. The outcrop ranges in width from a quarter of a mile to as much as four miles. The upper member of this formation is mostly gray to brown cross-bedded dark tufaceous sand, red clay, and gravel lentils. The formation is not a productive aquifer; most wells yield only sufficient water for domestic or stock use. The water is generally of inferior quality because of the mineral matter it dissolves from the tufaceous material.

The outcrop of the Tokio Formation in McCurtain County covers about 80 square miles in an irregular wedge, the point of which is about five miles southwest of Idabel. It is composed of gray cross-bedded sand, interbedded with gray and dark-gray shale. Because of clay and silt, transmissibility is generally low resulting in yields of less than 20 gallons per minute.29/ The sandy matter of the Tokio Formation suggests that it might be a good aquifer but interspersed clay and silt appreciably lower the permeability and transmissibility. Water quality from wells in the outcrop area is poor.

TEXAS

Underground reservoirs in Texas store approximately 1.25 billion acre-fee of potable water.30/ Of this vast amount, it is estimated that the potential yield of all aquifers, which would not seriously deplete storage, is about 5 million acre-feet annually.31/ As a result of geologic factors, these aquifers are distributed unequally throughout the state and do not necessarily coincide with locations of maximum need. Nevertheless, ground water furnishes about two-thirds of the more than 14 million acre-feet used annually for municipal, industrial, and irrigation purposes.

The state of Texas recognizes three major problems affecting ground water. The first is ground-water mining in the western part of the state caused primarily from heavy irrigation pumpage. The second major problem is the lack of sufficient quantitative information on the maximum sustained yields of aquifers, and the third major problem is existing or potential pollution of ground water resulting from discharge of both natural and man-made substances.5/

Several studies have been conducted on the ground-water situation in Texas, including those by the Texas Board of Water Engineers and its successors, the Texas Water Commission and the Texas Water Development Board, the main source of this report. In this report the aquifers of Texas have been divided into five geographic regions: the coastal area; the high plains; central, north central, and northeast Texas; southwest Texas; and the west Texas area. Major and minor aquifers in these areas are shown in Figures 12 and 13.

Coastal Area

A tremendous volume of fresh water is in transient storage in aquifers underlying the Gulf Coast region. The aquifers are generally composed of sand and gravel which alternate with silt and clay. This area can be divided into three areas containing significant amounts of ground water: the coastal sands, the Carrizo-Wilcox Sands, and the Sparta-Queen City aquifers.

Most ground water is withdrawn in the northeastern three-fifths of this region and these large withdrawals have caused two major problems. They are the encroachment of salt water near the coast, such as in

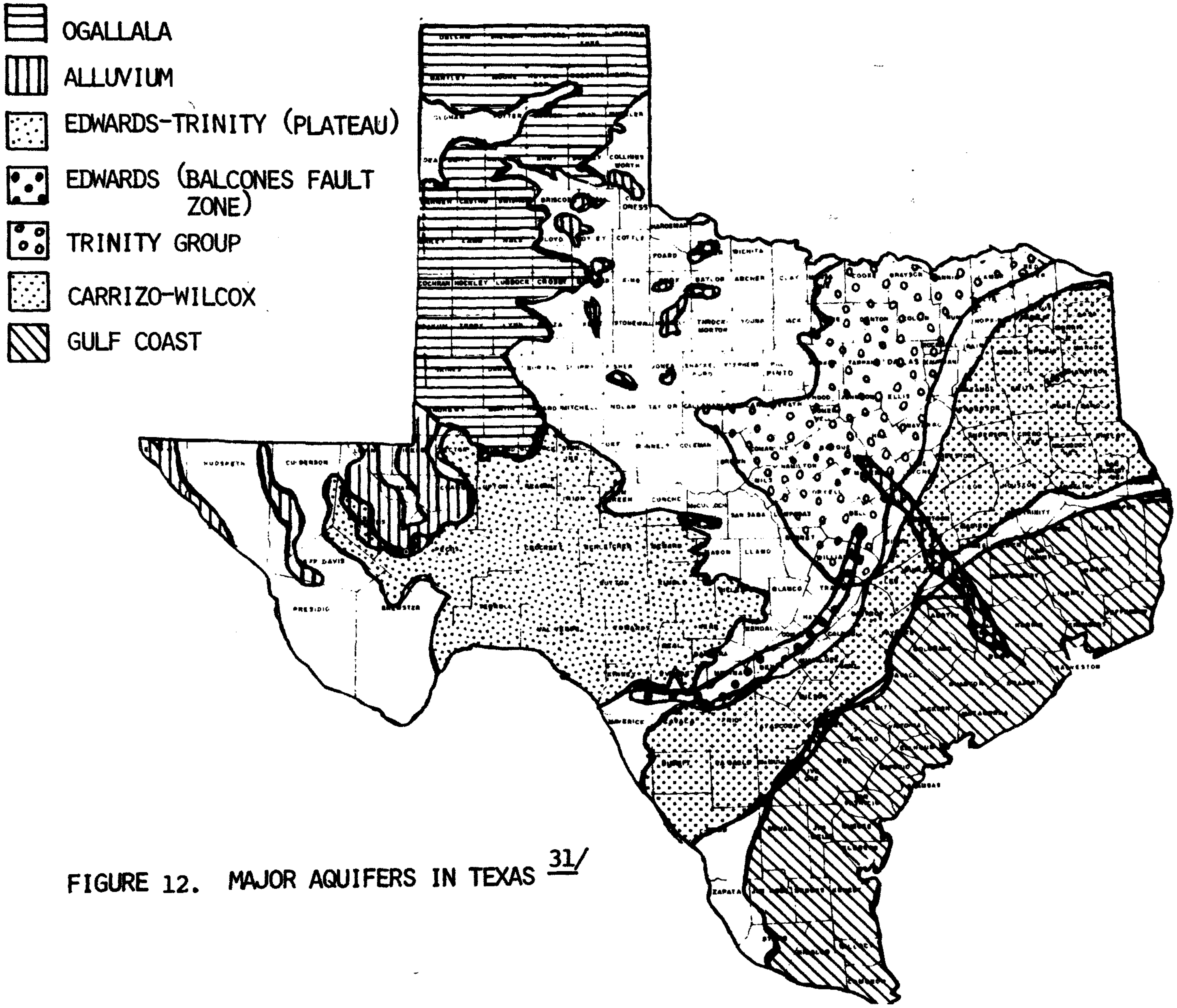


FIGURE 12. MAJOR AQUIFERS IN TEXAS 31/

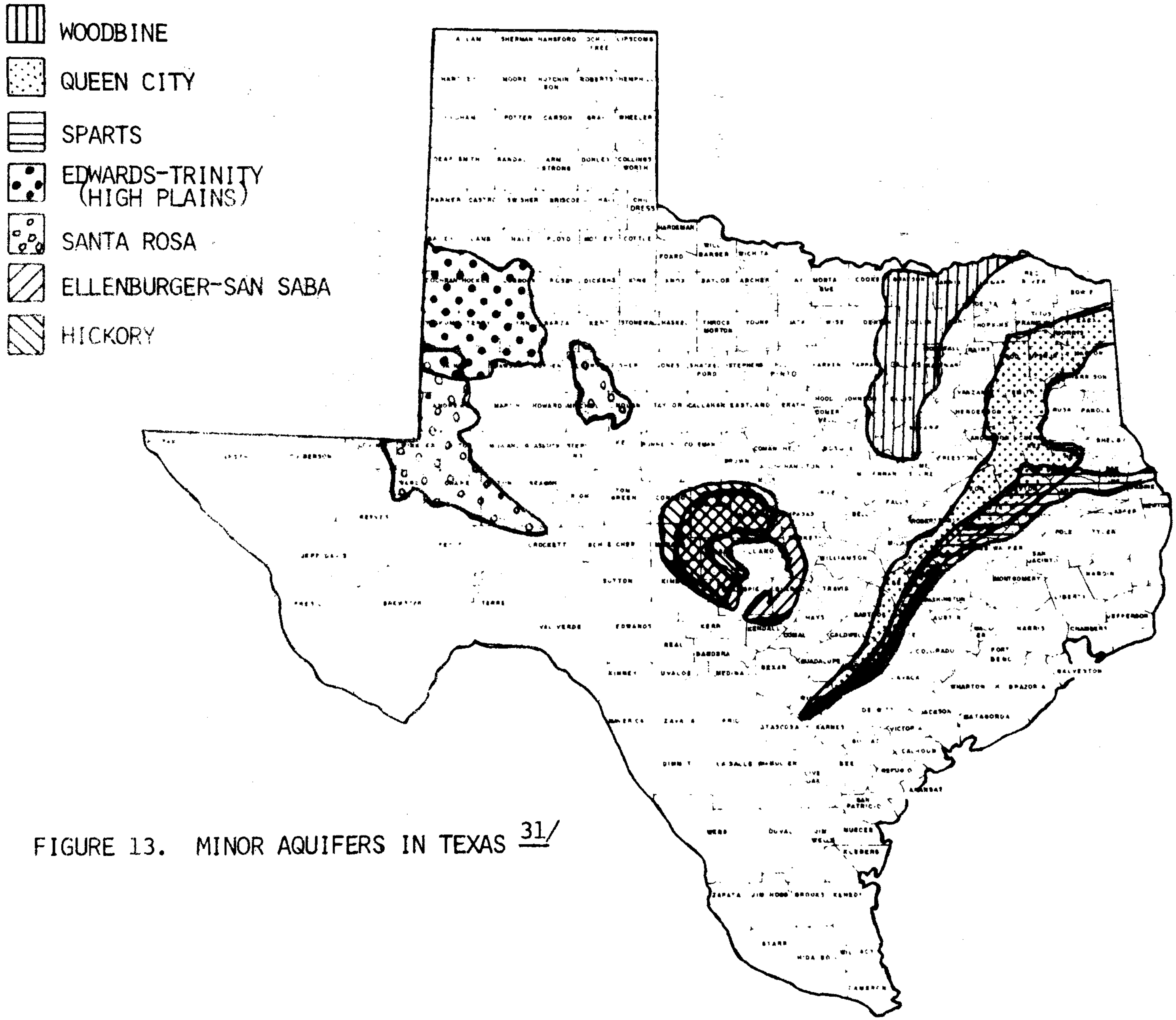


FIGURE 13. MINOR AQUIFERS IN TEXAS [31/]

Galveston County, and the subsidence of the land surface in the Houston-Pasadena-Baytown area of Harris County.

Because the coastal sands (Goliad-Willis-Lissie-Beaumont Formations) and the Miocene Sands (Catahoula-Oakville-Lagarto Formations) are lithologically similar and overlap in part of the Gulf Coast region, they are sometimes considered together as a single aquifer. They store a large amount of water ranging from 2,000 acre-feet per square mile in the Corpus Christi area to 13,000 acre-feet per square mile in the Houston area.32/

The Carrizo-Wilcox Sands which supply water for irrigation, municipal, and some industrial uses, extends from the Rio Grande northeastward across the entire state. These sands are actually composed of two separate formations. The Wilcox group of early Eocene Age contains sands which are good aquifers especially in the northeastern part of the state; however, the Carrizo Sand of middle Eocene Age is the principal aquifer of this belt and is especially productive in the south central part where fresh water occurs at a maximum depth exceeding 6,000 feet.5/ Ground water occurs in the Carrizo-Wilcox under artesian conditions, being confined by overlying beds of clay. The eastern portion of this aquifer is full; however, in the western portion, discharge by irrigation wells has exceeded the rate of annual recharge and water levels are dropping.

The Sparta-Queen City aquifers, extending from southwestern Texas into the area of the east Texas geosyncline, yield ground water of importance to local areas. The Sparta-Queen City aquifers yield small to moderate quantities of fresh to moderately saline water to wells in and near outcrop areas. Both the Sparta and the Queen City are regarded as minor aquifers, but where the two formations coincide, they may yield fairly large volumes of ground water.

High Plains

The Ogallala Formation, consisting of interfingered and intergraded lenses and layers of sand, gravel, silt, clay, and caliche, is the principal aquifer in the High Plains area, which is an erosional remnant of nearly flat country ranging from about 2,600 to 4,700 feet above sea level. The High Plains area begins at the north edge of the Edwards Plateau in northern Ector and Midland Counties and widens northward to the full width of the panhandle in the northeastern most two rows of counties. The east edge of the Plains is deeply scalloped by the valleys of the larger streams, and the Canadian River divides the Plains into northern and southern parts.

Large quantities of ground water are available from the Ogallala; however, pumpage from the aquifer is far in excess of the rate of replenishment which is about one inch annually. This heavy pumpage, principally for irrigated agriculture, has resulted in declines of the water table and lowering of well yields in some areas.

Water in the Ogallala is unconfined, and the useful life of the reservoir in each locality is determined principally by the water in storage, the rate and distribution of withdrawals, and the character of water-bearing strata. The total amount of water in storage in the High Plains is estimated to be in excess of 350 million acre-feet.32/

The northern High Plains includes an area of approximately 9,300 square miles in the Panhandle north of the Canadian River.5/ The zone of saturation in most places is 100 to 500 feet thick. Irrigation has developed slower in the northern High Plains than in the southern High Plains; therefore, at the current rate of withdrawal, the remaining water in storage will be adequate for many years.

The southern High Plains is the area of largest ground-water development in Texas. It covers about 25,000 square miles between the Canadian River and northern Ector, Midland, and Glasscock Counties. In the southern High Plains, ground water is generally of good chemical quality and is the principal source of water for all uses, of which irrigation is by far the largest. A large increase in irrigation has accompanied a substantial growth in population and municipal water demand. With the total ground-water recharge to the southern High Plains being small in comparison to the withdrawal, the supply is being seriously depleted. Measures such as conservative use of water, elimination of avoidable losses, and artificial recharge are being practiced and will prolong the life of the supply but cannot maintain it indefinitely.

Central, North Central, and Northeast Texas

There are a variety of ground-water bearing formations underlying central, north central, and northeast Texas. The major formations are: the Trinity Sands located in the northeastern and north central part of the state; the Woodbine Formation in the northeast; the Ellenberger-San Saba and Hickory Formations in the central part; and the Seymour Formation situated in north central Texas. The diversity of water quality and availability make it practical to discuss each aquifer separately.

In north central Texas, the Trinity Sands, composed primarily of the Paluxy and Travis Peak Formations of Cretaceous Age comprise the principal water-bearing formation. These sands are interbedded with layers of shale and thin beds of limestone. Most recharge to this aquifer is from precipitation and surface water sources and the largest percentage of discharge is by wells. Maximum yields of these wells vary from 50 gpm to as much as 2,000 gpm near Dallas. The largest user of ground water from this aquifer is the Dallas-Fort Worth area where in 1955 about 34 million gallons of water per day was pumped mostly from the Travis Peak Sands.5/ The total amount of water withdrawn from the entire Trinity Sands was about 60 million gallons per day in 1955 and the principal use was for municipal and industrial purposes. Water levels have been lowered so much that the cost of pumping has increased to very near the economic limit of feasibility and in many wells the drop in water levels has necessitated well reconstruction to continue production.

The Woodbine Formation, a minor aquifer of late Cretaceous Age, is one of the chief ground-water reservoirs in north central Texas. The Woodbine supplies small to moderate quantities of water to municipal and industrial wells in an area extending northward and northeastward from Waco to the Red River. The heaviest concentration of pumpage is in Dallas County where about 60 percent of the total 1960 pumpage was located.33/ This aquifer is a broad wedge of sand and sandy clay which is thickest near the outcrop and thins southeastward. The Woodbine is characterized by fine-grained sands of low permeability and low pumping yields which average about 130 gpm. The upper of the formation's two sand members generally yields saline water, and the lower yields water of good quality.

The Ellenberger-San Saba Aquifer underlies parts of Menard, McCulloch, San Saba, Kimble, and Gillespie Counties in central Texas. Although two separate geologic units, the Ellenberger and San Saba both consist of cavernous limestone and dolomite formations and are usually considered as one aquifer. This aquifer yields considerable water to springs and wells within the Llano region and is a source of water for irrigation and for small towns and communities, as well as for domestic and livestock-watering purposes. Development is small and occurs mostly in and very near its outcrop. The estimated total pumpage for 1960 was about 1,300 acre-feet with about 800 acre-feet for municipal use and 490 acre-feet for irrigation. Thickness of the Ellenberger-San Saba ranges from a few inches to over 2,000 feet and yields vary greatly from one well to another. Although some wells yield more than 1,000 gpm, most yield less than 500 gpm.34/

The Hickory Sandstone of upper Cambrian Age is the oldest groundwater aqiofer in Texas. Although it is not a major reservoir, it is of considerable local importance because it supplies the cities of Eden, Mason, and Brady, and furnishes limited supplies of water for irrigation chiefly in McCulloch and Mason Counties. The aquifer ranges in thickness from about 275 feet in the southeast part of the Llano region to 500 feet in the northwestern part.30/ Total pumpage from the Hickory in 1960 was about 10,000 acre-feet, of which 3,900 acre-feet was for municipal use, 270 acre-feet for industrial use, and 6,000 acre-feet for irrigation. Pumping rates from the Hickory range as high as 1,500 gpm but are usually in the range of 200 to 500 gpm.34/

The Seymour Formation, consisting of scattered terrace deposits of gravel, sand, and clay of Quaternary Age, is the principal aquifer in the Osage Plains region of north central Texas. Most of these deposits are small, but some are as long as 40 miles and as wide as 10 miles and range in thickness from 0 to 85 feet.5/ The larger deposits are in Wilbarger, Foard, Baylor, Knox, Wheeler, Collingsworth, Hall, Briscoe, Motley, and Dickens Counties.35/ In 1957, this aquifer supplied generally good quality water to about 1,600 irrigation wells and was a source of supply for 13 municipalities. Well yields range from 50 to more than 1,000 gpm.32/ Approximately 100,000 acre-feet of water available annually from 13 areas exceeds the present total withdrawal rate. However, pumpage in a few areas does exceed the estimated average annual recharge and pumpage from these areas may have to be reduced in the future.31/

Southwest Texas

The Edwards and Associated Limestones, the main ground-water reservoir in southwest Texas, actually forms two ground-water reservoirs. One underlies the Edwards Plateau where ground water is unconfined and the other, an artesian aquifer, underlies the Balcones fault zone. The hydrologic system of the plateau receives and stores large amounts of rainfall and slowly discharges these supplies as spring flow to perennial streams, which, in turn, recharge the artesian aquifer in the Balcones fault zone.

Although the Edwards and Associated Limestones underlie three major river basins (Nueces, San Antonio, and Guadalupe), it obtains about three-fourths of its recharge from its western part which is the Nueces River Basin.36/ Most of its discharge is through Comal Springs and San Marcos Springs in the eastern part of the area and through irrigation and municipal wells. The total discharge of the two springs in 1957 was about 210,000 acre-feet, and the total withdrawals from irrigation and municipal wells in 1957 was also about 210,000 acre-feet.32/

Pumpage of water from either the Edwards-Trinity or the Edwards Limestone (fault zone) where both aquifers occur directly affects the quantity of additional water available for development from the Edwards Limestone (fault zone) in the same basin and in adjacent basins. Because of the interrelationship of pumpage and its effect on the potential availability of additional water from the Edwards Limestone (fault zone), programs for altering or adding to the present rate of recharge will have far-reaching effects upon the economy of the area and of the state as a whole.

West Texas Area

Quaternary alluvium is the main aquifer in three relatively small but important areas in west Texas. These include the El Paso area, the Salt Basin, and the Pecos River Basin. These alluvial deposits consist generally of interconnected lenticular layers of sand and gravel interbedded with clay and silt and occur as remnants of once vast alluvial plains and as extensive stream deposits.

The El Paso area can be divided into three areas: the upper valley, which extends northward along the Rio Grande into New Mexico; the lower valley, which extends southeastward from El Paso to Fort Quitman; and the Mesa or Hueco Bolson, which extends northward into New Mexico and continues as the Tularosa Basin. The principal water-bearing beds are the Bolson deposits (valley fill) beneath the Mesa and the valley, and the younger surficial alluvium of the Rio Grande beneath the floodplain in the valley. The thickness of these deposits ranges to more than 4,900 feet, but only a relatively small part of the El Paso area receives ground-water supplies suitable for most uses.32/ Where fresh water is available, it is overlain, underlain, or adjoined by saline water, which represents an actual or potential source of contamination. The total amount of saline water, most of which is in the Bolson deposits, is probably several times as great as the amount of fresh ground water.

The Salt Basin area is a closed depression about 150 miles long and 5 to 15 miles wide. It extends from northern Presidio County across western Jeff Davis and Culberson Counties and northeastern Hudspeth County, continuing into New Mexico as the Crow Flats area. It can be divided into three main areas of irrigation called the Dell City, the Wildhorse, and the Lobo Flats. The chief aquifer is alluvium except in the Dell City area, where it is the highly permeable Bone Spring Limestone of Permian Age. Water in the Lobo Flats and Wildhorse areas is generally of good quality; however, that in the Dell City area is highly mineralized and contains objectional quantities of sulfate. Between 1950 and 1960, water levels declined as much as 19 feet in the Dell City area and 14 feet in the Wildhorse area; the decline was greatest in the Lobo Flats with declines up to 70 feet or more.5/

The Pecos River Valley is an alluvial area of substantial size in Reeves, Loving, Pecos, Ward, and Winkler Counties. Ground water is obtained from alluvial deposits and from troughs formed by subsidence of older beds and recharge is principally by runoff from the mountains to the west and southwest. Under natural conditions, water moves toward and is discharged into the Pecos River. Movement toward the river has been stopped or reduced in the heavily irrigated areas, and persistent declines in water levels indicate that the rate of pumping exceeds the maximum possible sustained yield. Irrigation development has apparently passed its peak and the Pecos River water is already fully appropriated. Since there are no other large sources of surface water, the Pecos Valley is faced with a serious lack of water supplies.

SECTION V

GROUND-WATER POLLUTION INDICATORS

Ground water is one of the most widely distributed resources of man and one of the most important. As such, it is subject to both natural and man-made contamination. To evaluate a ground-water pollution problem, it is necessary to have an understanding of indicators that reflect pollution and the concentrations at which these indicators affect beneficial uses of the water.

The concentrations at which indicators become pollutants depends upon the use to be made of the water but water pollution is generally indicated by excessive concentrations of the following:

1. Chemical indicators--Total dissolved solids, chlorides, sulfates, calcium, magnesium, fluorides, sodium, iron, boron, nitrates, phosphates, and others.

2. Biological indicators--Coliform organisms, biochemical oxygen demand, viruses, bacteria, etc.

3. Industrial indicators--pesticides, herbicides, acids, arsenic, heavy metals, detergents, phenols, gasoline, and others.

There are also many other elements that indicate pollution for a variety of reasons. An element may be a pollutant because of its toxicity--such as arsenic for humans and animals or boron for agricultural crops--or, because of its undesirable characteristic for a specific use--such as hardness in boiler waters. Standards for irrigation, domestic and a number of uses have been formulated by various agencies and some of these are presented in the appendix of this report.

Many pollution indicators reach the ground water because of man's activities, but many others contaminate ground water through natural processes not related to man. The great majority of the data referred to in this section of the report deals with water quality resulting from natural conditions. One exception may be over-pumping which sometimes causes intrusion of saline waters into otherwise fresh water areas. Very little data is available concerning specific pollutant concentrations in areas contaminated by man's activities, such as brine disposal pits or sanitary landfills, etc. The information presented in Tables 4 through 11 on pollution indicators does not imply any level of statistical reliability but is intended to give a general indication of the water quality parameters which have been detected and measured within the study area.

ARKANSAS

Although Arkansas has a large total water supply and relatively few water problems, limitations on ground-water availability or use are imposed by the chemical quality in nearly all parts of the state.

Ground water throughout Arkansas is subject to some mineralization. Much of this water has a high iron content, generally accompanied by hardness of the calcium bicarbonate type. The largest area of hard, irony water is the western two-thirds of the Mississippi Alluvial Plain.

The ground water is generally low in total dissolved solids, averaging about 271 mg/l and rarely exceeding 1,000 mg/l. The water is also very low in chloride and sulfate. Table 4 lists the major chemical constituents of the ground water in the more important water-bearing areas of the state.

Interior Highlands

Although the northwestern half of Arkansas, the Interior Highlands, contains limited ground-water supplies, the water is generally of good quality. There are, however, some natural and man-made pollutants that affect the ground-water supply.

Ground water in areas of cavernous limestone in the Ozark Plateaus, as in similar areas elsewhere in the country, is readily contaminated from surface sources and wells must be constructed properly to exclude the polluted water. These surface sources include septic tank effluents and industrial wastes.

Salt water is known to be present beneath the fresh ground water in Arkansas. In general, salt water lies at a much greater depth in the Highlands than in the coastal plain, probably because the rocks are older, higher and have had more time to have the saline water flushed out at greater depths.

Another source of saline water is the disposal of brines from oil and gas fields. A considerable part of the salt in ground water in the Arkansas River Valley area has resulted from the dumping of brine from oil and gas wells into the Arkansas River or into pits in the alluvium.8/

Gulf Coastal Plain

Nearly all the Gulf Coastal Plain, roughly the southeastern half of Arkansas, is underlain by one or more deposits that will yield fairly

Table 4. SUMMARY OF MINERALS IN GROUND WATER IN THE VARIOUS GROUND WATER REGIONS OF ARKANSAS

Location	Total Dissolved Solids (mg/l)			Chlorides (mg/l)			Sulfates (mg/l)			Total Hardness (as $CaCO_3$) (mg/l)		
	N	Range	A	N	Range	A	N	Range	A	N	Range	A
Interior Highlands												
Arkansas River Valley	72	37-1450	393	82	1.5-378	52.2	81	0.0-255	26.4	72	0.0-1100	165
Gulf Coastal Plain												
Cockfield Formation	63	27-958	212	63	2.2-58	8.6	63	0.0-470	22.4	63	5.0-488	47
Sparta Sand	82	37-776	217	82	1.0-304	44.2	82	0.0-218	7.3	82	4.0-288	62.7
Wilcox Formation ("1400 ft. Sand")	37	12-1170	157	67	0.0-540	82	67	0.0-100	4.8	67	1.0-328	18
Cretaceous Undifferentiated Deposits	9	124-637	387	97	3.2-2100	195.4	97	0.0-560	78.7	97	4.0-396	70.4
Quaternary Alluvium	89	80-652	262	298	0.5-1190	27.2	278	0.0-155	15.4	276	6.0-588	170

N - Number of determinations.
Range - Range in concentration for samples analyzed.
A - Average of concentrations for samples analyzed.

large amounts of good quality water. Because the ground water is derived chiefly from precipitation that falls as rain or snow, mineralization results from the water passing through rocks and soil to the zone of saturation.

The principal constituents that are picked up by this infiltration are calcium and bicarbonate. The $CaCO_3$ hardness ranges from 1.0 to 588 mg/l from the more productive aquifers and the average concentration is about 86.2 mg/l.7/ Water containing between 75 and 150 mg/l hardness is considered to be moderately hard.

Iron is another constituent that is present locally in objectional quantities. Iron is dissolved from many rocks and soils and concentrations range from 0.01 to 54 mg/l, generally exceeding the recommended standard quantity of 0.3 mg/l set by the U.S. Public Health Service.11/

Arsenic has been found in several areas including water wells near the Pine Bluff Arsenal in Jefferson County.

LOUISIANA

Although Louisiana contains vast amounts of ground-water supplies, it is faced with a growing number of problems. One problem is salt-water encroachment due primarily to heavy irrigation pumpage. Along with the problem of salt-water encroachment goes the potential problem of contamination of fresh water by salt domes and surficial "salt licks." Figure 14 shows the locations of salt domes which are concentrated largely in southern Louisiana; however, a fairly large number occur in the parishes immediately east of the Red Rivery Valley and also in a few parishes adjacent to the Mississippi River. In areas of shallow alluvial and terrace deposits, surface disposal of wastes is a critical problem.

Iron and hardness are a persistent problem over much of the state. Other constituents that are found to be present locally in the water in objectional quantities include fluoride, silica, sulfate, and chloride. Table 5 gives water quality data for the more important water-bearing areas of the state. Other sources of contamination present in some areas of the state include methane and hydrogen sulfide gas and oil field brines.

Southwestern Louisiana

Southwestern Louisiana is one of the largest areas of ground-water and surface water use and has several pressing problems, the most serious of which is salt-water encroachment. The transition from fresh to salt

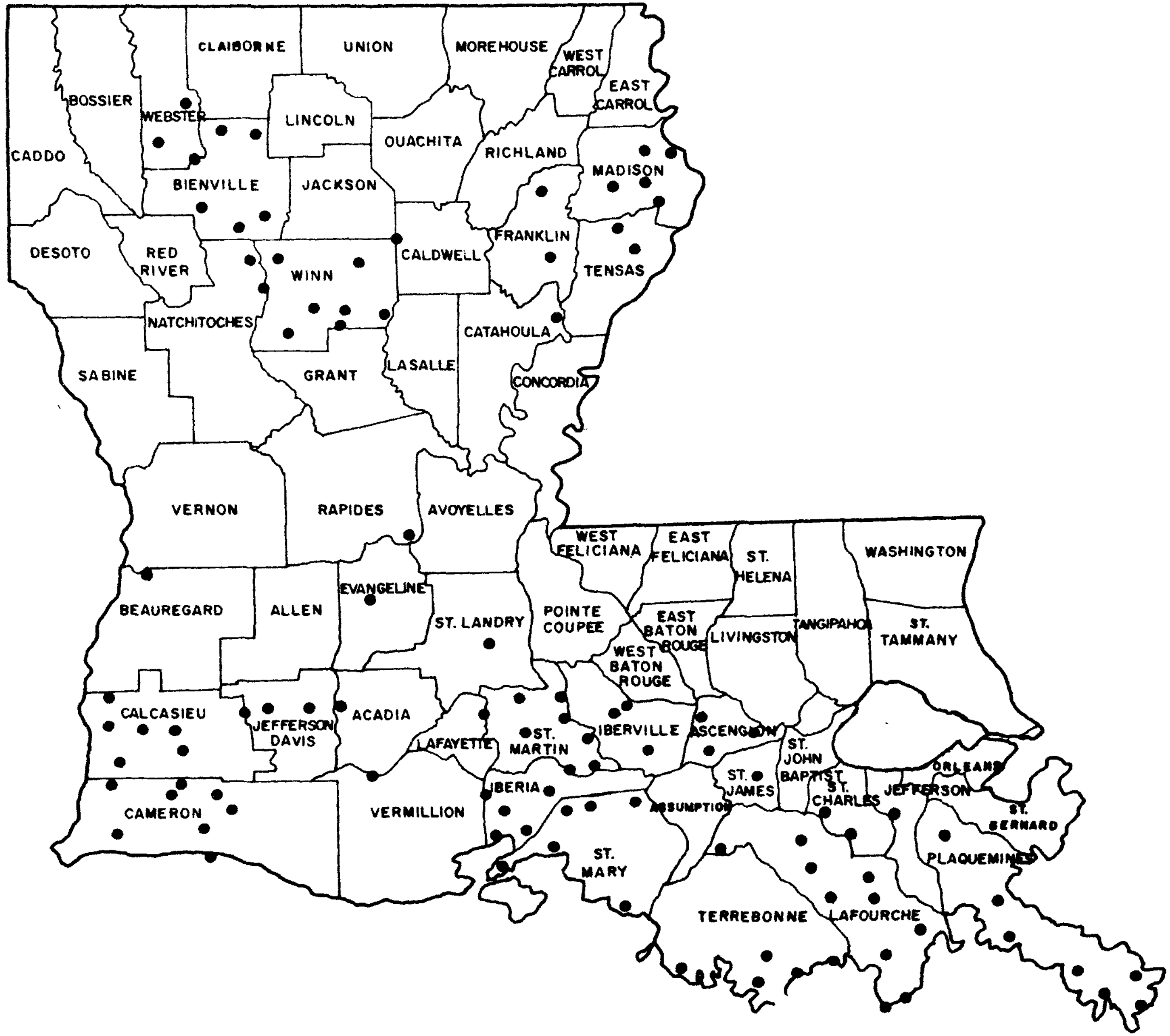


FIGURE 14. LOCATION OF SALT DOMES IN LOUISIANA

Table 5. SUMMARY OF MINERALS IN GROUND WATER IN THE VARIOUS GROUND WATER REGIONS OF LOUISIANA

Location	Total Dissolved Solids (mg/l)			Chlorides (mg/l)			Sulfates (mg/l)			Total Hardness (as $CaCO_3$) (mg/l)		
	N	Range	C	N	Range	C	N	Range	C	N	Range	C
Southwest Louisiana												
Atchafalaya	24	300-350	-	24	16-34	-	24	0.5-13	-	26	200-254	-
Chicot	32	220-248	-	29	4.2-20	-	33	0.0-17	-	29	116-181	29>100
Chicot-Atchafalaya	29	121-699	-	36	3.0-128	-	32	0.0-13	-	34	38-620	12>100
Evangeline	29	333-870	-	35	2-984	4>250	32	0.0-23	-	35	4-84	-
Baton Rouge Area												
Quaternary Alluvium	8	172-719	-	19	3.8-126	-	6	0.0-1.6	-	19	123-388	19>100
Shallow Sands (400-600 ft.)	11	184-1300	1>1000	13	3.8-113	-	11	0.8-8.6	-	13	6.5-347	1>100
Deep Sands (800-2800 ft.)	49	165-5290	1>1000	50	2.5-3050	2>250	50	0.0-12	-	49	0.0-319	1>000
Baton Rouge-New Orleans Area												
"700-Foot" Sand	30	382-3840	12>1000	34	42-2160	14>250	34	0.0-12	-	34	8-290	7>100
Mississippi River Alluvium	13	199-2839	2>1000	14	11-1470	3>250	13	0.0-23	-	14	81-446	12>100
Southeastern Louisiana	22	165-877	-	25	2.2-222	-	24	0.0-20	-	25	0.0-33	-
Northern and Central Louisiana												
Sparta Sand	32	43-1080	2>1000	33	20-214	-	30	0.2-237	-	32	0.0-168	1>100
Wilcox Group	48	3.5-4470	11>1000	56	2.5-1260	10>250	56	0.0-1080	5>250	56	0.0-975	12>100
Quaternary Alluvium of the Red River	76	51-3120	5>1000	79	2.0-687	3>250	54	0.0-495	1>250	79	8-1030	72>100

N - Number of determinations.
Range - Range in concentration for samples analyzed.
C - Number of determinations more than (>) or less than (<) selected concentrations.

water varies throughout the area, but it usually occurs in a fairly sharp zone. The base of fresh water is generally deepest in Northern Beauregard Parish where the Evangeline aquifer contains fresh water to depths greater than 3,000 feet below sea level.37/ The base of fresh water is shallowest along the coast and in the Atchafalaya River Basin.

The fresh ground water in southwestern Louisiana is generally low in chlorides and only in a few instances does it exceed 250 mg/l. The vast areas of salty or brackish water, however, contain up to 2,000 mg/l chloride.38/

The water varies from the calcium bicarbonate to the sodium bicarbonate type and tends to be softer with increased depth and distance from the outcrop areas. Some natural softening takes place due to the occurrence of natural zeolites in the underground deposits.

Water from many wells in southwestern Louisiana contains excessive amounts of silica. Silica concentrations in excess of 30 mg/l are not uncommon and occasionally concentrations of 50 to 60 mg/l are present.13/

Other constituents that are present locally in objectional quantities include iron and fluoride. In several areas the fluoride content exceeds 1.5 mg/l, the maximum allowable concentration recommended by the United States Public Health Service.

Another source of contamination to the ground-water supplies is the presence of methane gas. Methane concentrations in fresh water aquifers in southwestern Louisiana range from zero to 127 mg/l.39/ The areas of largest methane concentrations occur in the vicinity of three oil and gas-producing fields and in some wells in the vicinity of Lake Charles where continuous pumping has lowered water levels greatly. Generation of methane from organic matter within the fresh water aquifers and intrusion of methane into the aquifers from underlying oil and gas sands are two possible sources of this gas.

Water from the Evangeline and Jasper aquifers is generally of better quality than that from the overlying Chicot reservoir for uses other than irrigation. Typically, the water is of the sodium bicarbonate type, very soft, slightly alkaline, low in chloride content, and free of excessive quantities of dissolved iron.

Baton Rouge Area

Ground water in the Baton Rouge area varies from hard calcium bicarbonate type in the alluvium deposits to the soft sodium bicarbonate type in the deeper artesian sands.

The water typically exceeds 0.3 mg/l of iron and ranges as high as 18 mg/l in some parts of the alluvium. Hardness is variable according to its location and ranges from 123-452 mg/l.14/

Water from most of the deeper artesian sands is soft, alkaline and typically contains less than 0.3 mg/l of iron. Chloride concentrations are generally low except in areas where heavy pumping has resulted in salt water encroachment.40/

The shallow sands have been subject to encroachment of brackish water in the southern part of the Baton Rouge area. In reality, the fresh water in the aquifers of the Baton Rouge area is the contaminant because, initially, the aquifers were filled with salty water. The fresh water has flushed the brackish water from the formations throughout most of the area.

Baton Rouge-New Orleans Area

The chemical quality of the ground water in the Baton Rouge-New Orleans area varies greatly. Except for waters having high concentrations of chloride, all water is of the bicarbonate type. However, in some areas the water is hard to extremely hard and commonly contains iron in objectional quantities; in others, the hardness is low and the water is of the sodium bicarbonate type.

With the exception of the northeastern part of Ascension Parish, most shallow wells yield water that is very hard and relatively high in iron. The hard water containing large quantities of iron is generally associated with the Mississippi River Alluvium. The hardness, which is caused mainly by calcium and magnesium normally ranges from about 60 to 370 mg/l.41/ It has been noted that hardness increases with increasing chloride concentrations, thus, salty water may have a hardness higher than the above range. The concentration of iron ranges widely, generally from about 1 mg/l to more than 10 mg/l.

Except where there is local salt-water contamination, the chloride concentration in water from wells tapping the alluvium is generally less than 50 mg/l. Like other areas of the state, fresh ground water in the shallow aquifers has completely or partially flushed out the salty or brackish water from the formations. In the local areas where the salty or brackish water is still present, the chloride concentrations may be as high as 1,470 mg/l.15/ In general, the depth to which fresh water has displaced the salt water increases as the head of fresh water above sea level increases.

Deeper wells from the older deltaic deposits generally yield water that is relatively soft except where chloride concentrations are high. The decrease in hardness of water from deeper wells probably results from the greater distance the water has traveled from the source area, which allows greater opportunity for base exchange to take place.

In the northern part of the area, the "700-foot" sand yields fresh, soft water that is low in iron but has a distinct yellow color, generally attributed to organic debris which is common in alluvial and deltaic deposits.

Southeastern Louisiana

Ground water problems are not serious in southeastern Louisiana. Large quantities of soft, fresh water are available although there is concern about the high acidity in the northern part of the area and some waste of water from flowing wells.

Northern and Central Louisiana

The quality of ground water in northern and central Louisiana varies according to the area of the state and the formation it is derived from. The three formations that supply the majority of ground water for the area are the Wilcox Formation, Sparta Sands, and Quaternary Alluvium of the Red River Valley.

The Wilcox Formation, the oldest water-bearing sands of Tertiary Age, yield soft, high sodium bicarbonate water throughout much of the area. Water from most of the wells has an iron content greater than the maximum recommended by the U.S. Public Health Service for drinking water. Sulfate and chloride contents generally are below recommended limits, but the fluoride content commonly is greater than the recommended limit of 1.6 mg/l.42/ Dissolved solids concentrations usually exceed 500 mg/l and sometimes exceed 1,000 mg/l.

Salty water in the Wilcox group is found at depths that range from about 200 feet above sea level to more than 800 feet below sea level. The altitude of the base of fresh ground water ranges greatly; therefore, it is difficult to predict accurately the maximum depth of fresh water at any specified location.

The Wilcox group is subject to contamination by leakage from improperly plugged oil wells, movement of salt water in the vicinity of faults, downward movement of wastes in areas of surface disposal, and movement of salt water through confining beds of clay.

The Sparta Sand is the most important aquifer in northern Louisiana. It supplies ground water that ranges from soft to hard but generally contains less than 10 mg/l hardness. Dissolved solids content averages slightly more than 300 mg/l. In the unconfined aquifer, the water is soft, has a low dissolved solids content and acidic pH. The artesian water is alkaline and generally suitable for most uses, but iron content usually exceeds 0.3 mg/l.

The quality of water in the Red River Alluvial aquifer greatly restricts its use. The average hardness is 500 mg/l and the average iron content is 6 mg/l, both far above the concentration desirable for potable water.43/ The high hardness and iron concentrations in the water have their origin in the iron-bearing calcareous alluvium of the Red River through which the water moves.

The aquifer is contaminated in a few places by upward leakage of salt water from underlying formations. Such contamination generally is of small areal extent. One of the larger areas of salt water contamination is at Clarence, in Natchitoches Parish, where the water has concentrations of chloride as great at 8,000 mg/l.44/ However, salinity increases with depth and small quantities of potable water are available in the upper part of the aquifer.

NEW MEXICO

New Mexico is the westernmost state in the study area and the major ground-water quality problems are typical of most of the southwestern states. As with most of the study area, mineralization of the ground water is the most common and widespread quality problem. Nearly all ground water in New Mexico is derived from infiltration of precipitation and seepage from streams and is at least slightly mineralized because of contact with soil and rock.

Few of the aquifers in New Mexico contain exclusively fresh or saline water. Most aquifers may contain fresh water at one locality and saline water at another. In some parts of New Mexico all ground water is saline and in some of these areas all the aquifers yield comparatively small amounts of water.45/

Mineralization is normally described in terms of total dissolved solids and water containing more than 1,000 mg/l is classified as saline. The ground waters in the various regions are summarized in Table 6, and Figure 15 indicates the general areas of the state where the shallow ground water is saline. In most areas of New Mexico, mineralization or total dissolved solids results primarily from two specific ions--chlorides and sulfates. However, hardness is a problem in many areas of New Mexico as are fluorides and nitrates, and occasionally arsenic.

High Plains

The Ogallala aquifer of the High Plains contains some of the best quality water in New Mexico. Although fluoride concentrations commonly

Table 6. SUMMARY OF MINERALS IN GROUND WATER IN THE VARIOUS GROUND WATER REGIONS IN NEW MEXICO

Location	Total Dissolved Solids (mg/l)			Chlorides (mg/l)			Sulfates (mg/l)			Fluorides (mg/l)			Hardness (mg/l)			Percent Sodium (%)		
	N	Range	C	N	Range	C	N	Range	C	N	Range	C	N	Range	C	N	Range	C
High Plains	25	256-3680	7>1000	89	6.0-1750	19>250	65	15.0-2250	28>200	22	0.3-4.4	17>1.5	55	22-2400	9>1000	5	25.0-42	-
Rio Grande Valley	195	98-26500	38>1000	233	2.0-4310	55>100	210	3.5-16500	20>1000	170	0.0-4.0	17>1.5	227	11-5000	36>500 50>100	141	7.0-95	19>60
Canadian and Cimarron River Basins	97	96-8210	28>1000 16>2000	122	2.0-1390	17>100	123	4.9-5860	43>400	80	0.1-7.0	18>1.5	105	35-5360	39>300 50>100	98	7.0-97	21>60
Pecos River Basin	198	105-275000	133>1000	415	4.5-158000	97>250	394	29.0-10200	333>250	59	0.1-3.2	16>1.5	397	53-9330	319>500	127	0.0-79	6>60
Southwestern New Mexico	31	186-1659	3>1000	42	5.0-156	2>50	45	4.9-686	7>100	26	0.2-13.0	18>1.5	45	11-1094	12>200	28	24.0-93	17>60
Colorado Plateaus	200	71-4470	52>1000	227	1.4-4650	10>250	205	0.6-2880	84>250	180	0.1-7.0	22>1.5	181	3-2680	100>120	62	1.0-98	28>60
Central and Southcentral New Mexico																		
Tularosa Basin	529	45-112000	280>1000	670	4.0-66000	219>250	655	18.0-10270	428>250	314	0.0-20.0	45>1.5	464	24-16200	213>500	-	-	-
Estancia Valley	107	207-12300	-	165	3.0-5260	-	109	9.1-3230	-	99	0.0-3.8	-	108	160-8370	-	-	-	-
Crow Flats Area	6	400-3300	4>1000	21	2.0-275	1>250	21	72.0-2230	19>250	7	0.4-3.2	1>1.5	21	352-2500	-	10	0.0-5	-

N - Number of determinations.
Range - Range in concentration for samples analyzed.
C - Number of determinations more than (>) or less than (<) selected concentrations.

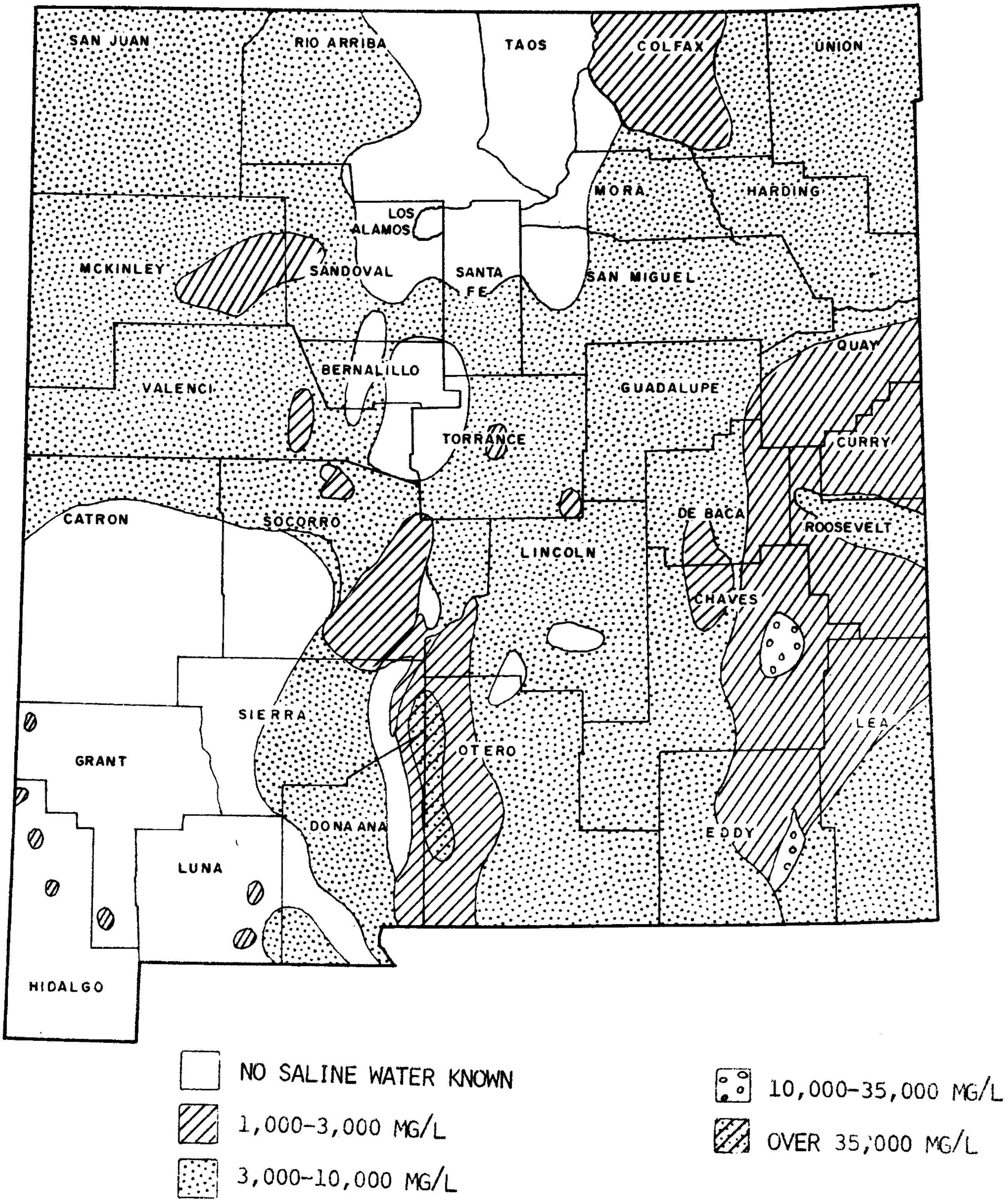


FIGURE 15. LOCATION OF SALINE GROUND WATERS IN NEW MEXICO 16/

exceed limits recommended by the U.S. Public Health Service, dissolved solids content is typically less than 1,000 mg/l. Recharge of the Ogallala on the High Plains is due entirely to inadequate precipitation and water use in this area is heavy. This combination plus a high evaporation rate leads to mining of the water supply and concentration of minerals in the remaining waters.

A typical water from the Ogallala contains approximately 25 mg/l magnesium, 50 mg/l sodium and potassium, 240 mg/l bicarbonate, 15 mg/l sulfate, 10 mg/l chloride, 2.5 mg/l fluoride, and variable concentrations of nitrates but generally less than 10 mg/l.46/

The Ogallala in some areas of the High Plains is above the water table and the Quaternary Alluvium is the major source of ground water. In the southern and western part of Lea County and in the Portales Valley, the Ogallala has been replaced by the alluvium.

Ground water from these Quaternary alluvial deposits is not as good quality as from the Ogallala and could be classified as slightly saline. Total dissolved solids are in the 1,000-2,000 mg/l range with chlorides from 100 to 600 mg/l and sulfates about 500 mg/l.45/ Water is generally high in silica (65-82 mg/l), moderately high in calcium-plus-magnesium, and low in sodium-plus-potassium.

Sandstone formations underlying the High Plains, though of low yield, are nevertheless important sources of water for stock and homes. Water quality in these formations is extremely variable but generally is more saline than either the Ogallala or the alluvium.

Oil is a problem in and around water in at least one location in the High Plains. An area of about a half-section east of Hobbs contains about six feet of oil of unknown origin covering the top of the ground-water table which is about 30 feet below the land surface.

Rio Grande Valley

The Rio Grande Valley contains the largest supply of fresh water in New Mexico. Because of the close interrelationship of the surface water with the ground water in this valley and because of continued recycling of available water, the quality of the ground water tends to decrease from the Colorado to the Texas line.

As with most of the state, mineralization is the principal water quality problem in the Rio Grande Valley. Most of the ground water in the valley near Santa Fe is low in dissolved solids (less than 300 mg/l), chlorides (less than 20 mg/l), and sulfates (less than 30 mg/l), although it could be classified as hard (155 mg/l $CaCO_3$).

In the area of Albuquerque, ground-water quality is more erratic but most wells still have less than 500 mg/l dissolved solids, 50 mg/l chlorides, and 250 mg/l sulfates. Water of the alluvial aquifer is more highly mineralized than that of the Santa Fe formation. Dissolved solids concentrations are highest at the water table but decrease rapidly in the upper few feet of the aquifer and then more slowly to the base of the aquifer.18/

Canadian and Cimarron River Basins

Ground water in the Canadian and Cimarron River Basin is scarce but generally is of fair quality. Most of the water is hard, some of it is very hard, but most of it is low in chlorides and free of odor and color. Sulfate is present in objectional concentrations in some waters. Some areas, such as western Colfax County, have ground water high in sodium chloride, sodium bicarbonate, and fluoride.

Pecos River Basin

Ground water throughout the Pecos River Basin is highly mineralized, as noted earlier in Figure 12. Virtually all of the ground water in the alluvium of the Pecos Valley south of Carlsbad is not potable. Mineral content increases progressively toward the Pecos River and generally downstream. Chloride concentrations range from less than 10 mg/l in rare instances to many thousands and even near saturation but most wells contain several hundred mg/l. Sulfate concentrations similarly are quite variable ranging up to several thousand mg/l.

Fluorides and nitrates may be problems in local areas but salinity is the major ground-water problem that overshadows all others in the basin.

Basins in Central and South Central New Mexico

The quality of ground water of the Estancia Valley differs considerably with the locality. Generally, in the alluvium, the mineral content becomes progressively higher from the outer edges of the valley to the central playa areas. Sulfates, chlorides, and hardness concentrations all range up to over 3,000 mg/l. Dissolved solids range from 207 to 6,170 mg/l and fluoride concentrations as high as 3.6 mg/l are found. Starting on a line about two to three miles east of Highway 41, ground water from there west in the Estancia Valley is generally of satisfactory quality for domestic, stock or irrigation supplies. Ground water to the east of this line is generally of poor quality--very high in salinity.

Salinity is also the major water quality problem of the Tularosa Basin. Almost 98 percent of the alluvial deposits in this basin contains sodium chloride brines with dissolved solids concentrations greater than 35,000 mg/l. The best quality water is found near the mountain fronts and generally increases in salinity with distance from the mountain front and with depth. Fresh water, or that containing less than 1,000 mg/l dissolved solids, is found at several locations of the Tularosa Basin. Two of the largest include an alluvial area south of Alamogordo and an area adjacent to the southern San Andres Mountains.19/

The great majority of the ground water of the Jornado del Muerto is also highly mineralized. The water is generally very hard but high chloride and sulfate concentrations are the principal contaminants that make the water impotable. Over 99 percent of the potential perennial yield of the more than 11 million acre-feet per year of ground water in the Jornado del Muerto is classified as impotable, using the definition of more than 500 mg/l of chloride or sulfate or more than 750 mg/l of both.47/

Basins in Southwestern New Mexico

Almost all the ground water used in the basins of southwestern New Mexico is from the alluvial deposits and is generally of good quality. In the Hachita Valley, the ground water is moderately hard and some contains excessive sulfates and fluorides but, generally, dissolved solids are less than 750 mg/l, sulfates less than 300 mg/l, and chlorides less than 50 mg/l.48/

In the Playas Valley, some of the ground water is soft but hardness and dissolved solids concentrations increase toward the northern and eastern parts of the valley. Sulfate concentrations are generally less than 80 mg/l but increase to more than 4,000 mg/l in a well in the northeastern part of the valley. Sodium concentrations are somewhat high and most wells sampled contain fluoride concentrations above the recommended maximum of 1.5 mg/l for public water supplies.49/

All of the ground water in the Animas Valley is relatively low in hardness, sulfates and dissolved solids. Sodium is moderately high, ranging up to 93 percent and most wells contain more than 60 percent which would be excessive in more highly mineralized water. Most of the ground water does contain fluoride concentrations in excess of 1.5 mg/l and one well contains as much as 13 mg/l.

The Mimbres Valley has the longest history of ground-water development in southwestern New Mexico and water is generally of good quality for most uses but some of the water does have a high fluoride content.

The San Augustin Plains is a large, almost uninhabited, basin of internal drainage in Catron and Socorro Counties. Much of the water in the central part of the basin is saline but in the southwestern part, ground water of relatively good quality is found.

Like the rest of southwestern New Mexico, ground water of the Gila and San Francisco River Basins is of good quality for most purposes. Although it could be classified as hard to moderately hard, dissolved solids range from 200-400 mg/l, chlorides and sulfates are usually less than 25 mg/l and fluorides are generally less than 1 mg/l.

Colorado Plateau

Like southwest New Mexico, the Colorado Plateau is an area of limited ground-water supplies but unlike the southwestern area, the widely available small quantities are often of poor quality.

Ground-water quality data for this area is limited but it is apparent that quality varies widely between the many different aquifers and even at different locations in the same aquifer. Ground water from the Gallup sandstone, the principal aquifer in the Gallup area, contains hard water in the range from 280 to 600 mg/l. Dissolved solids range from 740 to 968 mg/l and sulfates from 261 to 514 mg/l.20/

Similar quality water is obtained from the Chinle formation in the Fort Wingate area to the east of Gallup. Gound water used from both locations is generally low in chlorides although saline water is known to be at greater depth.50/

In the western part of San Juan County on the Navajo Reservation, small quantities of ground water are obtained from several formations, primarily sandstones. Most of this water is of relatively good quality with chlorides less than 100 mg/l and dissolved solids generally less than 1,000 mg/l. Sulfates, hardness, and sodium are high in some of the ground water used.

OKLAHOMA

Ground-water quality in Oklahoma varies greatly both with respect to the properties of the water-bearing rocks and the geographical location within the state. Quality in the west is generally inferior to that of the east due largely to the effects of rainfall and evaporation, and to the type of geologic formation. An exception to this generalization is the Ogallala Formation in the High Plains region where natural recharge is minor in relation to withdrawals.

Limestone rocks characteristic of the Arbuckle and Ozark Mountains produce relatively hard water due to the presence of calcium carbonate

Sandstones in Oklahoma generally yield a soft water containing principally sodium bicarbonate and sulfates with small concentrations of calcium carbonate.

The rocks of western Oklahoma contain much higher quantities of soluble salts than those in the east. Water from these formations is, therefore, more highly mineralized.

Water from terrace deposits or from stream alluvium again tends to be more highly mineralized in the western part of the state than in the east. Gound-water quality from these sources mirrors that of its surface counterpart with respect to chemical character but is usually a little higher in concentration. In these types of formations, both surface and ground-water quality tend to correlate with rainfall and evaporation with increases in mineralization occurring during prolonged droughts.

Deep aquifer water usually becomes more mineralized both with distance from the recharge zone and with depth. Although rare in Oklahoma, it has been found that in the Norman area shallow water is inferior to that found at greater depths.28/

Exceptions to the above generalizations occur in locations where oil field brines have contaminated both surface and ground water.

For purposes of describing ground-water quality in Oklahoma, the state has been divided into the High Plains, Western, and Eastern areas. The following section will discuss quality generally for those areas while more specific information can be obtained from Table 7, which uses the quality of municipal supplies to describe that ground-water source from which it is taken.

High Plains Area

The Ogallala Formation, which underlies most of the Oklahoma panhandle and much of Harper, Ellis and Roger Mills Counties, is composed mostly of sand and gravel with small amounts of clay. It is capped by a calcium carbonate rock called caliche.

Water from the Ogallala is of good quality with the exception of its moderate hardness which ranges between 150-300 mg/l expressed as calcium carbonate.51/ Chlorides are low and fluorides are moderately high at some times and locations.

Redbeds underlying the Ogallala do provide some water for stock watering, but it is generally very hard and high in chlorides and sulfates.

Table 7. SUMMARY OF MINERALS IN GROUND WATERS OF OKLAHOMA

Municipality	Source	Date	Total Dissolved Solids (mg/l)	Chlorides (mg/l)	Sulfates (mg/l)	Total Hardness (mg/l)	Sodium (mg/l)	Fluorides (mg/l)
HIGH PLAINS AREA								
Boise City	Ogallala	11/20/51	324	26	63	226	24	1.3
		12/63	280	24	37	153	20	1.4
Guymon	Ogallala	11/20/51	331	8.5	77	239	21	1.2
		12/64	305	12	85	192	20	1.98
Shattuck	Ogallala	1/18/51	296	12	11	230	14	0.0
		8/62	274	24	34	200	48*	0.2
		8/62	276	22	33	224	28*	0.2
Beaver	Alluvial/Terrace (North Canadian)	8/18/51	413	55	51	234	56	0.3
		2/65	330	34	36	222	26	2.02
		11/29/39	-	49	38	174	-	-
		?/61	326	34	13	184		-
Laverne	Alluvial/Terrace (North Canadian)	11/9/52	556	52	114	350	54	0.7
		2/64	600	84	74	340	71	1.05
Woodward	Alluvial/Terrace (North Canadian)	2/20/51	197	26	23	107	18	0.0
		6/65	340	64	82	152	37	0.3
WESTERN OKLAHOMA AREA								
Thomas	Rush Springs	7/26/51	618	26	183	352	70	0.1
		5/65	1150	40	1180	1048	80	0.75
		5/65	1200	40	1200	992	100	1.2
Hinton	Rush Springs	6/30/52	347	16	13	192	50	0.1
		6/64	320	24	33	258	35	0.0
Ft. Cobb	Rush Springs	8/23/51	318	7.2	79	220	13	0.3
		6/64	590	22	405	564	25	0.52
Apache	Rush Springs	8/22/51	296	7.0	12	254	15	0.1
		6/65	370	38	98	206	31	0.2
Rush Springs	Rush Springs	8/1/51	407	23	77	288	20	0.1
		7/63	280	10	32	216	7*	0.75
Marlow	Rush Springs	9/8/50	522	127	84	266	91	-
		4/65	380	16	125	272	34	0.52
Edmond	Garber	12/1/49	712	150	68	82	243	1.4
		5/65	580	84	55	136	140	1.0
Moore	Garber	6/30/52	279	7.8	6.7	222	23	0.1
		7/63	290	12	8	220	43*	0.45
Lexington	Garber	6/30/52	574	42	84	398	58	0.3
		2/64	310	16	27	220	32	0.38
Ringling	Wichita	8/21/51	675	18	66	3	277	1.3
		6/64	600	24	61	12	320	1.2
Healdton	Wichita	12/13/51	1060	139	15	12	437	1.5
		4/65	1120	192	100	32	720	2.86
Hollis	Alluvial/Terrace (Salt Fork)	8/10/50	410	14	54	250	39	
		12/63	420	14	43	274	31	0.75
Tipton	Alluvial/Terrace (North Fork of Red)	6/8/53	778	162	87	336	160	0.7
		9/65	680	138	1	276	148	0.75
Davidson	Alluvial/Terrace (Red)	1/30/52	516	48	59	334	56	0.7
		6/65	590	90	90	352	72	1.05
Wynnewood	Alluvial/Terrace (Washita)	8/14/52	516	48	59	334	56	0.7
		3/65	680	56	65	352	195	1.47
Maysville	Alluvial/Terrace (Washita)	12/13/51	731	38	69	590	50	0.3
		3/65	920	110	195	616	79	0.45
Yukon	Alluvial/Terrace (North Canadian)	6/30/52	807	66	138	505	103	0.5
		6/62	702	84	-	408	13*	0.7
		6/62	403	84	-	156	9*	0.7
Waynoka	Alluvial/Terrace (North Canadian)	6/9/51	310	16	32	202	76	0.1
		8/64	220	26	25	232	74	0.38
Crescent	Alluvial/Terrace (Cimarron)	10/23/51	642	112	54	400	76	0.1
		11/64	280	28	19	158	38	0.52
Tonkawa	Alluvial/Terrace (Arkansas)	11/24/52	644	16	216	423	50	0.1
		11/63	640	42	245	466	54	0.3
Kaw City	Alluvial/Terrace (Arkansas)	10/23/52	616	90	76	384	65	0.3
		2/64	790	142	91	412	88	0.38

Table 7. SUMMARY OF MINERALS IN GROUND WATERS OF OKLAHOMA (Continued)

Municipality	Source	Date	Total Dissolved Solids (mg/l)	Chlorides (mg/l)	Sulfates (mg/l)	Total Hardness (mg/l)	Sodium (mg/l)	Fluorides (mg/l)
EASTERN OKLAHOMA AREA								
Drumwright	Vamoosa	7/25/50	300	8.2	63	208	-	-
		9/63	350	20	37	84	103*	0.05
Bristow	Vamoosa	7/24/51	457	54	44	314	38	0.1
		5/65	680	252	44	360	96	0.0
Stroud	Vamoosa	7/23/51	2480	400	1080	528	619	0.9
		6/64	450	16	123	42	41	1.64
Prague	Vamoosa	10/24/51	409	11	29	12	161	0.3
		1/64	375	18	10	24	160	0.45
Boley	Vamoosa	7/24/51	263	12	8.8	221	14	0.1
		6/65	450	16	123	42	41	1.64
Seminole	Vamoosa	5/1/51	244	4.5	47	124	40	0.3
		6/65	235	12	37	156	23	0.52
Roff	Arbuckle	10/26/51	468	91	35	297	66	0.3
		9/64	470	95	22	284	69	0.75
Sulphur	Arbuckle	3/9/51	344	5.0	16	330	7.1	0.0
		9/64	320	12	0	300	8	0.52
Marietta	Trinity	3/2/51	427	13	45	48	145	0.1
		7/65	450	30	53	36	210	0.82
Kingston	Trinity	3/19/48	612	21	87	22	-	0.1
		3/65	570	18	45	8	40	0.6
Caddo	Trinity	12/27/52	503	20	32	2	201	0.1
		12/63	420	16	49	22	150	0.45
Bennington	Trinity	8/16/51	827	74	38	4	336	1.3
		12/63	870	78	39	16	332	1.36
Boswell	Trinity	12/27/52	621	83	70	394	43	0.0
		7/63	427	36	73	310	14*	0.3
Ft. Towson	Trinity	6/11/53	189	11	11	148	6.0	0.1
		12/64	195	12	15	188	4	0.2
Garvin	Trinity	8/16/51	308	16	42	40	100	0.9
		4/65	305	24	42	48	92	0.68
Haworth	Tokio	12/27/52	69	17	0.3	16	9.6	0.0
		2/65	52	14	5	30	13	0.45
Stillwell	Boone	9/11/51	147	6.2	4.1	120	3.9	0.0
		12/63	150	12	10	128	2	0.38
		12/63	165	10	20	136	23*	0.12
Locust Grove	Boone	8/30/51	129	5.5	6.5	100	3.5	0.0
		4/65	95	12	12	66	10	1.36
Commerce	Boone	9/6/51	159	8	16	123	9.6	0.5
		4/65	200	22	26	136	20	0.2
Miami	Roubidoux	5/15/51	217	42	15	135	29	0.3
		2/65	360	102	15	134	68	0.52
Quapaw	Roubidoux	9/6/51	152	4	18	130	4.4	0.3
		12/64	140	8	10	118	7	0.2
Afton	Roubidoux	9/6/51	758	348	18	172	220	1.8
		12/64	850	379	10	184	144	1.3
Davis	Alluvial/Terrace (Washita)	8/14/52	646	82	38	388	78	0.0
		9/64	620	94	5	376	63	0.3

*Calculated

Water from alluvial deposits varies greatly in its chemical composition, ranging from that similar to the redbeds to that comparable to the Ogallala. Alluvial deposits along the North Canadian and Cimarron are higher in mineral composition than the Ogallala.

Western Oklahoma Area

A major source of ground water in southwestern Oklahoma is the Dog Creek and Blaine Formations in Harmon and parts of Greer and Jackson Counties. The aquifer consists of interbedded shale, gypsusm, anhydrite, dolomite, and limestone. Due partly to the type of rocks in the formation and to apparent over-development of the aquifer, water quality is very high in sulfates (1,500-2,000 mg/l) and often high in chlorides.52/

As in most sandstone aquifers. water quality in the Rush Springs Formation is good except for moderate hardness, which is generally between 200-300 mg/l. This is due to patches of gypsum on the outcrop which have contributed sulfate to Rush Springs water. Otherwise, both the Rush Springs and Elk City aquifers are of good quality suitable for domestic, municipal, irrigation, and industrial use.

The Garber-Wellington Formation lies principally in Oklahoma and Cleveland Counties. It consists of sandstone, shale, and conglomerate. The chemical quality of this aquifer is generally good and suitable for most purposes. Dissolved solids are less than 500 mg/l in Oklahoma County but may go up to 1,500 mg/l in Cleveland County.25/ Water is moderately hard in the outcrop area and characterized by calcium and magnesium bicarbonate. In the Norman area the water is very soft, being of the sodium bicarbonate type. Farther downdip in McClain County and in western Oklahoma County the sandstone grades into shale, and the water is highly mineralized. In other areas, wells obtain fresh water from depths of 1,000 feet.

The Wichita Formation provides small quantities of water to much of Stephens County and parts of Garvin and Carter Counties. Being of about the same age and composition as the Garber-Wellington, its chemical characteristics are similar. Like most waters from sandstone, it can be rather high in sodium bicarbonate and sulfate. The water is moderate to high in fluorides.

In some unusual cases, private wells obtain water from the Arbuckle in the vicinity of Lawton. In this area, the water is a soft, sodium bicarbonate type and contains high concentrations of fluorides.

Alluvial and terrace deposits are most important along major rivers, but some small municipalities have developed sources along tributaries. Generally, these deposits are of the poorest quality in the western part of the area where sodium chloride and gypsum deposits exist. Ground water, much like surface water, tends to improve toward the east by moving away from these mineral deposits and dilution becomes effective. Alluvial and terrace deposits of the Cimarron River, Salt Fork of the Arkansas, and Elm Fork of the Red Rivers in the west are particularly high in chlorides.28/

Eastern Oklahoma Area

The Vamoosa Formation, like the Garber-Wellington, is composed of sandstone, shale, and conglomerate. It extends as a narrow formation from Seminole County northerly to Osage County where it outcrops. The presence of large amounts of shale and siltstone in the outcrop area limits its use in the northern part of the formation. Although water quality is generally good, hardness and sulfate present the most troublesome problems. Hardness is generally in the range from 300-1,500 mg/l 25/; however, in a 1951 sample from Stroud's municipal supply, hardness was reported to be 2,480 mg/l and sulfates amounted to 1,080 mg/l.

Well development in the Arbuckle Formation is at the present time sparse but it serves as a large potential water supply for parts of Pontotoc, Murray, and Johnston Counties. Although water in the Arbuckle is moderately hard, it is otherwise low in dissolved solids and is considered good for most purposes.53/

The Trinity Sands exist along the southern border of Oklahoma from Love County to the Arkansas state line. A number of private and municipal wells take water from this formation. Water quality is generally good and is characterized as being of the sodium bicarbonate type with low hardness except in a few locations. A few samples indicate that this water contains amounts of one or more constituents in excess of recommended limits.54/ In one instance, a fluoride concentration of 3.0 mg/l was reported which exceeded the drinking water standard of 1.5 mg/l. Mineralization in the Trinity tends to increase slightly downdip from the outcrop area.

There are four water-bearing formations in the extreme southeastern corner of Oklahoma, other than the Trinity and the river alluvium. These are the Goodland, Tokio, Woodbine, and Washita. Quality data for these formations is very scarce but indications are that these waters are often high in dissolved solids with the Woodbine and Washita being particularly troubled by chlorides. One sample from the Goodland was high in sulfates with a concentration of 778 mg/l.

The Boone Formation, located in the northeastern part of the state, consists mainly of fractured massive chert with beds of cherty limestone in the lower part. It is one of three major aquifers located in the same general area. In addition to analyses of municipal supplies which take water from this formation, as shown in Table 7, Table 8 presents a statistical summary of water quality in the Boone Formation.

Table 8. SUMMARY OF CHEMICAL ANALYSES OF WATER FROM BOONE AQUIFER 27/

	Concentration (mg/l)			Number of
	Maximum	Median	Minimum	Analyses
Hardness	328	154	26	28
Sulfate	79	10	0.2	28
Chloride	103	10	0.2	28
Nitrate	79	5.2	0.1	25
Total Dissolved Solids	494	236	106	28

Where the aquifer is more deeply buried than 200 feet, it becomes less favorable as a water resource both from the standpoint of quality and quantity.

The Roubidoux Formation consists of sandy and cherty dolomite. It is of generally good quality in Ottawa County where it is characterized as a calcium bicarbonate type, but it changes to sodium chloride farther west in Craig and Mayes Counties and becomes unusable for most purposes. The water in Craig County also contains hydrogen sulfide. In addition to Table 7, which deals with municipal supplies, Table 9 summarized water quality in the Roubidoux.

Table 9. SUMMARY OF CHEMICAL ANALYSES OF WATER FROM THE ROUBIDOUX AQUIFER *27/

	Concentration (mg/l)			Number of
	Maximum	Median	Minimum	Analyses
Hardness	420	146	118	32
Sulfate	124	16	0.3	32
Chloride	780	79	1.6	32
Nitrate	8.0	0.8	0.0	32
Total Dissolved Solids	1570	276	140	32

*Includes several analyses of water from other deep aquifers.

The Burgen Sandstone is a third major formation in the northeastern part of the state. It is mainly fine to medium-grained sandstone with some shale, limestone and dolomite. Many of the wells in this formation yield hard water but the sulfates, chlorides, and nitrates are generally low. A summary of water quality for this formation is presented in Table 10.

Table 10. SUMMARY OF CHEMICAL ANALYSES OF WATER FROM THE BURGEN SANDSTONE 27/

	Concentration (mg/l)			Number of
	Maximum	Median	Minimum	Analyses
Hardness	404	118	9	20
Sulfate	166	16	0.6	20
Chloride	92	12	2.4	20
Nitrate	26	1.1	0.0	20
Total Dissolved Solids	900	221	118	20

The alluvium along the Arkansas River is one of the most favorable sources of water in the northeastern part of the state. It yields relatively large amounts of water of low mineral content and is chemically suitable for most purposes.55/ Most other alluvium deposits in this part of the state are characterized as being hard and many samples indicate that the dissolved solids exceed 500 mg/l. Generally, sulfates, chlorides, and nitrates of the Arkansas River alluvium are low.

Two samples from the Red River alluvium in southern McCurtain County show that the water, at least in that location, is of good quality with dissolved solids being less than 200 mg/l and all other parameters being well within the criteria for drinking water.54/

Generally, water quality in alluvial deposits in the eastern Oklahoma area tends to mirror that of the stream with perhaps higher mineral concentration. Exceptions to this occur broadly over the area, a result of the activities of man particularly with respect to contamination by oil field brines.

TEXAS

Texas is a state plagued by many ground-water problems. The ground-water quality is threatened by the discharge of wastes, by increases in mineralization as a result of recycling of irrigation return flows and seepage losses, modification through pumping of the natural hydrodynamics of aquifers, just to name a few.

The chemical quality of the ground water varies from aquifer to aquifer and from place to place within the same aquifer. Table 11 indicates the concentration of the major chemical constituents in the various aquifers throughout the state. Other chemical constituents that may be present in excessive amounts include fluoride, iron, hydrogen sulfide and methane gases, and silica.

Coastal Area

Coastal-Miocene Sands

Ground water from the coastal-Miocene sands is generally fresh to moderately saline, with salinity increasing toward the Gulf. The concentrations of chemical constituents range widely. Throughout most of the eastern part of the area, the ground water is low in dissolved solids, generally containing less than 500 mg/l. Sodium and bicarbonate are the principal constituents and the water is comparatively soft. The presence of iron and dissolved gases are problems locally.

The ground water generally becomes more saline in the southern part of the aquifer and in some areas highly saline water immediately overlies and underlies the fresh water aquifer.56/ In the Rio Grande Valley, ground water pumped from the aquifer for irrigation and municipal use typically contains between 1,000 and 1,500 mg/l of dissolved solids.65/

Carrizo-Wilcox Sands

The chemical quality of the ground water from the Carrizo-Wilcox Sands varies with location and depth. Ground water that is relatively low in mineral content and suitable for most purposes is found in and near outcrop areas and the quality generally deteriorates downdip. The water is generally soft; however, moderate to very hard water may be encountered in local areas. Most water that is being used from the aquifer contains less than 1,000 mg/l dissolved solids. Iron, silica, and hydrogen sulfide and methane gas may be present in objectionable quantities locally. The Wilcox Sands have lignite stringers in some places that impart an undesirable color to the water.

Sparta-Queen City Aquifers

The Sparta-Queen City Aquifers contain water of good chemical quality that extends downdip for a considerable distance and remains fairly uniform in quality. The ground water is soft and the dissolved solids

Table 11. SUMMARY OF MINERALS IN GROUND WATER IN THE VARIOUS GROUND WATER REGIONS OF TEXAS

Location	Total Dissolved Solids (mg/l) N	Total Dissolved Solids (mg/l) Range	Total Dissolved Solids (mg/l) C	Chlorides (mg/l) N	Chlorides (mg/l) Range	Chlorides (mg/l) C	Sulfates (mg/l) N	Sulfates (mg/l) Range	Sulfates (mg/l) C	Total Hardness (as $CaCO_3$) (mg/l) N	Total Hardness (as $CaCO_3$) (mg/l) Range	Total Hardness (as $CaCO_3$) (mg/l) C
Coastal Area												
Coastal Sands-Miocene Sands	837	20-14356	92>1000	1060	6.0-8500	63>250	843	0.0-2490	41>250	721	0.0-2389	32>500
Miocene Sands	385	12-15100	15>1000	380	0.5-3060	22>250	377	0.0-608	2>250	361	1.0-1960	35>100
Coastal Sands	649	217-129957	154>1000	811	12-72000	383>250	737	0.0-10870	76>250	752	12-29400	101>500
Carrizo-Wilcox	1130	12-25342	204>1000	1458	0.5-15050	206>250	1257	0.0-4000	103>250	1384	0.0-3040	461>100
Sparta and Queen City	56	29-1361	7>1000	56	2.0-464	2>250	56	0.0-336	5>250	56	2-228	6>100
High Plains	189	199-9733	55>1000	276	1.6-3000	37>250	272	11-4570	62>250	264	13-2790	55>1000
Central, North Central, and Northeast Texas												
Trinity Sands	361	104-41414	138>1000	409	2.4-2880	54>250	405	5-4380	113>250	400	1.0-3320	58>500
Woodbine Formation	91	444-5650	72>1000	136	2.4-1540	18>250	132	11-1460	33>250	129	1.9-610	15>100
Ellenburger, San Saba, and Hickory	14	561-598	-	14	76-101	-	14	32-105	-	14	342-450	12>350
Seymour Formation	286	91-55400	96>1000	286	3-35100	87>250	286	0.0-1340	81>250	286	6-20000	54>500
Southwest Texas												
Edwards-Trinity	417	231-69000	141>1000	431	4-3600	64>250	424	4.6-6800	120>250	419	145-2590	34>1000
Edwards Limestone	20	311-10300	4>1000	20	18-4500	8>250	20	10-1800	5>250	17	9-1610	6>500
West Texas Area												
El Paso Area	228	970-4807	2276*	228	340-1990	743*	228	422-2390	960*	-	-	-
Big Bend Area	317	188-2980	227>1000	322	7-1790	178>250	320	13-2370	212>250	341	37-3240	173>1000
Pecos River Basin	136	134-74300	43>1000	203	3.2-58600	113>250	190	10-6100	76>250	184	64-10400	43>1000

N - Number of determinations.
Range - Range in concentration for samples analyzed.
C - Number of determinations more than (>) or less than (<) selected concentrations.
*Average

range from about 100 to less than 700 mg/l. Some excessive amounts of iron are present locally and a number of wells tapping these aquifers have been reported to contain hydrogen sulfide gas. Improper casing and casing leaks in oil wells, as well as improper disposal of wastes and inadequate protection measures, have allowed water of poorer quality to enter the fresh water producing strata.

High Plains

The chemical quality of the ground water in the Ogallala aquifer varies widely within relatively short distances. The ground water is generally hard and in almost all cases its fluoride content exceeds the 1.5 mg/l limit recommended by the U.S. Public Health Service for municipal supplies. The water typically contains between 300 and 1,000 mg/l dissolved solids, of which calcium, magnesium, and bicarbonate are the principal constituents. In general, the water of better quality occurs in those areas where the depth to water is greatest. Waters that are highly mineralized because of natural causes are often associated with areas of shallow water-table conditions, notably areas near water-table lakes and near draws. This is evident in the vicinity of the Lost Draw complex of Terry, Lynn and Dawson counties. In areas where the water table is at or very near the land surface, evapotranspiration processes produce highly mineralized ground waters by the concentration of residual salts.34/

Central, North Central, and Northeast Texas

Trinity Sands

Ground water derived from the Trinity Sands formation is typical of the sodium bicarbonate type and is generally of good quality. Dissolved solids concentrations are usually less than 1,000 mg/l and the chloride and sulfate content is low. In a few limited areas near the outcrop area, the ground water contains excessive amounts of iron.

Water in the outcrop areas is generally hard but otherwise of good chemical quality. Eastward, downdip from the outcrop, the water becomes softer, but total solids, sodium, sulfates, chlorides, and fluorides increase. Toward the east, in deeper parts of the aquifer, dissolved solids range from about 500 to 1,500 mg/l.30/

Evidence of encroachment of salt water has caused concern in some areas underlain by the Trinity Sands. Salt water contamination in the heavily pumped Sherman area has caused increases in chloride content in many of the public-supply wells.35/ Improper plugging of oil and water test holes has allowed saline water in overlying beds to enter the fresh water-bearing zones of the Trinity Sands in many areas.

Woodbine Formation

The Woodbine Formation supplies considerable amounts of variable quality ground water. This water is characterized by a high sodium bicarbonate content and generally high concentrations of iron, dissolved solids, sulfates, fluorides, and in some places chlorides. Except for higher iron concentrations and localized hardness, Woodbine water is usually of best quality in the outcrop area that extends from central Johnson County across eastern Tarrant County, eastern Cooke and western Grayson County to the Red River. Downdip to the east, the water becomes progressively more mineralized and exceeds U.S. Public Health Service recommended limits in many locations.

Ellenberger-San Saba and Hickory

Ground water usually occurs in the Ellenberger-San Saba aquifers under artesian head and is usually of good quality, although very hard. Dissolved solids content is consistently less than 1,000 mg/l. The chemical quality of the ground water deteriorates rapidly away from the outcrop areas and at distances greater than 20 miles downdip, the water is generally unsuitable for most uses. In the northwestern part of the aquifer, mineralization is due to sodium and chloride and in the southeastern part to calcium and sulfate.

The Hickory Formation contains water of the sodium bicarbonate type and, although sometimes objectionably hard, is generally suitable for most uses. Dissolved solids generally range from about 300 to 500 mg/l. The poorest quality water used is found in the vicinity of Eden, in Concho County where the dissolved solids range from about 1,000 to 1,500 mg/l.

Few contamination problems have occurred except at great distances from the outcrop areas, where there may be a possibility of saline waters being drawn into a cone of depression caused by excessive pumpage. Local contamination has occurred at Melvin in McCulloch County and into uncased wells or where salt water has entered the well through corroded casings.34/

Seymour Formation

Ground water from the Seymour Formation is very hard, and the dissolved solids content generally exceeds the standards recommended by the U.S. Public Health Service. Sulfate and chloride content is generally high, sulfates ranging up to about 1,200 mg/l.35/

Salinity has increased in much of the water from the Seymour. This is due primarily from excessive pumpage from the ground-water sources.

Ground water in these areas also contains relatively high concentrations of nitrate, which are considered to be undesirable for human consumption.

Southwest Texas

Edwards-Trinity (Plateau) Aquifer

Ground water from the Edwards Plateau aquifer is generally very hard and has a wide range in dissolved solids. The dissolved solids tend to increase in a northerly direction. Calcium, magnesium and bicarbonate are commonly the principal chemical constituents. Locally, concentrations of fluoride range up to 2.8 mg/l.

Salinity increases toward the west where the aquifer is overlain by younger geologic formations. The water in these younger formations contains saline water and has probably leaked into the fresh water aquifer. Oil field brines are another source of contamination that contributes to the salinity of the Edwards-Trinity Aquifer.

Edwards-Balcones Fault Zone

Ground water from the Edwards and Associated Limestone (Balcones Fault Zone) is almost uniformly calcium bicarbonate water of good quality, except it is very hard. The hardness generally exceeds 200 mg/l. Dissolved solids are relatively low, as in Bexar County where they average around 300 mg/l. The mineral content of the water increases as the artesian pressure decreases along the southern and southeastern boundary of the aquifer.

Highly saline water also containing hydrogen sulfide gas occurs in the limestone beds south of the heavily pumped areas of the Balcones Fault Zone. As a result, there is a possible threat of saline water intrusion into the fresh water supplies.

West Texas Area

El Paso Area

Ground water supplies in the El Paso area range from fresh to very saline. Fresh ground water constitutes a small fraction of the total quantity of water in storage. Where fresh ground water is available it is underlain, overlain, or adjoined by slightly saline water, thus, endangering the quality of the fresh water. The water is generally soft to moderately hard, but varies greatly areally and with depth.

Salt Basin Area

The quality of ground water ranges between wide limits, but most is of relatively good quality. The ground water occurs chiefly in deposits of Quaternary Alluvium and is, for the most part, hard and high in fluoride content. In many areas, the water is unsuitable for domestic purposes because of the high sulfate content.

South of Van Horn in Culberson County, water from Quaternary deposits is typically low in dissolved solids, chloride, and sulfate content. As you move northward into the Wildhorse Flat area, the ground water increases in mineralization, as well as chloride and sulfate content. Even further northward in the Dell City area, ground water is slightly to moderately saline. Dissolved solids range from less than 1,000 mg/l east of the Culberson County line to nearly 8,000 mg/l near the southwest edge of the Salt Lakes.56/ Hardness concentrations average around 1,200 mg/l and fluorides average about 1.4 mg/l.

The increasing salt content of the ground water is a serious problem in the Dell City area. As irrigation continues and ever-increasing amounts of excess water are applied in order to leach the accumulated salts from the soil, it can be expected that the salinity of the ground water will increase even further.

Pecos River Valley Alluvium

Ground water in the Pecos River Valley is derived mainly from alluvial deposits of Quaternary Age. The quality of this water varies with location and depth. Normally, wells penetrating the deeper parts of the alluvium yield water with higher mineral concentration than wells tapping the shallower alluvial material.

Dissolved solids range from around 200 to 13,000 mg/l with the water nearer the Pecos River containing the highest concentration of dissolved solids. Water of poorer quality near the river has moved into some fresh water areas where heavy pumpage has lowered the water levels. The fresh water typically contains 700 to 800 mg/l of sulfate and chloride and usually contains less than 200 mg/l of bicarbonate.

In some areas of the Northeastern Pecos Valley, waste water from oil production and possibly other sources has, apparently, contaminated the alluvial aquifer, resulting in higher mineral concentrations than normally is expected.

SECTION VI

CAUSES OF GROUND-WATER POLLUTION

In the previous section, some of the measured parameters of ground-water pollution were discussed and summarized for each section of the project area. Most of the available data is related to mineral parameters probably resulting from natural conditions although little attempt was made previously to assign a cause of pollution.

In fact, poor quality ground water may result from a combination of several contributing factors or sources. In this section, various conditions or activities which have a known or suspected polluting effect on ground water are discussed approximately in the order of their significance in the project area:

Natural Pollution

Oil Field Brines

Well Construction

Overpumping

Irrigation Return Flows

Land Application of Wastes

Solid Wastes

Evapotranspiration by Native Vegetation

Animal Wastes

Waste Lagoons

Accidental Spills of Hazardous Materials

Subsurface Waste Disposal

Artificial Recharge of Aquifers

Other Causes

Locations and specific pollution cases are not intended to be all-inclusive but can serve as examples of pollution types and locations. Those cases cited are only the ones obvious enough to be noticed by a complainant and bad enough to be investigated. Undoubtedly, there are dozens of other cases that were noticed and investigated but did not come to the attention of the authors. There are also probably thousands of other instances of ground-water pollution that are yet to be recognized as such.

Natural Pollution

Natural pollution occurs to some extent throughout the five-state area but is especially important in several locations in Texas, Oklahoma and New Mexico. This problem undoubtedly affects the quality of more ground water in the project area than all other sources of contamination combined.

Mineralization due to leaching is the most common type of natural pollution. Natural leaching may take place within a water-bearing aquifer or within the soils and rocks of the watershed area. Natural accumulation of soluble minerals is greatest in areas of low precipitation, especially where ground water is near the surface and evaporation and transpiration combine to concentrate the minerals in the waters left behind. Precipitation percolating through the salt laden soils or ground-water movement takes some of the minerals in solution and carries them into the aquifer. Where hydrogeology permits, the resulting highly mineralized water may even return to the surface as springs and contaminate surface water.

The source of much highly mineralized water in the south central states is located in an area known as the Permian Basin (Figure 16) which underlies large sections of Oklahoma, New Mexico and Texas. Rock formations of Permian Age are composed of red and gray gypsiferous shale, siltstone, sandstone, gypsum, anhydrite, dolomite, and sometimes halite. Halite usually occurs as lenses in relatively impervious shales, but thick massive beds are not uncommon. Leaching of the salt is generally accomplished by small quantities of water which pass through small joints and fractures.

In the Permian Basin, salt water occurs at depths of less than 100 feet to more than 1,000 feet. In much of the area, leaching of salt-bearing formations near the surface and regional circulation of water from outcrop areas on the west to outcrop areas in the east result in springs and seeps which contaminate much of the surface water of the Pecos, Arkansas, Red and Brazos Rivers. Although flow from these springs is small, chloride concentrations in the water range up to 190,000 mg/l depending on the dilution by fresh water. Alluvium near these springs is saturated with high chloride, high sulfate waters and evaporation

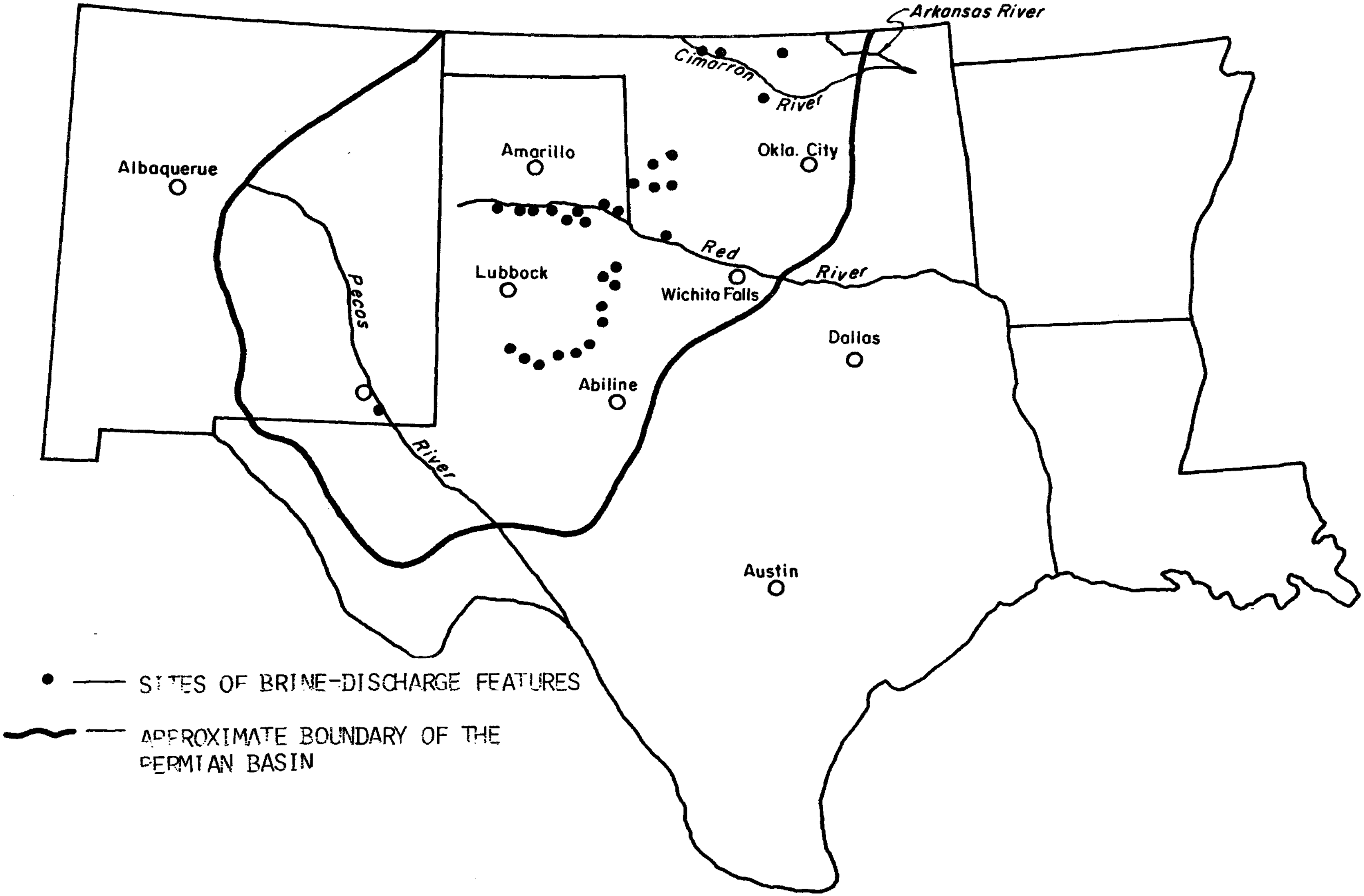


FIGURE 16. APPROXIMATE BOUNDARY OF THE PERMIAN BASIN

from the surface causes the formation of salt crust during dry weather. These springs are estimated to contribute over 20,000 tons of sodium chloride per day to the waters of the Arkansas, Red, Brazos and Pecos Rivers.

Although not as obvious at the surface as in the Permian Basin, natural leaching of minerals into the ground water affects tremendous volumes of ground water in other parts of the five-state area. A fairly typical cross-section of the water quality of the intermountain valleys of south central New Mexico is shown in Figure 17. This particular cross-section indicates that most of the ground water of the Tularosa Basin contains more than 35,000 mg/l of dissolved solids. Near the basin recharge area--the mountains on the west--ground water near the surface is relatively fresh with less than 1,000 mg/l of dissolved solids. However, as the water moves into the basin through the salt laden alluvial material, soluble minerals are dissolved, adding to the mineral content of the water.

Where bedrock is igneous and alluvial fans are composed of detritus from igneous rocks, percolating waters will be of calcium magnesium bicarbonate type. Where the bedrock and alluvial deposits are moderately soluble limestones and dolomites, the water in the alluvial fans is a relatively fresh calcium bicarbonate type. Alluvial fans which receive runoff from areas underlain by soluble evaporite deposits contain water high in calcium sulfate and sodium chloride.19/

The effect of natural leaching can be seen in relative amounts of fresh and saline ground waters available in parts of south central New Mexico, as summarized in Table 12. Potable water is defined as having less than 250 mg/l chlorides or sulfates, inferior water has more than 250 mg/l of chlorides or sulfates but less than 750 mg/l of both, and impotable water has more than 500 mg/l of either or more than 750 mg/l of both.

Table 12. SUMMARY OF ESTIMATED GROUND WATER AVAILABLE IN TULAROSA BASIN AND VICINITY 47/

	Potential Perennial Yield (Ac.-Ft./Yr.)		
Area	Potable	Inferior	Impotable
North Jornada del Muerto	30	200	11,000,000
North Tularosa Basin	30	200	6,000,000
Crow Flats-Dell City Area	300	1,000	4,000,000
Southern Tularosa Basin	60,000	5,000	65,000,000

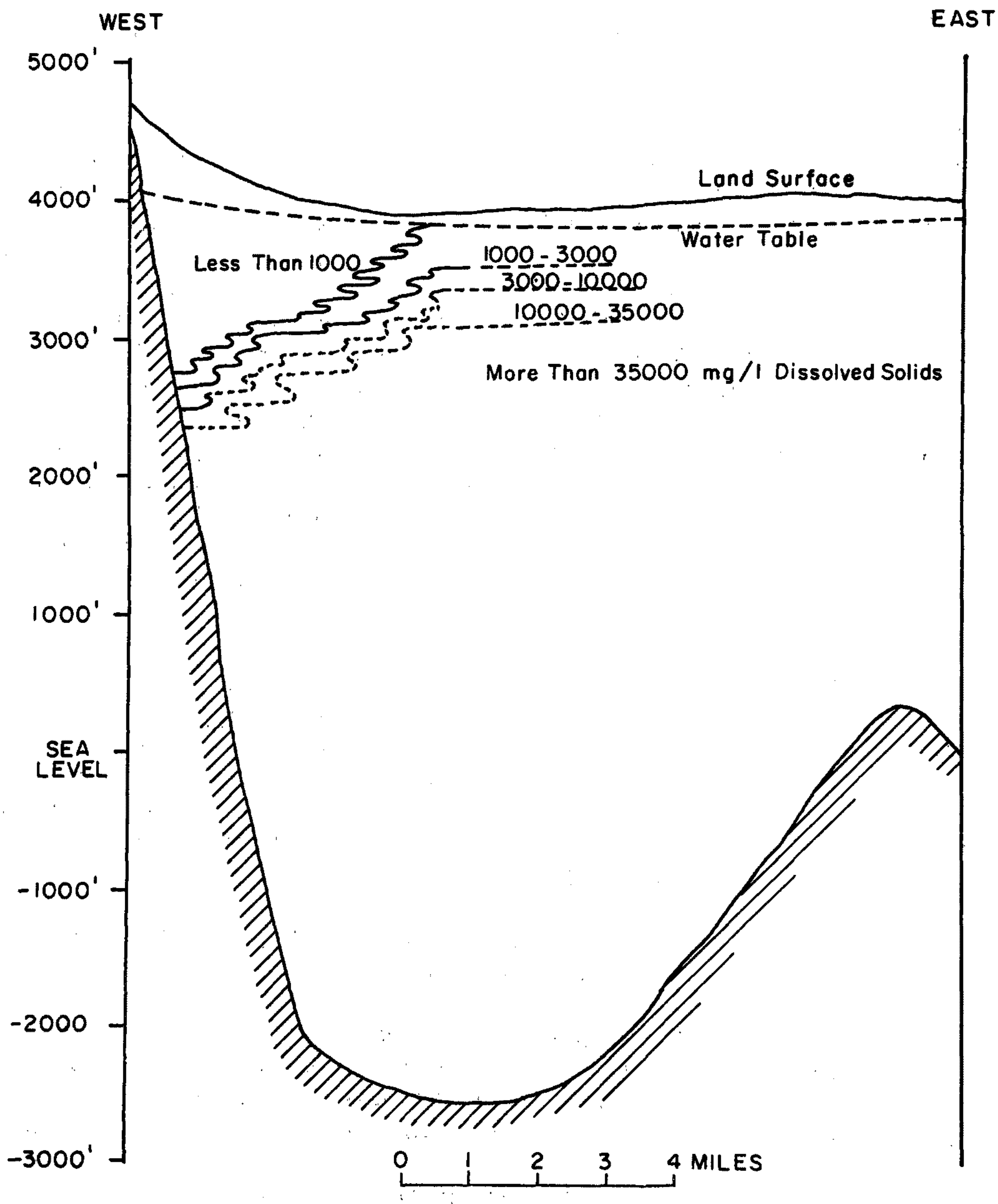


FIGURE 17. A TYPICAL CROSS-SECTION OF THE WATER QUALITY [19] OF THE TULAROSA BASIN

Saline water from natural leaching is a common problem in all of the states in the project area. In fact, salt water can be found at some level in almost any part of the region and, as noted earlier, is by far the most common contaminant of ground water. However, other natural leachates are localized problems in parts of the project area.

In Runnels County, Texas, nitrates in extremely high concentrations in ground water are believed the result of leaching of natural deposits. Over 80 percent of 800 wells sampled in the area have nitrate concentrations above the Public Health Service recommended limit of 45 mg/l. Many wells contain nitrate concentrations of over 500 mg/l, and some are more than 1,000 mg/l.58/ These extremely high concentrations are much more than can be attributed to man-related sources of the area.

Other minerals are found in localized parts of the project area. Fluorides in excess of Public Health Service recommended limits are common in parts of eastern New Mexico and western Texas. Iron is a common natural contaminant in many areas, notably in the western two-thirds of the Mississippi Alluvial Plain in Arkansas, the open pit mining areas of southeastern Oklahoma, and the alluvium of the Baton Rouge, Louisiana area. Zinc can be found in the ground water near Blackwell, Oklahoma. Radioactivity is a natural contaminant around uranium mining areas such as Karnes City, Texas; Claremore, Oklahoma; and Gallup, New Mexico. Caustic or acid problems in ground water are notable in bauxite mining areas such as Bauxite, Arkansas.

Organic pollutants from natural sources are also problems in some areas. Nitrogen gas, methane, hydrogen sulfide and carbon dioxide gases are found in many shallow aquifers in northeast Texas, southwest Arkansas, and western Louisiana. The source of these gases is believed to be the decay of lignitic or carbonaceous material naturally occurring in the aquifer. In 1970, three well drillers in Cass County, Texas, died from breathing gases escaping from such a source.

Because of the immense and unknown hydrological patterns associated with natural pollution in ground water, there appears to be little opportunity of preventing such contamination. For instance, it is theoretically possible to prevent recharge to salt-bearing formations and prevent further leaching of brines to the surface; however, the practical problems of finding and sealing thousands of square miles of recharge areas preclude serious consideration except in very unique small areas.

Oil Field Brines

In 1969 the states of the project area produced over 70 percent of the total United States crude oil from more than 300,000 producing wells.59/ Each oil or gas well is a potential or actual source of pollution to aquifers because of improper control of gas, oil, salt water, or the many chemicals used in drilling and production operations. Production of crude oil is usually accompanied by the production of wastewater of variable but usually high chloride content. The amount of this salt water produced is also quite variable and may range from zero to as much as a dozen or more barrels of brine for each barrel of oil produced. This ratio generally increases with the age of the well and is fairly high in the south central states. In 1963 the five states of the project area produced about 1.8 billion barrels of oil and slightly over 5 billion barrels of brine water.60/ Since oil was discovered in 1902, Texas alone has produced over 31 billion barrels of crude oil--36 percent of the total U.S. production.59/

Until about the last decade, the common methods of oil field brine disposal consisted of discharge to streams or to "evaporation" ponds. In both cases, brine-contaminated aquifers became commonplace in most or all areas of oil production as infiltration from the streams and ponds moved to the ground water. Thousands of unlined brine pits were in use in the five state area until only a few years ago when they were prohibited by the oil regulatory agencies of the respective states. Texas was one of the first states to enact a state-wide ban on unlined pits in January 1969, and other states have adopted similar regulations. Despite this ban, and the fact that few of the brine contaminated areas have been mapped, enough have been located to indicate a serious ground-water pollution problem for many years to come. Because of the slow movement of ground water, brine-contaminated ground water is only now being discovered in many areas of oil development abandoned 20 or 30 or more years ago. It is probable that such discoveries will continue for many years. It is also apparent that even if no more brine contamination occurs, the slow ground-water movement will require many years and even centuries for natural cleansing and rehabilitation of the aquifers.

With the ban on unlined evaporation pits, oil companies were forced to construct pits lined with an impervious material. Brines theoretically must now be evaporated or injected back into the subsurface, either back into the oil-bearing formation or into another formation far enough removed from fresh water aquifers to prevent contamination. Nevertheless, there are numerous reported and suspected violations of these regulations, primarily by economically marginal oil producers. Such violations may be in the form of bypassing brine pits, by accidental or deliberate rupture of pit liners, overflowing waste pits, or by leakage from broken lines.

Another problem has been the inadequate design of brine disposal wells. It has been common practice in the past to use abandoned production wells for brine disposal. Since the wells were not designed, cased or cemented for brine injection, there have been numerous instances of injection wells with undetected ruptures beneath the surface where injected brines have seeped into fresh water aquifers for many years before being discovered. Some state regulatory agencies have somewhat alleviated this problem by requiring injection tubing inside a casing filled with an inhibited fluid under pressure so that ruptures can be detected by changes in the fluid pressures.

Currently, most oil field brines are returned to subsurface formations either for waterflooding--increasing the pressure in an oil producing formation--or just as a disposal method. However, even with properly designed and constructed injection wells, brine disposal is not without real or potential problems. Much of the problem results from the nature of early oil exploration and to abandoned and inadequately plugged oil, gas, and injection wells. Thousands of such wells are scattered throughout much of the project area. For many years of oil exploration, it was a common practice to abandon test holes without proper plugging--thereby leaving a vertical pathway of contact between the various subsurface formations.

The contamination problems inherent in such a ground-water environment are apparent. Whether the source of the brine is injection from the surface or natural brines in a subsurface formation, unplugged wells offer a connection to the fresh water aquifer. In some cases, artesian pressure alone may be adequate to force salt water up the well and into the fresh water aquifer. In other cases, injection of brine into the formation may increase the pressure sufficiently to move formation salt water up the well.

Some idea of the magnitude and location of oil field brine problems can be obtained by looking at the crude oil production. Of the estimated 74,000 salt water injection wells in the United States in 1970, about one-half of these were in Texas alone with another 15,000 in Oklahoma, and over 1,000 in Arkansas.61/ In the five-state area, 365 of the 502 counties have produced some oil or gas. The only large nonproductive areas are in Arkansas and New Mexico. New Mexico produces from the northwest and southeast portions of the state--the great majority of the production is in Lea County alone. Arkansas oil production is in the extreme southern portion of the state with additional gas fields in a few west central counties. One major area of oil production is along the Gulf Coast of Texas and Louisiana. In fact, almost 95 percent of Louisiana's oil production is along the Gulf Coast. As indicated in Figure 18, other areas of much production include northeast Texas and an area approximately parallel to the coast but extending from west Texas and southeastern New Mexico across Texas and central Oklahoma.

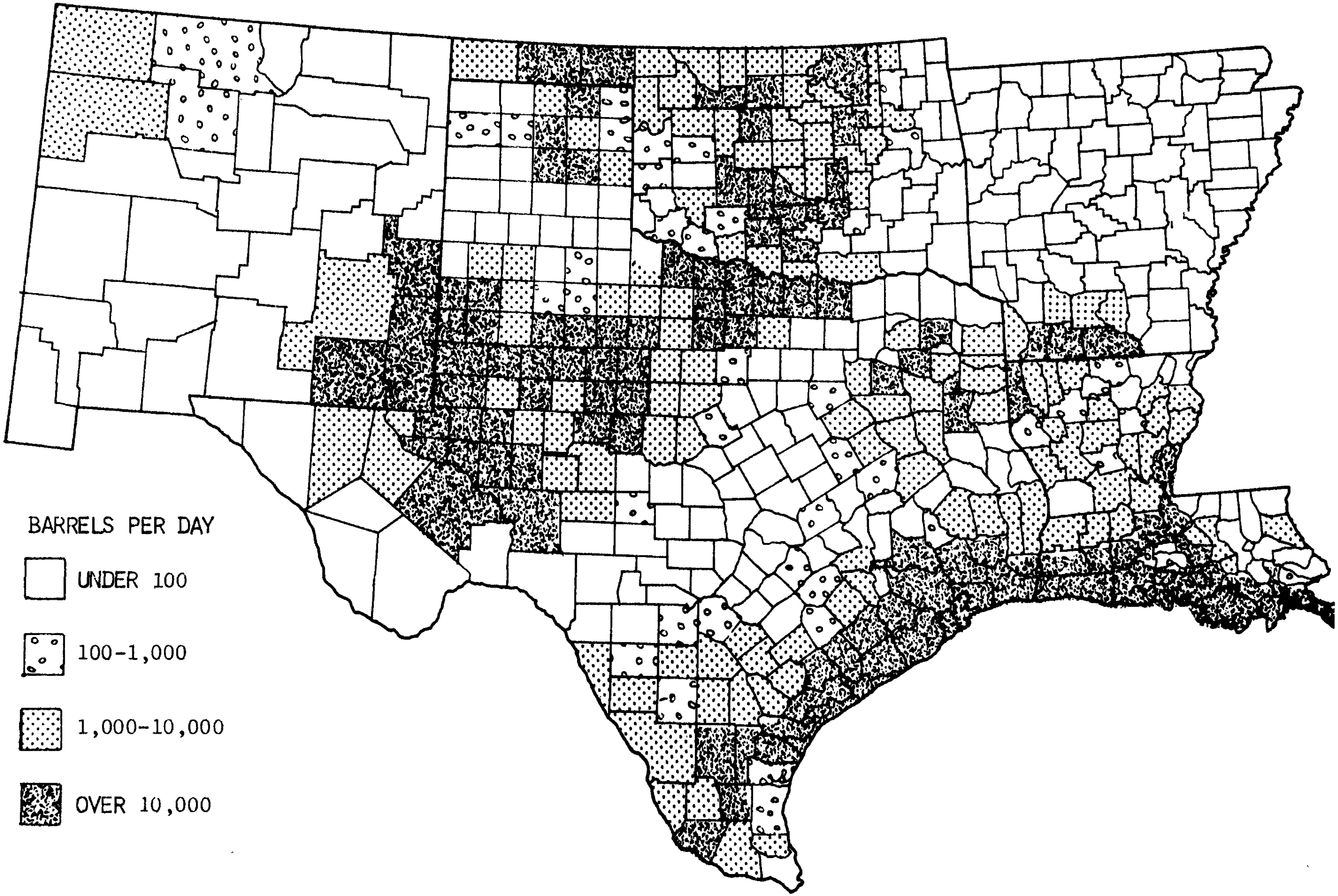


FIGURE 18. CRUDE OIL PRODUCTION

Although there are no reliable statistics on the total number of wells drilled in the five-state area since oil production began, there were more than 15,000 test wells drilled in Texas in 1963, and more than half of these were abandoned without completion. 60/ The percentage of dry holes and the more than 300,000 producing wells, plus an unknown number of depleted wells, would indicate that more than 1,000,000 holes may have been drilled in the five states in search of oil and gas. If the wells were distributed evenly, there would be almost two per square mile over the entire five states.

Many streams have been contaminated by salt water from the disposal of oil field brines and ground water lying adjacent to these streams is subject to salt water intrustion. Arkansas streams that have been most affected are in the southern part of the state and include Bodcaw, Cornie, Smackover, and Lapile Creek, Bayous Dorcheat, and the southern reaches of the Ouachita River. 63/ In Oklahoma, the Arkansas, Canadian, Cimarron and Red Rivers and many of their tributaries have been affected. Similarly, most of the major streams in Texas, especially the Brazos and Pecos Rivers, have been contaminated by oil field brines.

Examples of ground-water pollution from oil field brines are legion in many parts of the five-state area, especially Texas and Oklahoma, and many cases are documented in published and open-file reports of the respective state regulatory agencies. Brine pits, both active and abandoned, have been implicated as sources of ground water pollution in Baylor 64/, Cochran, Colorado, Comanche 65/, Cook, Dawson 66/, Ector 67/, Gaines, Glasscock 68/, Harris 69/, Karnes, Knox, Montague 70/, Pecos, Matagordo, Runnels 71/, Rusk 72/, Victoria 73/, Wilbarger 74/, Wilson and Winkler Counties in Texas, just to name a few.

Much ground water in eastern Oklahoma has been contaminated by oil field brine pits, notably in Garvin, Pontotoc and Seminole, Oklahoma, Pottawatomie, Lincoln, Okfuskie and Creek Counties. Several municipalities in this area of Oklahoma, including Shawnee, Stroud, Meeker and Chandler, have had to abandon ground water supplies in favor of surface water sources. The ground water sources have either been polluted directly by leakage from brine pits or brines entering the Canadian River from the oil fields have recharged the aquifer along its course and subsequently contaminated the municipal wells. 75/

In Lea County, New Mexico, an aquifer contaminated by a leaking brine disposal pit has been renovated by pumping the salt water from the fresh water aquifer and using the contaminated water for waterflooding in a nearby oilfield. 76/ In Miller County, Arkansas, remedial measures and economic damage have been examined for an aquifer contaminated by both a brine pit and a faulty brine disposal well. 77/

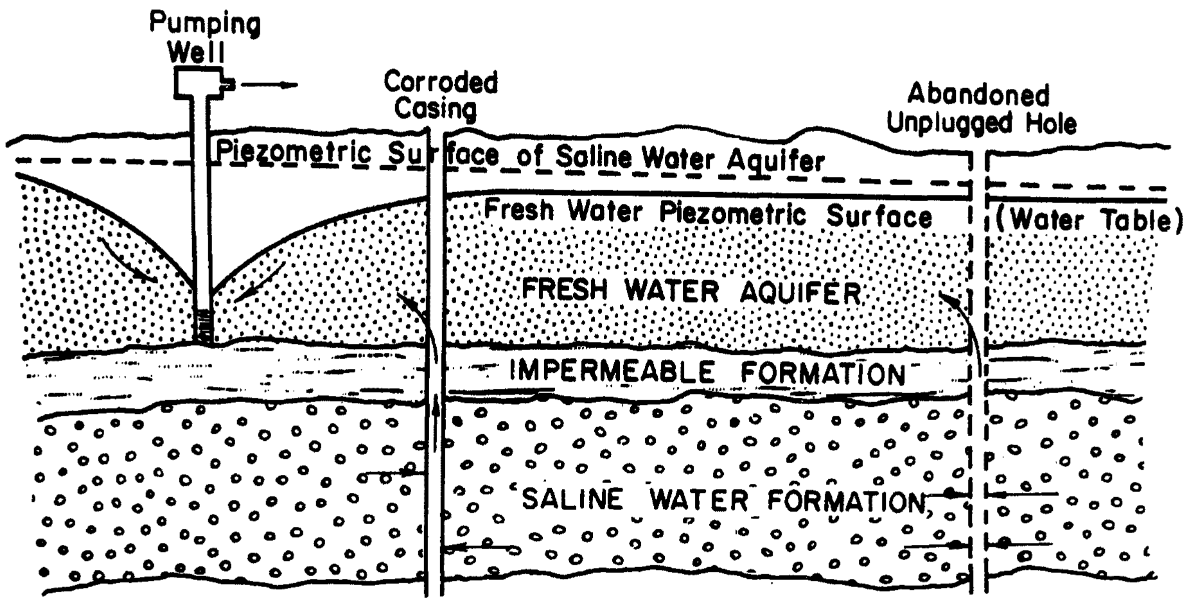
Brine injection wells, both waterflood and disposal wells have also demonstrated their capacity for pollution in Coleman County, Texas,78/ where salt water from a waterflooding operation has moved through inadequately plugged oil test wells and into the Trinity Formation. Similar problems from brine disposal wells have been noted in Karnes, Victoria 73/, and Wilbarger 74/ Counties, Texas, and Garvin County, Oklahoma. In Wood County, Texas, brine and gas were found to leak through fault zones into fresh water. In Shackelford County, Texas, salt water seeps at the ground surface resulted from brine disposal wells.

Well Construction

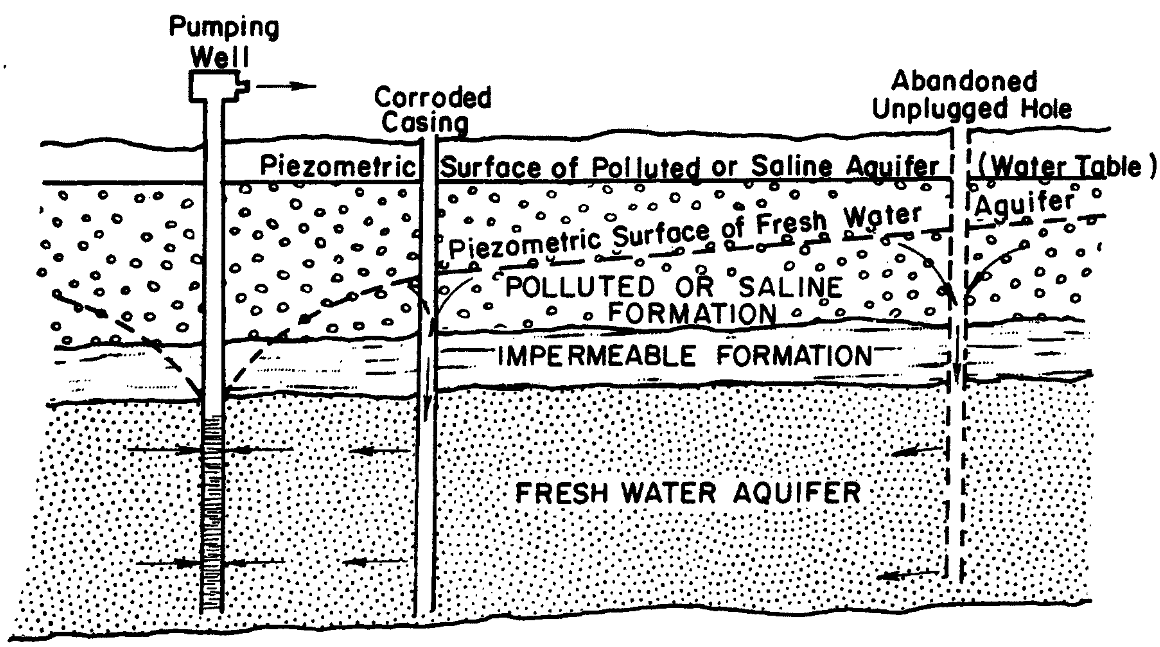
Improperly constructed wells are a threat to the quality of ground water throughout the project area and are sometimes considered the major cause of ground-water pollution. Such wells offer an avenue of contamination to fresh water aquifers from a variety of surface sources or from subsurface formations of inferior quality water.

Contamination from surface sources is possible where the casing is not properly sealed to an adequate depth below the ground surface. Such contamination problems are prevalent in cavernous limestone areas such as the Edwards Plateaus in Texas and the Ozark Plateaus of Arkansas. The most serious problems result from improperly constructed wells that penetrate formations with undesirable quality water. If the confining strata are not properly sealed, the poor quality water may move up or down the well, depending on the hydraulic gradients, and into fresh water aquifers as shown in Figure 19. Pumping of the fresh water will increase this movement. These conditions exist throughout the five states and some of the more notable problems are along the Gulf Coast in both Texas and Louisiana, in the Wintergarden area southwest of San Antonio and in east Texas. The Trinity Sands in the heavily pumped Sherman, Texas area has shown signs of salt water encroachment from overlying saline formations because of improper plugging of oil and water test holes.35/

Uncased or unplugged wells or wells with rusted or leaky casing, especially those abandoned, further complicate the pollution problem. As noted in the preceding section, thousands of these wells dot the region. Many are water wells but most are exploration and oil production wells that may penetrate many formations of both good and bad quality water in addition to oil and gas formations. Although the states of the project area now have regulations calling for proper plugging of wells to isolate zones of oil and gas and zones of good water and saline water, thousands of abandoned, unmarked wells cannot even be located. Because of the time elapsed, the different legal conditions under which they were drilled, changes in property ownership, etc., responsibility for plugging cannot be determined for many of these wells that are located.



UPWARD FLOW THROUGH OPEN, UNSEALED, OR CORRODED CASING



DOWNWARD LEAKAGE THROUGH OPEN, UNSEALED, OR CORRODED CASING

FIGURE 19. UPWARD FLOW AND DOWNWARD LEAKAGE THROUGH OPEN, UNSEALED, OR CORRODED CASINGS

Unplugged wells and artesian brine aquifers have resulted in reported flowing salt water wells in Knox, Hopkins, and Young Counties, Texas. In Hopkins County, one abandoned oil test hole was flowing between 100 and 125 barrels per day of brine water before it was plugged. Salt water has moved into fresh water zones via poorly constructed or unplugged wells in Crockett, Duval 80/, Fisher 81/, Glasscock 68/, Runnels 71/, and Scurry 82/ Counties, Texas. Examples of natural gas contamination due to faulty well construction can be found in Caldwell 83/, Bastrop 79/, Comanche 84/, and Wharton 85/ Counties. Sea water was found to move through an abandoned water well into the fresh water zone in the Trinity Bay area of Chambers County, Texas.

Texas and New Mexico now have water well driller licensing laws which specify rules and regulations for plugging of wells that encounter undesirable water. New wells are located on maps and logs are filed with the appropriate state regulatory agency in each state.

Overpumping

Ground-water depletion is sometimes considered the only result of overpumping but water quality deterioration is more often the first and major detrimental effect on an aquifer. As discussed in an earlier section on natural pollution, saline water can be found at some level at most locations in the five states of the project area. In many locations, there is a direct interface between fresh and saline ground water such as beneath the gulf coast of Texas and Louisiana. However, many inland fresh water aquifers also are in direct contact with saline water. In most cases, the heavier, saline water underlies the fresh water. Therefore, where wells are too deep or where excessive pumping reverses the hydraulic gradient, saline water may be drawn into zones formerly composed of fresh water.

Overpumping is a common problem throughout eastern New Mexico, western Texas and Oklahoma, and much of Louisiana and eastern Arkansas. Figure 20 shows the depth to the base of the fresh water in the Coastal Plain of Arkansas. Care must be taken while drilling and pumping wells in this area to avoid pumping the saline waters which lie below the fresh water. The flow lines in Figure 21 demonstrate how salt water can migrate up into the fresh water zone when a well is pumped. As overpumping lowers the water table and the relative thickness of the fresh water zone, the movement of salt water up into the well becomes more pronounced.

The potential for horizontal movement of salt water caused by overpumping is typified in Figure 22. This is a generalized section showing the principal aquifers south of the Baton Rouge as they dip gently in the direction of the Gulf Coast.86/ Fresh water has entered the aquifers in the recharge area and flushed out salt water originally occurring

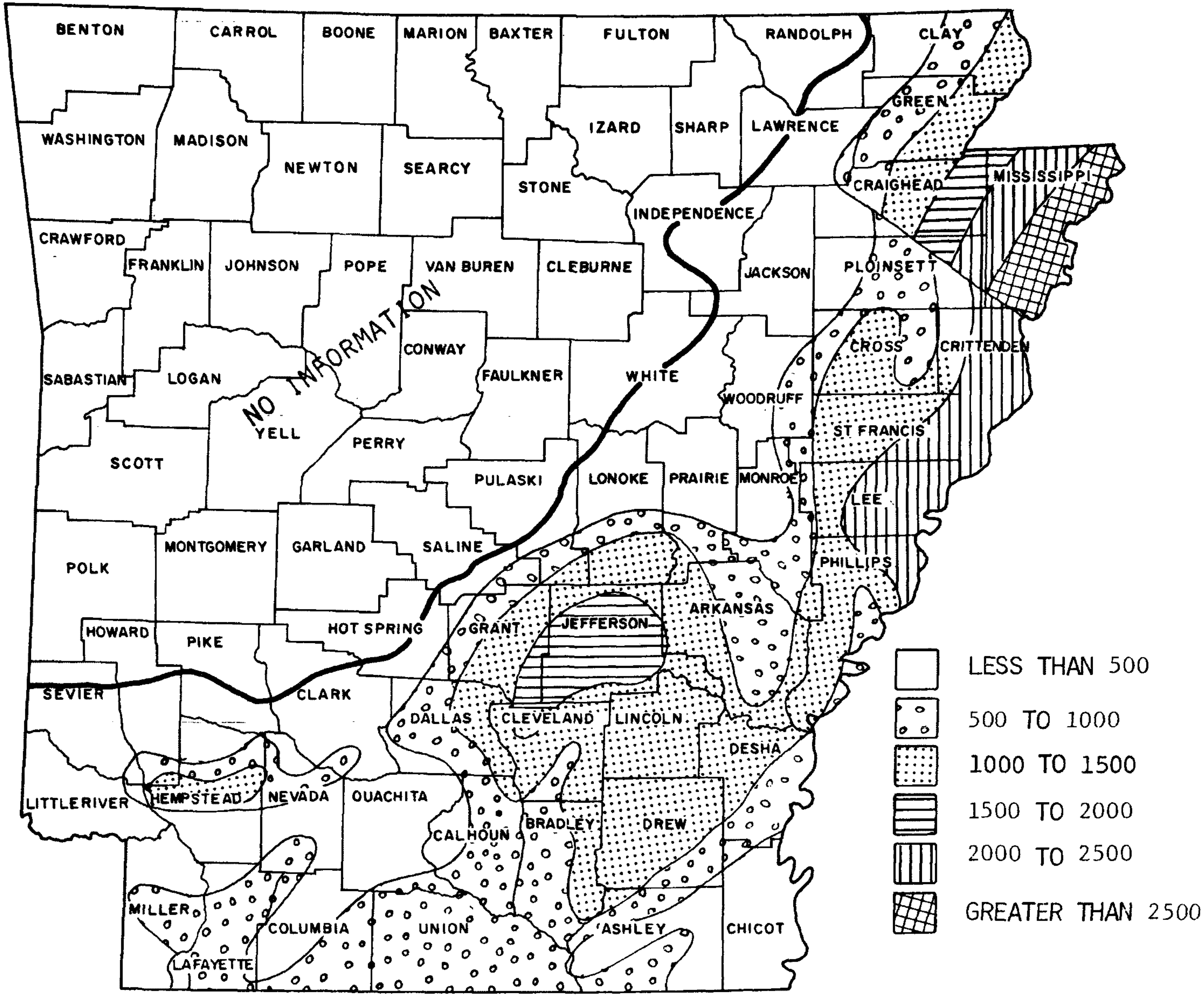


FIGURE 20. APPROXIMATE DEPTHS TO THE BASE OF FRESH WATER IN ARKANSAS

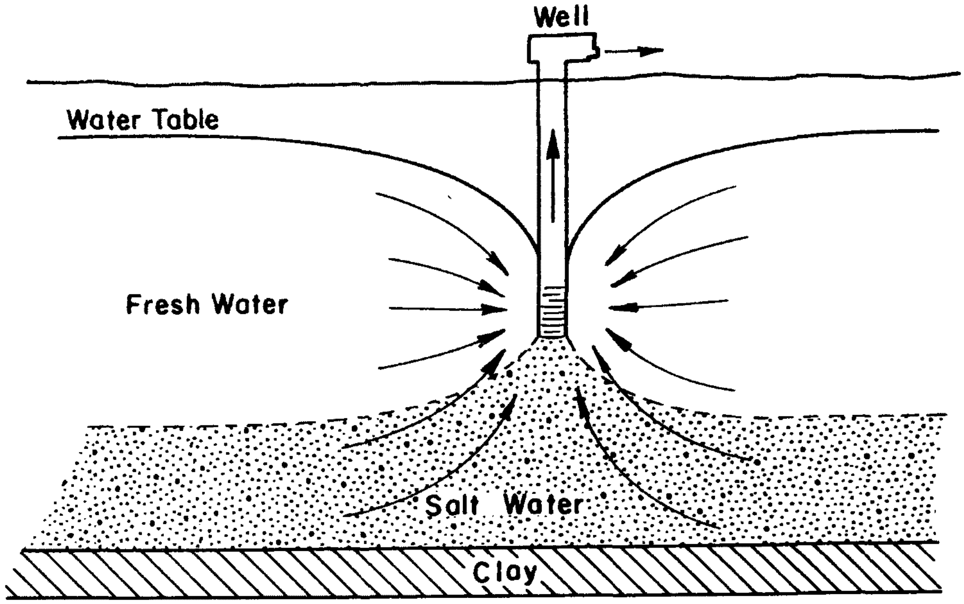


FIGURE 21. MIGRATION OF SALT WATER UP INTO THE FRESH WATER ZONE WHEN A WELL IS PUMPED

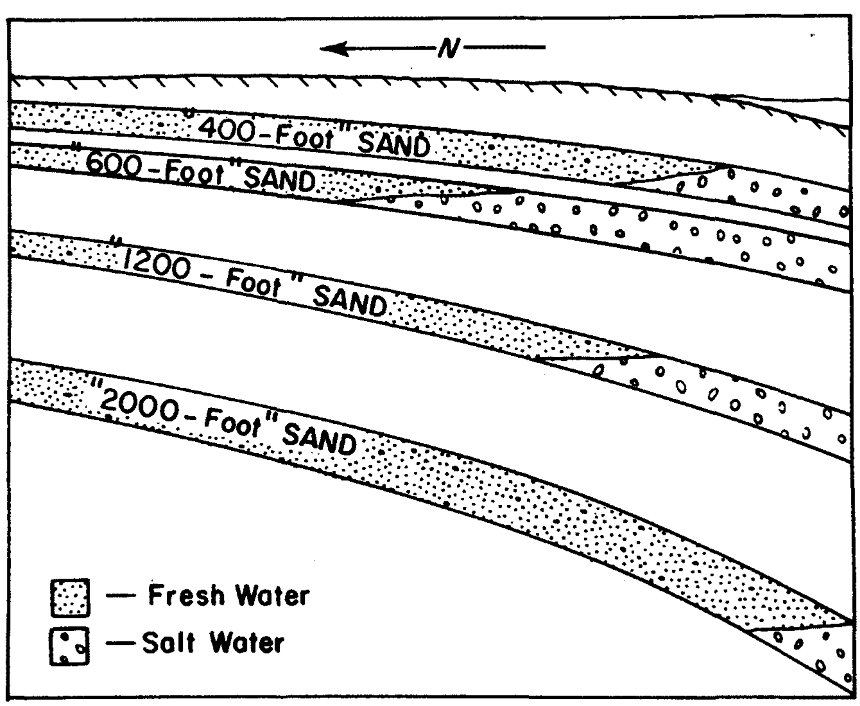


FIGURE 22. POTENTIAL FOR HORIZONTAL MOVEMENT OF SALT WATER CAUSED BY OVERPUMPING

there. Salt water fronts in each aquifer generally parallel and are typical of aquifers along the Texas-Louisiana Coast. Excessive pumping of these aquifers in some locations has lowered the hydrostatic pressure so that the salt water fronts are moving inland. Salt-water encroachment has been especially prevalent in the Baton Rouge and Lake Charles areas of Louisiana and in the Houston, Galveston-Texas City, and Matagorda-Lavaca Bay areas of Texas.

Heavy withdrawals for irrigation along the Pecos River Valley, especially in Pecos and Reeves Counties of Texas have caused similar gradient reversals along the Pecos River. Normally, the fresh water aquifer discharges water to the river but with the lowered water tables, highly mineralized water from the river and adjacent formations is recharging the aquifer.

Also in Texas, overpumping has resulted in salt water intrusion of the Beaumont clay aquifer in Brazoria County, the Seymour Formation in Knox County, the Chicot aquifer in Orange County 87/, and the alluvium in Ward County. 88/

Irrigation Return Flows

Irrigation return flow is water diverted for irrigation purposes that finds its way back into a supply. Through irrigation return flow, salts are concentrated by evapotranspiration and other substances are conveyed from irrigated lands to the ground water by infiltration. Pollutants in irrigation return flows may come from many sources before, during, and after irrigation. These sources include animals, soils, fertilizers, pesticides, industrial and municipal wastes, and even natural sources such as fixed nitrogen from lightening, etc.

Whenever water is diverted for irrigation use, the quality of the return flow is degraded. In irrigation, pure water is extracted by the plants from the water supply, resulting in a concentration of those dissolved solids which are characteristic of all natural water supplies. In addition, much of the water applied to the soil is evaporated leaving the dissolved minerals on or near the land surface where they may be leached to the ground water.

All irrigation water contains dissolved minerals (salts) and some of these salts will accumulate in the soil unless leached from it by excess irrigation water or by natural precipitation. The major pollution problems associated with irrigation return flows in the project area are in the arid portions of Oklahoma, New Mexico and Texas where water is in short supply. Natural precipitation in this region is insufficient to leach the salts from the soil and excess irrigation is generally adequate only to move the salts from the topsoil to the subsoil or to the ground water. However, while increasing salt concentration, irrigation may remove other pollutants. Nutrients and other organic wastes deposited on land with irrigation water may be used by the crop, fixed by the soil, or degraded so that they are not contained in the irrigation return flow.

Irrigated agriculture provides the economic base for much of the south central states, especially western Texas and Oklahoma and eastern and central New Mexico. The 1969 acreages under irrigation in the five states of the project area are given in Table 13 and the major irrigation areas are indicated in Figure 23.

Table 13. IRRIGATED ACREAGE IN 1969 89/

Arkansas	1,435,000
Louisiana	580,687
New Mexico	1,000,000
Oklahoma	619,278
Texas	8,200,000

The major area of water quality deterioration from irrigation return flows in the project area is the Rio Grande Basin in New Mexico and Texas. Other problem areas caused by irrigation return flows include the Pecos River in New Mexico and Texas and the Arkansas River in Oklahoma and Arkansas. Of possible future significance is the proposed Navajo irrigation project in the San Juan River Basin of northwestern New Mexico and the Concho irrigation project in the Canadian River Basin of northeastern New Mexico.

There were over two million irrigated acres in the Rio Grande Basin in 1969.89/ Essentially all of this irrigation is scattered along the arid expanse of the 1,900 miles of river from southern Colorado to the Gulf of Mexico. Because the river water is used over and over again, each successive use further degrades the water quality which generally becomes progressively worse downstream. Also because of the close interrelationship between the surface water and ground water in the river alluvium, there is a tendency for the quality to deteriorate downstream both in surface water and ground water.

Diversions for irrigation occur throughout the length of the Rio Grande both in New Mexico and Texas and a close correlation exists between the irrigated areas, decreased discharge, and increased salt load of

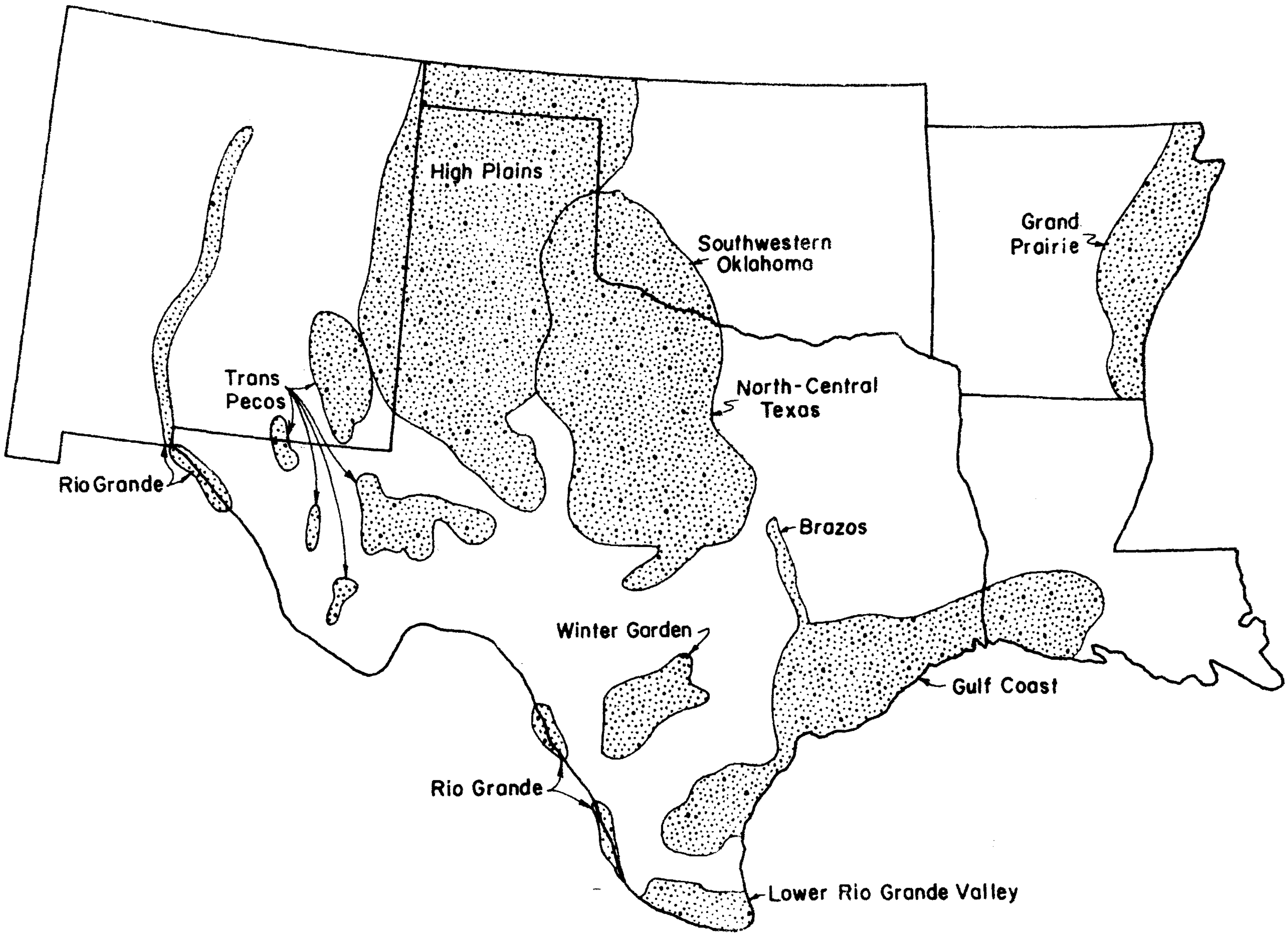


FIGURE 2[illegible]. MAJOR IRRIGATION AREAS OF THE FIVE SOUTH-CENTRAL STATES 31/

the river. Between Otowi Bridge near Santa Fe, New Mexico and Fort Quitman, Texas south of El Paso, there are more than 250,000 irrigated acres. While the flow in this stretch of river is decreased to one-fifth of its original value, the dissolved solids concentration is increased almost tenfold and the total salt load is almost doubled, as shown in Table 14.89/

Table 14. MEAN ANNUAL DISCHARGE AND DISSOLVED SOLIDS CONCENTRATIONS AT SUCCESSIVE LOCATIONS ALONG THE RIO GRANDE

	Discharge	Dissolved Solids
Otowi Bridge, New Mexico	1079	221
San Marcial, New Mexico	853	449
Elephant Butte, New Mexico	790	478
Caballo Dam, New Mexico	781	515
Leasburg Dam, New Mexico	743	551
El Paso, Texas	525	787
Fort Quitman, Texas	203	1691

Irrigation return flow is also one of the major reasons for the highly mineralized ground and surface waters of the Pecos Valley in both New Mexico and Texas. Because of the water-short climate of the Pecos Valley, the importance of the ground water to the general hydrologic system is greater than in most stream valleys. In most parts of the Pecos Basin, water used for irrigation is already relatively high in mineral content. Return of excess irrigation water to the hydrological system further concentrates these minerals but this return flow is critical to an already negative water balance in the basin. The major irrigation areas in the basin are near Roswell and Carlsbad, New Mexico and near Pecos, Texas.

The San Juan River Basin in northwestern New Mexico is a part of the project area where irrigation return flows may seriously affect the ground water in the future. The Navajo Indian Irrigation Project now under construction will irrigate 110,000 acres in the San Juan Basin. There is some concern that salts may be concentrated in the irrigation return flows by leaching of the gypsiferous deposits of the area as well as by the irrigation process.

There are other large areas of irrigation in the region but return flows from these do not pose the threat to the ground water that the aforementioned areas do. The greatest effect on quality of surface and subsequently ground water is during periods of low flow in the streams so common to the Rio Grande and Pecos.

In the High Plains geographic region of Texas and New Mexico, very little of the return flow rejoins the river systems. Most of the leachate rejoins the ground water but because of the high quality of the ground water, the large storage capacity of the underground reservoirs and the kind of geologic formations present, the effect of the return flow on the ground-water quality has hardly been noticeable. However, as the amount of water in the Ogallala Aquifer decreases, the effect of irrigation return flow on quality of the ground water will increase.

There is considerable irrigation in the gulf coastal area of Texas and Louisiana as well as the Mississippi Valley of Arkansas. However, these are regions of excess precipitation and irrigation return flows are not a large part of the hydrological system. Most of these return flows are highly diluted with precipitation, with high capacity ground-water reservoirs and by streams in the area so that the mineralization effect on water quality is minimal or, at the worst, a local problem. An unknown factor could be the effect of agricultural chemicals such as pesticides and herbicides where return flows may reach the ground water. There is very little data related to this subject but one study in the Texas high plains indicated little pesticide or herbicide contamination of agricultural runoff water.90/

Land Application of Wastes

Wastewaters have been applied to land in some manner since the inception of water carriage systems. Sometimes application to the land has been designed such as with septic tank-soil absorption systems, infiltration-percolating systems, spray-runoff systems and cropland irrigation systems. Oftentimes, land application has been incidental to the waste disposal such as seepage from sewers, waste-filled streams or just spills.

Although land systems have been used for both municipal and industrial wastewaters for many years, most have been relatively small scale with major emphasis on disposal.91/ However, within the last few years, there has been an upsurge of interest in land systems for treatment and/or reuse of wastewaters.

Cesspools, disposal pits and sewage farms were the early methods of land disposal. Septic tank-soil absorption systems have largely replaced cesspools for individual homes and remain the greatest single use of soil for wastewater disposal at the present time. "Sewage farm" is a term which is not used much anymore because of its repugnance to the general population but the principal of using municipal effluents for irrigation is very much in evidence throughout the United States. This is demonstrated by the construction of a 90 million gallon per day system to spray-irrigate about 6,000 acres of farmland in Muskegon County, Michigan with municipal and industrial wastes.

Thomas and Harlin 92/ grouped the most promising approaches to land spreading into three categories: (1) infiltration-percolation, (2) cropland irrigation, or (3) spray-runoff. Cropland irrigation is a well-established practice in the project area and has developed because of a need for water as well as a waste-management approach. According to a 1965 survey, many municipalities in Texas have practiced cropland irrigation continuously for over 30 years--some as long as 70 or 80 years.93/ Over 160 towns and cities in the five south central states use sewage effluent for land application and the great majority, including San Antonio, Amarillo, Abilene and Lubbock, Texas, practice irrigation of cropland, parks, golf courses and cemeteries.

Despite the long history of use, there is little information relating to the effect on ground-water quality. The nature of wastewater irrigation is to use much more water than is generally used from fresh water sources and a substantial portion of the applied wastewater percolates through the soil to the ground water. The limited data available indicate that over-irrigation with municipal wastewater can contribute to undesirable levels of nitrate in the ground water. Lubbock, Texas has been using cropland irrigation of municipal effluent for several years and reportedly has developed a mound of relatively high nitrate water under the irrigation area. 94/ A similar problem has developed at Hobbs, New Mexico.95/ Despite nitrate problems, there appears to be little other ground-water quality problems associated with irrigation with either treated or untreated municipal effluents but there is a general lack of quantitative data as a basis for this judgment.

Infiltration-percolation systems have also been used for many years as a disposal practice with little effort to maximize the treatment capability. However, within the last few years, considerable interest and research has been directed toward optimizing the treatment capability. Infiltration-percolation systems are designed for high hydraulic loading rates, require rapidly permeable soils and length of drying and wetting periods greatly influences the treatment efficiency, especially nitrogen removal. Since crops and plants are not involved, the treatment efficiency is entirely dependent on the filtering and ion-exchange action of the soil. Because essentially all of the wastewater percolates to the ground water, the influence on ground water quality is significant.

Except for septic tank systems, infiltration-percolation systems are not widely used in the five-state area. However, septic tank systems are widely used and constitute a significant ground-water problem throughout the region. State authorities in New Mexico consider septic tanks to be the major contributor to ground-water pollution in the Albuquerque area as well as many rural areas. The major problem in the Rio Grande Valley at Albuquerque is the high water tables and the high concentration of septic tanks in the valley. It is estimated that there are 25,000 septic tanks in southern Albuquerque.95/ Water wells in this area are also shallow and many are contaminated with chlorides, nitrates and coliform organisms.

Of growing concern is the tremendous growth of mountain homesites in the Rocky Mountains of New Mexico where septic tanks are used but soil and geologic conditions are not conducive to efficient removal of pollutants. Similar problems occur in many other rural areas of New Mexico as well as the other states of the project area. In 1960, 27 percent of the housing units in New Mexico used septic tanks or cesspools. The percentage was 25, 38, 24, and 28 for the states of Arkansas, Louisiana, Oklahoma, and Texas, respectively.96/ It is unlikely that these percentages have changed significantly since 1960.

The overall effect of these infiltration-percolation systems can only be estimated but it is apparent that they can be a source of ground-water pollution in some areas under some conditions. In areas such as the Edwards Plateau in central Texas where porous limestone formations predominate near the surface, septic tanks are of great concern. Also in areas where the ground-water table is near the surface, such as the Albuquerque Valley and the Coastal areas of Texas and Louisiana, septic tanks are considered significant causes of ground-water problems.

Bacterial contamination from septic tanks has been noted in ground waters of Atacosa 57/, Newton 97/, Jack, Montague, Travis 98/, McLennan, Potter 99/, Stephens, and Knox Counties in Texas, as well as Bernalillo County, New Mexico.

Certainly the soil has demonstrated a tremendous capacity for absorbing and degrading both industrial and municipal wastewaters. Problems with infiltration-percolation systems such as septic tanks arise when not enough soil contact time is available before the waste reaches the ground water. This condition results both in areas of high ground-water tables and areas of porous rock formations.

Spray-runoff is a relatively recent approach to land disposal which has found most application to industrial wastes. This technique is most suitable to use on tight soils where more than half of the applied wastewater is returned directly to the surface water as controlled runoff. Treatment efficiency depends on physical, chemical, and biochemical processes that take place as the liquid trickles slowly along the soil surfaces.

Of all the land treatment or disposal systems, spray-runoff probably has the least effect on ground-water quality because most of the applied wastewater runs off the surface and much of the remainder is lost through evapotranspiration. In a well-operated system, the fraction of wastewater that does reach the ground water is of good quality. The Campbell Soup Company of Paris, Texas treats about three MGD of cannery wastewaters on about 300 acres of specially prepared grassland without any discernible deterioration of ground-water quality.100/

With the increasing pressure to clean up waste effluents and the increasing interest in recycling processes, it is probable that soil treatment systems will increase in popularity, especially in the project area because of suitable year-around temperatures. The limiting factor in all these soil systems appears to be the nitrogen concentrations in the effluents.

Solid Wastes

In 1967 there was an estimated 10 pounds of household, commercial and industrial solid wastes generated each day for every man, woman and child in the United States. Of this amount, more than half was collected by municipal and private waste collection agencies for recycle, processing and/or disposal. Landfilling, the most prevalent method of disposal in the United States accounted for over 90 percent of the collected solid waste at an estimated 12,000 individual landfill sites.101/

The project area is rather typical of the rest of the United States in respect to solid waste management and mismanagement. Open dumps and burning was formerly the accepted method of disposal. The tendency has been to locate dumps and landfills in abandoned gravel pits or other low-lying areas where ground-water is in contact with or at least in close proximity to the waste materials.

With increased emphasis on curbing air pollution and nuisance conditions related to open dumps, more attention is being given to converting such operations to sanitary landfills. A sanitary landfill can generally be described as a disposal operation where solid wastes are dumped into an excavated area and covered over daily without causing pollution or nuisance conditions.

Although few landfills meet this relatively simple criteria, there are very few reported case histories of serious contamination of ground water that can be directly attributable to leachates from sanitary landfills. In Harris County, Texas, a garbage dump was reported to be the source of ammonia nitrogen contamination in ground water.102/ There are undoubtedly many more unreported cases of people routinely using water contaminated somewhat by land disposal of solid wastes.

Precipitation, surface water runoff characteristics, evapotranspiration, the location and movement of ground water, and solid waste content all determine characteristics of leachates from landfills. However, the literature confirms that such leachates usually contain high concentrations of total dissolved solids, calcium, magnesium, BOD, acidity and alkalinity and gases such as carbon dioxide and methane. The lack of reported serious problems can be attributed to the great capacity of most soils to attenuate the contaminated leachates generated from landfill operations and possibly to the lack of monitoring of landfill operations

The soil provides sites for the microbial degradation of the organics as well as a surface where inorganics are adsorbed and ion exchange reactions replace the more undesirable ones. The extremely low velocity of ground water movement provides the time necessary for these reactions and confines most of the degradation processes to the immediate vicinity of the landfill. The soluble degradation products are further attenuated by the vastness of ground-water formations simply by dilution.

Ground-water pollution by solid wastes becomes a problem because this attenuation process does not work efficiently for all geological formations. In unconsolidated formations of coarse sand and gravels with high permeabilities or consolidated formations such as limestone or shale with fissures, faults or fractures, not enough time is available to complete the degradation process. Ground-water flow is often fast enough in these types of formations to permit poorly degraded and diluted leachates to appear at considerable distances from the landfill or dump site.

The major solid waste threat to ground-water quality in the future will probably be from the land disposal of industrial wastes. Many such wastes decompose slowly or not at all and can impart odor, taste, and even toxic characteristics to ground water at extremely low concentrations. With the increased amount and complexity of solid industrial wastes produced and the trend toward more stringent surface water quality standards, many more industries will probably look to land for industrial waste disposal.103/ There may be practically no basis for establishing guidelines for disposal of many of these new compounds. The part of the project area most likely to encounter such problems is along the gulf coast of Texas and Louisiana where the chemical and petrochemical industries are concentrated.

Almost unnoticed because they are generally located in sparsely populated areas, mining and mineral processing wastes are generated in the United States at four times the rate of municipal wastes. These wastes include mine wastes, mill tailings, washing plant rejects, processing wastes, and slag and fly ash.104/ Mining and milling wastes that cannot be reclaimed are generally disposed of on the soil, thereby creating the potential for leaching of contaminants into the ground water.

New Mexico has considerable mining activity with uranium in McKinley and Valencia Counties, copper in Grant County, molybdenum in Taos County and potash in Eddy and Lea Counties. Arkansas mines sulfur from Lafayette, Columbia, and Union Counties; bauxite from Saline and Pulaski Counties; and mercury from Pike County. Oklahoma produces copper from Jackson County and zinc from Ottawa County. In addition, processing mills for zinc and associated minerals are located in Blackwell, Henryetta, Bartlesville, and Tulsa, Oklahoma.

Most of Louisiana's mining is limited to sulfur and other nonmetals. Sulfur is mined in Plaquemines, Terrebonne, and Calcasieu Parishes. Salt is mined in several parishes and Louisiana is one of the leading salt producing states in the United States.

Texas has a varied assortment of mining and milling activities scattered throughout the state. Mercury is mined in Brewster and Presidio Counties, iron ore--usually from open pits--is mined in Cherokee, Morris, Cass, and Nachodoches Counties. Sulfur is mined from several counties including Liberty, Jefferson, Pecos, Culberson, Fort Bend, Brazoria, Andrews, Ector, Hockley, Van Zandt, Wood, Metagorda, Wharton and Franklin. As noted earlier, Karnes County has some uranium mining. Mills for processing the different metals are located in Calhoun, Milam, Webb, Neuces, El Paso, Morris, Harris, Brazoria, Galveston, Potter, and Moore Counties.

Another source of solid waste is agriculture which generates nearly 10 times as much wastes as municipalities. About three-fourths of this is animal manure which is discussed in a later section but about one-fourth includes such items as logging debris, crop residues, and food processing wastes.104/

Evapotranspiration by Native Vegetation

Water-loving plants that derive their water by sending roots down to the water table are sometimes referred to as phreatophytes, especially if they consume large amounts of water without commensurate benefits to man. Phreatophytes do not belong to any specific plant family but the common characteristic is their heavy use of a large supply of water. They occupy about 15 million acres of land in the western states. In New Mexico 300,000 acres of phreatophytes are estimated to use 900,000 acre-feet of water, and in Texas 262,000 acres are estimated to use about 436,500 acre-feet of water per year.105/

The effect of phreatophytes on ground-water quality is the same as from evaporation--the concentration of minerals. Generally, transpiration of water by plants is greater than evaporation from bare soil because roots of many plants lift water much higher than it can be lifted by the capillary action of the soil. Depending on the type of vegetation, mineral content of the ground water, depth to water table, soil texture, length of growing season, hours of daylight, temperature, rainfall and humidity, phreatophytes may transpire as much as 10 acre-feet per acre of water each year. Generally, water use is greatest during a long, hot growing season, with little precipitation and low humidity and a ground-water table near the surface.

Obviously, phreatophytes exert their greatest effect on water quality in water-short areas such as the deserts of New Mexico and west Texas and where the water table is near the surface. The greatest effect is felt along the Rio Grande and Pecos Rivers of New Mexico and Texas. It was estimated by the Pecos River Compact Commission in 1949, that if 15,000 acres of salt cedar on the delta above Lake McMillan could be controlled, an additional 39,000 acre-feet of water annually might be added to the water in the Pecos River.

Phreatophytes also occur extensively in the humid sections of the project area and use great amounts of water. However, because of the greater rainfall, the effect on water supplies and quality is proportionately less serious than in the more arid areas.

Animal Wastes

Animal waste is a relatively new environmental problem--at least on the large scale of today. Until 10 or 15 years ago, most beef animals were raised on pasture land where wastes were easily assimilated into the soil without significant surface or ground-water contamination. With the increasing demand for more and better quality meat, livestock producers have responded with thousands of large concentrated feeding operations. During 1972 there were over two million beef cattle in feedlots in Texas and most of these were located in feedlots of 1,000 to 50,000 head capacity.

During a beef animal's stay of 120-150 days in a feedlot, it will produce over a half-ton of manure on a dry weight basis. The heavy concentrations of animals overtaxes the natural assimilative capacity of the receiving soil. Rainfall runoff that comes in contact with the manure carries high concentrations of various pollutants into receiving ponds and streams. Ground water can then be contaminated by leachate from the receiving ponds and streams or from the feedlot itself.

There remains considerable controversy regarding the extent of the effect of feedlots on ground-water quality. Nitrates in high concentrations have been found under some feedlots in some soil profiles. In Corgell County, Texas, a feedlot was considered a source of contamination to the Paluxy Aquifer.106/ The Texas Water Quality Board, the state agency regulating waste discharges in Texas, is concerned enough to require permeability tests of soils under newly constructed feedlot runoff collection ponds. When such soils indicate excessive permeability, lining of waste holding ponds with a relatively impermeable material is required.

Fortunately, from a ground-water standpoint, about three-fourths of the fed cattle in the five states are located in feedlots in the panhandle area of northwest Texas and western Oklahoma where relatively deep ground-water tables, low rainfall amounts and impermeable soil barriers combine to restrict the downward movement of waste leachates. Analysis of ground-water samples from beneath 80 feedlots in this area indicated little contamination reaching the water table.107/ It was determined that local surficial material and regional soils patterns are closely related to quality of ground water beneath feedlots.

Large feedlots are scattered over much more of the project area and several are probably located on geologic formations conducive to ground-water pollution. For example, in the Edwards Plateau of central Texas, relatively shallow soils overlie porous limestone formations which could recharge feedlot pollutants to the ground water before they can be assimilated by the soil.

Permeability and depth to the water table are the major considerations for feedlot location because permeability controls the rate of movement of water and pollutants that might be with it and both control the time of travel. Given time to react with the soil, most pollutants will be removed from feedlot leachates by a combination of sorption, biodegradation and even dilution. Even though nitrogen converted to nitrates is very mobile in ground water, given time and the proper soil medium, biological denitrification can reduce the nitrates before they reach the ground water.

Although the potential for localized pollution of a water table aquifer with nitrates is great under animal feeding areas, the limited acreage of feedlots in most areas makes widespread ground-water pollution unlikely.

Waste Lagoons

Lagoons or ponds are one of the oldest forms of wastewater storage and disposal and perhaps should be rated higher as a cause of ground-water pollution. However, the most significant pollution in the subject five state area has been caused by so-called evaporation ponds for oil field brines and these were discussed in an earlier section. In reality, most "evaporation" ponds were actually seepage pits. Only in arid western Texas and Oklahoma and eastern New Mexico is evaporation adequate to evaporate large volumes of water.

Lagoons have been used for many other wastes in addition to oil field brines. They have been used extensively for municipal wastes, animal wastes, and practically every type of industrial waste, especially as regulations concerning stream discharge have become more strict. Thousands of sewage lagoons are scattered throughout the five state area and undoubtedly contribute much seepage to the ground water. Fortunately, except for nitrates, contaminants common to municipal wastes are attenuated rapidly in most soil environments underlying such lagoons. Exceptions could occur in fractured or cavernous limestone formations such as occur in the Edwards Plateau area of Texas. As noted earlier, nitrates move freely with the ground water and are often found in relatively high concentrations under sewage lagoons.

Lagoons used for storage of industrial wastes are a serious threat to ground water in industrial areas. The petrochemical industry concentrated along the gulf coast, especially around Houston and Baton Rouge, produces a myriad of waste products which are often stored in lagoons. Many of these waste products are highly toxic and highly mobile in ground water.

Examples of ground-water contamination from waste lagoons have been reported in Howard County, Texas at two locations. At one location, hydrocarbons from refinery holding ponds seeped into the ground water. At another, unlined pits used for disposal of slaughterhouse wastewaters were indicated as sources of bacteriological contamination of nearby wells.108/ Acid waste discharge to unlined pits were identified as a pollution problem in Terry County, Texas.109/ In Andrews 110/ and Travis 111/ Counties in Texas, municipal oxidation ponds have been implicated in ground-water pollution.

Fortunately, industry and regulatory officials are becoming more cognizant of the threat of industrial, municipal and agricultural waste lagoons to the ground water and many such lagoons are being lined with impermeable materials.

Accidental Spills of Hazardous Materials

Many materials that are normally considered as hazardous provide a significant benefit to modern society while many materials not normally considered hazardous can have severe damaging effects if accidentally released. Although most attention in the past has concerned hazardous material that was an immediate threat to human life and property, increasing attention is being given to those materials that threaten environmental quality such as oil spillage.

Hazardous material problems are generally thought of as transportation accidents but many spills originate from storage and production facilities. Numerous fish kills have resulted from leaks from storage tanks and lagoons. Most concern about spills of hazardous material has been related to surface water and air pollution such as oil spills and rupture of gas storage tanks but ground water can be severely affected, too.

The project area contains most of the petroleum and petrochemical industry of the United States. As noted earlier, oil is produced in a great majority of the counties of the five states involved and thousands of miles of transmission lines for oil and gas crisscross the region and along with petroleum storage tanks create a significant potential for ground-water pollution. The oil contamination mentioned earlier near Hobbs, New Mexico probably results from a leaking oil well or transmission line.

Because of its widespread use and its mobility in ground water, gasoline is a common pollutant. Leaking service station storage tanks have polluted ground waters in Childress 112/, Coleman 113/, Hamilton 114/, Starr and Tom Green 115/ Counties in Texas.

The petrochemical industry, which is heavily concentrated along the Texas and Louisiana Gulf Coast presents a special problem. Not only is the production, storage, transportation and use of the thousands of toxic products a major potential pollutant but treatment, storage and disposal of waste by-products is even more of a threat to ground water.

Subsurface Waste Disposal

Subsurface disposal of waste has been practiced in this country for many years beginning with oil field brines, as discussed earlier. Other industries began using injection wells around 1950. and by 1968 there were over 60 such wells in Texas and Louisiana alone; presently, the number is about 175 for the project area.

The concept of subsurface injection of wastes involves the introduction of waste into a permeable formation hydraulically isolated from both higher and lower formations by impervious confining layers. It is important to note that fluids already fill the void in those formations into which wastes are injected. In order for the receiving formation to accept the waste, it is necessary that the injected fluid be at a higher pressure than that naturally existing in the receiving formation This pressure may result from an applied pressure at the well head or may be gained by the weight of fluid standing in the injection tubing. In either case, the pressure within the receiving formation must be increased, and it is this increased pressure that must be considered when evaluating the effect of a subsurface injection well on groundwater.

Since the receiving formation contains natural fluid and a pressure must exist in order to force waste into and through the formation, it follows that the waste can only be accepted by compressing or displacing the fluids involved or by compressing the formations containing or confining the fluids.

If an injection well is located in an area where natural or man-made connections exist between the injection formation and other formations, the increase in pressure may force injected or native fluids into other formations containing fresh water or to points of surface discharge. Even without the existence of these avenues for fluid migration, injection pressures may reach a critical point great enough to fracture confining formations or damage parts of the injection system, allowing fluids to escape into surface or subsurface water resources. Since pressure increases are greatest near the point of injection, most failures can be expected in or near the injection well.

The exact number of industrial disposal wells in the study area is difficult to determine. The literature is not consistent in this respect for a number of reasons including the rapid rate of growth over the past few years, deletions when use is discontinued, and differences in classification.

Table 15 provides a general accounting of the number of disposal wells in the study area.

Table 15. WASTE DISPOSAL WELLS IN STUDY AREA*

	1965[116]	1968[117]	1971
Arkansas	0	0	--
Louisiana	10	28	62[118] (includes 3 municipal wells)
New Mexico	1	1	--
Oklahoma	1	4	13[119]
Texas	30	35	91[120] (includes 4 municipal wells)

*Does not include wells used for disposal of oil field brines.

Disposal wells in the study area are mostly associated with the chemical industry, oil refineries, and metal product plants. Wastes that are injected vary greatly and include many types of organic and inorganic compounds, acid and alkalis, salts, cooling and wash water, and in some cases treated municipal sewage.

There have been no reported incidences of ground-water pollution attributable to the practice of industrial waste injection in the study area. The potential for damage is, however, evidenced by a recent case in which a United States District Court enjoined an industrial firm from disposing of liquid waste by means of an injection well system until abandoned oil and gas wells within a 2½ mile radius of the injection well were adequately plugged.

Of the five states in this study area, only Texas has specific laws and regulations dealing entirely with the deep well disposal of industrial wastes.117/ The other states assume jurisdiction based on other legislation related to the production of oil and gas, the disposal of wastes in general, or laws pertaining to the protection, conservation, and development of fresh water.

In addition to the possibilities of pollution that do exist in well disposal of industrial waste, another complicating factor exists in the recovery of damages in the event such pollution does occur. By its nature, ground-water laws have been characterized as vague, uncertain, and inadequate.121/ In his article, Kreiger points out: "Because what goes on beneath the surface of the earth cannot be seen, it is difficult to comprehend the problems of the underground, let alone fashion meaningful and enforceable rules to govern subsurface activities."

Walker and Stewart 122/ summarized the legal proceedings for adjudicating matters associated with injection wells. They class such matters into the doctrines of trespass, negligence, nuisance, and strict liability. These doctrines and the violation of state statutes prohibiting the pollution of ground water constitute the legal constraints and liabilities associated with subsurface waste disposal.123/

The obligation for the plaintiff to prove that damages have occurred and that they result from subsurface injection will often be difficult, expensive, and time consuming. By the nature of ground-water movement, damages may not become apparent until long after a ground-water resource has been polluted. A ground-water resource that has been damaged is likely to remain damaged for a protracted period while efforts to restore an aquifer will prove difficult and costly.

Artificial Recharge of Aquifers

With the increasing demands on the normal water resources, ground-water recharge is gaining increasing attention throughout the United States. In huge arid sections of the five south central states, ground water is being mined at an alarming rate and in some locations, current supplies are good for less than 20 years at the present rate of use. As noted earlier, heavy ground-water withdrawals along the gulf coast have reversed the natural hydraulic gradients and permitted intrusion of salt water into heretofore fresh water zones. For these reasons and because soil filtration is an economical and efficient method of tertiary treatment of wastewaters, aquifer recharge will become increasingly important in the recycle and conservation of water resources.

Although artificial recharge is used extensively along the California coast to prevent, retard and reverse sea-water intrusion, there is presently no significant adoption of this practice along the Gulf Coast. However, with the continued overdraft of coastal aquifers around Houston and Baton Rouge, some type of recharge may be necessary, especially around Houston where land subsidence is a problem.

There are a number of recharge wells in the high plains area of Texas where water is being recharged to the Ogallala Formation. Sources of the recharge water are playas or natural lakes that dot the area and collect surface runoff during heavy rainfall periods. Ordinarily, the water collected in playas is rapidly evaporated in the semi-arid climate of the high plains.

Artificial recharge is also of interest in the high plains because of plans to import water to the area. Water storage in the Ogallala is highly desirable because large storage volumes are available, water is available to users wherever the aquifer exists, little or no water is lost from the aquifer by evaporation, ground-water quality is usually good, ground-waters are not easily polluted, and often there is no other feasible storage site.

Despite the many apparent advantages of artificial recharge, many questions remain concerning the introduction to the aquifer of pollutants with the recharge water. Little is known of the fate of such pollutants in the ground-water environment. Nitrates are a significant problem, especially where municipal effluents are used as recharge water. Nitrates are a primary constituent of such effluents and are not appreciably altered by movement through the ground-water environment.124/

Where agricultural wastewaters, such as runoff collected in playas, are recharged, pesticides and other agricultural chemicals are of concern. However, analysis of water from 39 playas in the high plains of Texas did not indicate pesticide concentrations that would be hazardous if recharged to the ground-water.90/ Analyses were made for six pesticides in common use in the area. Of unknown importance are the dozens of other agricultural chemicals that were not analyzed for and may be in the runoff water.

Treated municipal effluents have been recharged for several years, both intentionally 125/ 126/ and unintentionally, without known serious ground-water contamination problems--except for possible nitrate increases. Most of the recharge in the five south central states is unintentional. It has been estimated that one-third of all sewage effluents from western Texas towns is recharged to the ground water by infiltration.127/

Again, the major hazard may not be from contaminants routinely checked in municipal wastewaters but from the dozens of new industrial and household chemicals that find their way into the sewer.

There are also other physical and chemical problems related to artificial recharge and water quality. Clogging of the soils can occur from suspended sediments in the recharge water. Chemical precipitation can occur if the aquifer water and the recharge water are not chemically compatible and algal or bacterial growths are often a problem near the point of recharge.

Other Causes

There are many other activities or sources of ground-water pollution applicable to the project area. Over-fertilization of agricultural lands can be a source of excess nutrients, especially nitrogen, in the groundwater. Similarly, pesticides are widely used in the region and much is still unknown concerning their fate in the subsurface environment. Leaking sewers are common in all areas and thermal pollution can have serious effects in industrial areas where heated wastewaters are discharged to the ground water.

Undoubtedly, there are numerous other causes of ground-water pollution--both known and unknown. It should be borne in mind that any material that reaches the soil or surface water has the potential to reach the ground water.

SECTION VII

RESEARCH AND OTHER NEEDS

Traditionally, ground-water research or related investigations have been concerned chiefly with availability, hydrology, or simply the measurement of inorganic quality parameters. It has only been in relatively recent times that ground-water investigations have dealt with the cause and effect aspects of quality alterations. Ground-water investigators, therefore, find a great many areas for which effort is needed in order to protect, enhance, and in some cases restore the quality of ground-water resources.

Although this section will primarily be concerned with the technical aspects of ground-water quality, it cannot be implied that the totality of problems rests with technical solutions alone. Indeed, many pollutional problems do rest with technical solutions alone. Many other pollutional problems can only be eliminated or avoided by appropriate rules and regulations soundly based and for which adequate resources are available for their implementation.

Additionally, the solution to existing and potential subsurface water resource problems will depend greatly on the cooperation of public, private, and academic institutions. For example, industry and government may be required to marshal their resources to eliminate natural salts which contaminate both surface and subsurface water resources. Municipalities, irrigators, and industry must work together to control the overdevelopment of aquifers and the resulting intrusion of waters of poor quality. The development of river basin plans must incorporate subsurface water resources because of their inseparability. Universities and consultants should work actively to assure that wastewater and solid waste treatment facilities are designed in the interest of ground-water quality protection.

Above all, the makers of policy and the public in general must continually be informed of the value and magnitude of our ground-water resources and that the natural restoration of ground water may take hundreds or thousands of years after a single introduction of polluting material.

General Research Needs

Basic to the needs of ground-water research are the development of reports such as this for the rest of the country. One such report has been completed for the southwestern United States 2/ and, at this writing, another is just beginning for the North Atlantic States. These should be prepared regionally by experts familiar with particular geographical areas so that their knowledge of that area and their association with consultants, universities, water resources agencies, and regulatory agencies in that area can be combined to produce the most comprehensive assessment of existing and potential ground-water pollution problems.

The development of technology is a necessary and first step to any successful attack in the unusually complicated area of ground-water investigations. In order to predict, with some certainty, the fate of pollutants in the subsurface environment, it is necessary to understand the environment itself as the receptor of those pollutants. New drilling techniques should necessarily be developed so that physical, chemical, and biological measurements of the subsurface environment can be made accurately. A difficult example would be the measurement of the oxidation-reduction potential.

Another area where technology is needed is that of pollutant identification. Information is particularly lacking in organics and in indicators of organic pollution. The use of stable isotope ratios shows great promise in characterizing the source of pollutants while coprostinol or its degradation products could possibly be developed as indicators of fecal pollution. Additionally, the general aspects of collecting, handling, and analyzing samples from the subsurface environment should be standardized to the extent possible so that comparability between different investigators can be established.

The results of basic or applied research are for little purpose unless an avenue is developed by which these results can be made clearly and simply available to those who will eventually put them into practice. The National Ground Water Quality Symposium held in Denver in August of 1971 presented such an avenue of technology transfer by its composition of actual case histories followed by detailed discussions by those in attendance.

Specific Research Needs

Natural Leaching

While this is the greatest single problem in the study area affecting both surface and subsurface waters, it is also one of the most difficult to attack. It is a natural phenomena extending in most cases over broad geographical areas. Some work is being done by the U.S. Corps of Engineers particularly as the problem affects surface water. The problems are probably of more concern to surface supplies than ground water because once the subsurface flows emerge at the surface, the damage becomes much more widespread. The phenomena is, nonetheless, subsurface in origin and should be addressed here in terms of alleviating predominantly surface pollution.

1. Technology associated with demineralization has been advanced to a considerable degree. Work remains to be done on the application of these techniques to waters of this chemical composition so that the economics of providing at least small quantities of water can be established.

2. The development of technology to collect small heavily mineralized alluvial flows should be pursued along with ways to lower alluvial water tables in order to prevent surface accumulation of brine crystals which are washed into streams during periods of runoff.

3. Opportunities for secondary oil recovery by waterflooding exist in many of the areas where natural brines are present. Since the volume of water needed for waterflood greatly exceeds that available from natural brine springs, the possibility of using these natural brines for this purpose should be investigated. Collection facilities and incompatibility due to high sulfate concentration in the natural brines may present obstacles that will have to be resolved.

4. Deep well disposal of natural brines is being studied by the U.S. Corps of Engineers. This work should be encouraged particularly in view of the disposal of brines into formations which naturally discharge into the sea.

5. In situ evaporation rates should be established for the various natural brines encountered in the study area. This would allow for optimizing systems of disposal or use which are a function of volume.

Oil Field Brines and Other Materials

The practice of disposing of oil field brines has changed over the last decade. The use of evaporation pits has almost been abandoned in favor of subsurface injection either for waterflood or disposal. The protracted use of pits has resulted in the discharge of large volumes of brines to both the saturated and unsaturated subsurface environment and is likely to remain a problem for many years even though the use of pits is generally abandoned. Technology for brine injection either for disposal or waterflooding is generally available but the consequences of these types of brine disposal on ground-water resources has not been fully evaluated. Ideally, brines should be returned to the formation from which they were extracted.

1. Techniques for locating areas of subsurface brine pollution should be developed so that these areas can be investigated. Remote sensing and resistivity techniques show promise.

2. Aquifer restoration should be demonstrated and encouraged particularly in areas where polluted ground water can be used for waterflooding.

3. The geologic and hydraulic relationship between fresh water aquifers and brine disposal formations must be evaluated in order to establish sound disposal criteria in forms of disposal volume and pressure. Economic techniques for making these appraisals should be improved and demonstrated so that regulatory agencies could regulate disposal activities more soundly and in individual fields, if necessary.

4. Existing inspection and monitoring techniques should be evaluated and, if necessary, modified to assure that the pollution potential to ground water is minimized.

5. A conceptual appraisal of the pollutional hazards of using oil field drilling fluids and chemicals should be made. The results of such an appraisal would dictate future studies, if required.

6. A handbook should be developed by a firm with exceptional expertise in the field of design, construction, and operation of disposal or waterflood wells. The handbook should dwell on techniques, materials, treatment, operation, monitoring, and training.

Well Construction

As pointed out in the previous section, well construction is a major source of ground-water pollution. Well construction pertains both to water wells and to other man-made penetrations particularly associated with the oil and gas industry. In all cases, these problems should not exist in the future because technology is available for their control.

1. With respect to water wells, any additional research that is needed would be primarily in their location with

respect to either subsurface or surface sources of pollution. These items will be covered at least in concept in other sections pertaining to research needs.

2. State regulatory agencies should license drillers, review design, and inspect completed wells to assure that the latest drilling and completion techniques are practiced.

3. Opportunities for continuing education should be made available to drillers. Perhaps this could be done in cooperation with the National Water Well Association where adequate state programs are lacking.

4. Well owners should be encouraged to receive periodic inspections to assure that the integrity of their well continues to provide pollution protection.

5. Intermixing between aquifers can result from improper cementing. Procedures should be developed by which this type of pollution can be discovered before extensive damage is done. This should be followed by reworking the well or abandoning and plugging to prevent further pollution.

Many problems of pollution result from existing wells, particularly in the oil and gas industry, which were inadequately constructed or abandoned many years ago. Most research will be associated with the location of these penetrations when unknown and evaluating the pollutional potential of those for which the location is known.

1. Develop technology for locating abandoned oil and gas test wells. Remote sensing shows some promise while pollutant concentration vectors may be considered.

2. Tracer techniques should be developed to describe the extent and manner of pollution resulting from abandoned wells.

3. Technology should be improved to describe hydraulic conditions in an area where a pollutional potential exists in connection with abandoned wells. This will establish criteria by which the potential can be evaluated.

4. Technology should be improved to adequately plug wells which have been located as described above.

Overpumping

When overpumping occurs, water levels decline and the movement of mineralized water into the aquifer is possible. In other cases, fresh water may be over brackish water and pumping can cause intermixing.

In the first case, state water resource agencies can regulate overpumping by using available technology. In the second case, technology should be developed which will permit the pumpage of fresh water overlying mineralized water. Some success might be gained using two pump techniques or, in rare cases, the creation of separatory barriers.

Irrigation Return Flows

The practice of irrigation has detrimental effects on water quality mostly in terms of mineralization. Irrigation can have beneficial aspects such as denitrification, phosphate removal in the subsurface return flows, and biological improvement.

1. Investigations should be undertaken to define specific pollutants reaching ground water and the magnitude of each.

2. Conduct basic studies of the precipitates and exchange reactions which occur as water moves through mineralized soil.

3. Conduct basic studies related to adsorption of phosphates, heavy metals, and various agricultural chemicals which may be carried into the soil with irrigation water.

4. Subsurface return flow quality prediction techniques should be developed along with economic evaluations which might result from control measures imposed on irrigative systems.

5. Research and demonstration projects should be initiated to determine the response to various practical quality control measures for subsurface return flows.

Septic Tanks

Septic tanks have received a great deal of study over a long period of time mostly with respect to design and efficiency. In recent years, many people have moved out of the cities either to summer homes or retirement communities, many of which are located near streams or reservoirs. This practice has again given rise to the need for additional research of septic tanks but of a somewhat different nature. The pollution of ground water is gaining importance, as well as the contribution of nutrients to reservoirs, often after the effluent has passed through the ground water.

1. As in other types of waste treatment, a need exists for the identification of persistent pollutants in both the unsaturated soils and in the ground-water table.

2. The use and development of stable isotope ratios shows promise in tracing septic tank effluents into and through the ground water and often to surface reservoirs.

3. Investigations should be made leading to decision criteria for the allowable density of septic tanks before collection and central treatment facilities are required.

Land Application of Wastes

The practice of applying liquid and solid waste to the land for treatment and disposal is gaining momentum in the study area. These practices include spray irrigation, flooding, and spray runoff. The latter poses the least threat to ground water since it is confined to areas where the infiltration rate is low. While the theory of these practices shows considerable promise with respect to the removal of pollutants, care must be taken to assure that design and operation are not abused and ground water is not polluted.

1. A handbook should be prepared outlining the design criteria for these systems particularly with respect to ground-water hydrology and the necessity for an underdrain network.

2. Stable isotope ratio techniques or other means of waste identification should be perfected by demonstration in these types of waste disposal systems. These tools are needed in order to accurately monitor the ground-water quality and detect failures at an early stage.

3. Vertical soil and moisture profiles above the saturated zone should be studied to identify the presence and define the characteristics of movement of pollutants, particularly those of a recalcitrant nature.

4. Ground-water samples would be collected below and down gradient from disposal sites to define, at least by class, those pollutants which persist over time and distance either in the form of the parent parameter or its degradation products.

5. Criteria must be developed which dictates the need for underdraining based on water quality criteria.

Solid Waste Disposal

Most research to date has been confined to the contribution of inorganics from landfills and dumps. Generally, it is suggested that future research deal with organics and their degradation products and the establishment of regulations limiting the types of waste that may be disposed of in this fashion.

1. Vertical soil and moisture profiles above the saturated zone should be studied to identify the presence and define the characteristics of movements of pollutants, particularly those of a recalcitrant nature.

2. Ground-water samples should be collected below and down gradient from solid waste disposal sites to define, at least by class, those pollutants which persist over time and distance either in the form of the parent parameter or its degradation products.

3. Those pollutants which prove to be particularly persistent and toxic must be identified so that they can be handled in a separate fashion and not allowed to enter ground water.

4. The contribution to and solubility of heavy metals in ground water should be studied.

Evapotranspiration by Native Vegetation

The prospect of salvaging valuable water now being wasted by comparatively useless vegetation, while at the same time decreasing the accompanying mineralization of the water supply, has provided an attractive goal for many engineers and scientists. Various programs of vegetation eradication have been attempted with very limited success. The growth usually returns within a short period of time. Erosion resulting during the eradication period has created serious soil loss problems in the eradication areas and sedimentation problems in the nearby stream channels. Nevertheless, the authors believe that research along the following lines could be fruitful:

1. Development and evaluation of replacement vegetation having lower water use characteristics than the water-loving phreatophytes.

2. Investigation of the possibilities of leveling areas of phreatophyte growth and utilizing the areas for agricultural production. Such a program should involve consideration of subsidization because of the intermittent flooding, poor soil conditions and low yield potential.

Animal Wastes

The study area contains a number of agricultural operations where large numbers of either cattle, chickens, and, less frequently, hogs are placed in small areas. These pose a pollutional threat to both surface and ground water. Some work has been completed covering cattle feeding in the High Plains of Texas and other investigations are underway for both alluvial deposits and limestone areas. These studies are concerned with the effect of cattle feeding operations on ground water.

1. These studies should be continued until various waste handling techniques are investigated for the types of geologic conditions that exist in the study area. The work should identify the organic and inorganic pollutants that reach ground water under the various geologic conditions encountered.

2. Research should particularly address the fate and movement of hormones and antibiotics into and through the ground water.

3. Work should be done concerning the possibility of waste treatment lagoons sealing after a period of use. If sealing does occur, its mechanism should be determined for the geological conditions encountered. If sealing does not occur in a reasonable time, efforts should be made for artificial sealing.

Waste Lagoons

Waste lagoons have been constructed for many types of wastes on many types of soils and, in most cases, little consideration has been given to protecting the underlying ground water. Research needs here are similar to those suggested for other means of waste treatment.

1. The identification of persistent pollutants and their degradation products is needed for both unsaturated and saturated zones.

2. Stable isotope ratio techniques or other means of waste identification should be perfected and demonstrated for those types of waste facilities.

3. Research should be conducted concerning the capacities of various soil types to seal after a period of use. Techniques should be developed to accelerate natural sealing when possible and assure that such seals remain intact.

4. Decision criteria is needed which dictates the need for artificial lagoon seals.

Accidental Spills of Hazardous Material

Accidental spills are both diverse and numerous. Although data are not readily available to describe the magnitude of these types of problems, it is evident that detection and control technology is needed. Because of the diverse nature of this type of potential pollution, the following are only suggestions of the types of work needed.

1. The concept of continuous monitoring of pipelines should be investigated so that failures can be detected early and the extent of pollution can be minimized.

2. Techniques should be developed to detect leaks in buried gasoline storage tanks.

3. Research is needed which will lead to the in situ degradation or treatment of spilled hydrocarbons which have entered the subsurface environment.

Subsurface Waste Disposal

With more stringent regulations covering the discharge of effluents to the environment, the use of injection wells may provide an attractive alternative to more conventional techniques. Research is needed to assure that the subsurface disposal of waste is a true alternative with respect to environmental protection.

1. Develop a manual covering the design, construction, operation, monitoring, and maintenance of well disposal systems. Such items as material selection for various

wastes should be included. The manual should be developed by a company with considerable experiences in the field. Provisions should be made to add to the manual as new technology is developed.

2. Since many problems would be based on pressure increases, projects should be initiated which evaluate the effects of pressure increases in the subsurface.

3. Efforts are needed to relate hydraulic formation fracturing to subsurface waste injection.

4. A model should be developed to serve as a tool in the appraisal of the effects of each subsurface waste injection project.

5. Research is needed to define the movement and degradation of wastes in an environment such as that found in deep formations.

6. A compilation of existing laws and regulations of the states should be made.

7. Methodology should be developed for monitoring the effects of subsurface waste injection projects.

Aquifer Recharge

Aquifer recharge is accomplished both intentionally and as a result of other activities discussed in this section such as septic tanks, irrigation, and lagoons. Intentional recharge may be accomplished in a number of ways, including spreading, ponding, or the use of wells. Research needs suggested here are confined to water quality aspects and, as such, are much like those in other research suggestions. Research needs on the physical aspects of recharge are better addressed by others and are not included.

1. Pollution identification techniques are needed to assure that the aquifer is not degraded by recharge.

2. Both the saturated and unsaturated zones should be investigated to assure that no parameter present in the recharge water is accumulating or otherwise persistent in undesirable concentrations.

3. The fate of any constituent of the recharge water should be determined to assure degradation products are non-polluting or synergistic.

SECTION VIII

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This report is based on assistance and information from many agencies and individuals. Much of the water resource and water quality information was obtained from reports of the U.S. Geological Survey and various state agencies. Additional information was supplied by many other publications and most of these and some of the private individuals are listed in the bibliography.

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SECTION IX

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SECTION X

GLOSSARY OF TERMS

Aquifer - A geologic formation which contains water and has the capability of transmitting it from one point to another in quantity to permit economic development.

Aquifer Restoration - Restoration of the water quality in a polluted aquifer to its normal quality, usually by removing the source of pollution and the polluted ground water.

Artificial Recharge - The addition of water to the ground-water reservoir by activities of man, such as irrigation or induced infiltration from streams, wells, or spreading basins.

Beneficial Use of Water - The use of water for any purpose from which benefits are derived, such as domestic, irrigation, or industrial supply, power development, or recreation.

Brackish Water - Water containing dissolved minerals in excess of acceptable normal municipal, domestic, and irrigation standards, but less than that of sea water.

Cambrian Age - Oldest period of geological history in the Paleozoic Era.

Cenozoic Age - Era of geological history from the beginning of the Tertiary (first period in the Cenozoic Era) to the present.

Cretaceous Age - Youngest period of geological history in the Mesozoic Era.

Closed Basin - A basin is considered closed with respect to surface flow if its topography prevents the occurrence of visible outflow. It is closed hydrologically if neither surface nor underground outflow can occur.

Confined (Artesian) Aquifer - An aquifer which is bounded above and below by formations of impermeable or relatively impermeable material.

Connate Water - Sea water held in the interstices of sedimentary deposits and sealed in by the deposition of overlying beds.

Deep Well Disposal - The disposal of waste materials by injection into a subsurface formation, usually at much greater depth than known fresh-water aquifers.

Degradable - Capable of being decomposed, deteriorated, or decayed into simpler forms with characteristics different from the original. Also referred to as biodegradable.

Degradation of Water Quality - Decrease in water quality due to increased concentration of any substance classified as a pollutant.

Demineralization - The process of removing the mineral salts from water.

Depletion (Ground-Water) - The withdrawal of water from a ground-water source at a rate greater than its rate of replenishment, usually over an extended period of several years.

Dissolved Solids - Chemicals in true solution.

Evaporation Pits - Ponds commonly used to store wastewaters, theoretically for evaporation. In most cases, there is probably more water lost through infiltration than by evaporation.

Evapotranspiration - The sum of the quantity of water used by vegetative growth in transpiration or building of plant tissue and the quantity evaporated from adjacent soil or plant surfaces in a given specified time.

Ground Water - Underground water that is in the zone of saturation.

Ground Water Basin - A ground water reservoir together with all the overlying land surface and the underlying aquifers that contribute water to the reservoir. In some cases, the boundaries of successively deeper aquifers may differ in a way that creates difficulty in defining the limits of the basin.

Ground Water Mining - See Depletion (Ground-Water).

Ground Water Recharge - Inflow to a ground water reservoir.

Ground Water Reservoir - An aquifer or aquifer system in which ground water is stored. The water may be placed in the aquifer by artificial or natural means.

Ground Water Storage Capacity - The reservoir space contained in a given volume of deposits. Under optimum conditions of use, the usable ground water storage capacity volume of water that can be alternately extracted and replaced in the deposit, within specified economic limitations.

Hydrologic Cycle - The circuit of water movement from the atmosphere to the earth and return to the atmosphere through various stages or processes as precipitation, interception, runoff, infiltration, percolation, storage, evaporation, and transpiration.

Igneous Rock - Rock formed by volcanic action or great heat.

Infiltration - The process whereby water passes through an interface, such as from air to soil or between two soil horizons.

Land Subsidence - The lowering of the natural land surface in response to: earth movements; lowering of fluid pressure; removal of underlying supporting material by mining or solution of solids, either artificially or from natural causes; compaction due to wetting (Hydrocompaction); oxidation of organic matter in soils; or added load on the land surface.

Mesozoic Age - The geological era after the Paleozoic and before the Cenozoic eras.

Metamorphic Rock - Rock formed by a change in structure due to pressure, heat, chemical action, etc.

mg/l - Abbreviation for milligrams per liter.

Milligrams Per Liter - The weight in milligrams of any substance contained in one liter of liquid. Approximately equivalent to parts per million.

Mineralization - The process of accumulation of mineral elements and/or compounds in soil or water. See also Salinization.

Mining of Ground Water - See Depletion (Ground-Water).

Natural Brines - Highly mineralized water resulting from percolation of ground water through soils or rocks containing soluble minerals.

Natural Leaching - The process whereby percolation of water through soils and rocks dissolves material from the formation.

Nutrients - Compounds of nitrogen, phosphorus, and other elements essential for plant growth.

Overdraft - The amount by which pumpage of ground water exceeds the safe yield of the ground water aquifer or basin.

Oxidation-Reduction Potential - Denotes the potential required to transfer electrons from the oxidized form to the reduced form.

Perched Ground Water - Ground water supported by a zone of material of low permeability and located above an underlying main body of ground water with which it is not hydrostatically connected.

Percolation - The movement of water within a porous medium such as soil.

Perennial Yield (Ground Water) - The amount of usable water of a ground water reservoir that can be withdrawn and consumed economically each year for an indefinite period of time. It cannot exceed the natural recharge to that ground water reservoir.

Permeability - The property of a material which permits appreciable movement of water through it when actuated by hydrostatic pressure of the magnitude normally encountered in natural subsurface water.

Pesticides - Chemical compounds used for the control of undesirable plants, animals, or insects. The term includes insecticides, weed killers, rodent poisons, nematode poisons, fungicides, and growth regulators.

Phreatophyte - A plant that habitually obtains its water supply from the zone of saturation, either directly or through the capillary fringe.

Playas - Flat floored lakes formed in undrained natural depressions.

Pleistocene Age - The first epoch of the Quaternary Age of geological history.

Pliocene Age - Most recent epoch of Tertiary Age and just prior to beginning of the Quaternary Age.

Pollution - The presence of any substance (organic, inorganic, biological, thermal, or radiological) in water at intensity levels which tend to impair, degrade, or adversely affect its quality or usefulness for a specific purpose.

Quaternary Age - Division of recent geological history from the end of Tertiary Age in the Cenozoic Era to the present.

Recharge - See Ground Water Recharge.

Recharge Basin - A basin provided to increase infiltration for the purpose of replenishing ground water supply.

Return Flow - That part of a diverted flow which is not consumptively used and which returns to a source of supply (surface or underground).

Safe Ground-Water Yield - The annual pumpage that can be sustained without permanent change in ground water storage.

Saline Water - Water containing dissolved salts. See also Brackish Water.

Salinity - Salt content concentration of dissolved mineral salts in water or soil.

Salinization - The process of accumulation of soluble salts in soil or water. See also Mineralization.

Salt Balance - A condition in which specific or total dissolved solids removed from a specified field, stratigraphic zone, political area, or drainage basin equals the comparable dissolved solids added to that location from all outside sources during a specified period of time.

Salt Water Barrier - A physical facility or method of operation designed to prevent the intrusion of salt water into a body of fresh water. In underground water management, a barrier may be created by injection of relatively fresh water to create a hydraulic barrier against salt water intrustion.

Salt Water Intrusion - The invasion of a body of fresh water by salt water. It can occur either in surface or ground water bodies.

Secondary Oil Recovery - The injection of water into an oil producing formation to increase pressure so as to increase the percent of recoverable oil.

Seepage - The gradual movement of a fluid into, through, or out of a porous medium.

Suspended Solids - Solids which are not in true solution and which can be removed by filtration.

Sustained Yield - Achievement and maintenance, in perpetuity, of a high-level annual or regular periodic output or harvest of the various renewable land and water resources.

Stable Isotope Ratio - Refers to the tendency of isotopes of different mass of the same chemical species to react at different rates when undergoing the same chemical biological reaction.

Total Dissolved Solids (TDS) - The total dissolved solids in water, usually expressed in milligrams per liter (mg/l).

Waste Water Reclamation - The process of treating salvaged water from municipal, industrial, or agricultural waste water sources for beneficial uses, whether by means of special facilities or through natural processes.

Waterflooding - See Secondary Oil Recovery.

Water Quality - A term used to describe the chemical, physical, and biological characteristics of water, usually in respect to its suitability for a particular purpose.

Water Right - A legally protected right to take possession of water occurring in a water supply and to divert that water and put it to beneficial use.

Water Table - The surface in a ground-water body at which the water pressure is atmospheric.

SECTION XI

APPENDIX A

WATER QUALITY STANDARDS 2/

The extent of undesirability of a given level of pollution in water is dependent upon the use or intended use of the water. Standards of quality of water used for domestic water supply have been established by the National Technical Advisory Committee on Water Quality Criteria 128/, and the U.S. Public Health Service 129/. Tables A-1 and A-2 presented herein, are taken from their reports.

Various agencies have set standards of quality for waters used for other purposes. Table A-3 gives standards for livestock watering as reported by McGauhey 130/. Tables A-4, A-5 and A-6 present irrigation water quality standards as suggested by the Economic Research Service 131/. Table A-7 gives standards for water used in various industrial processes as reported by the American Society for Testing Materials 132/.

Table A-1. SURFACE WATER CRITERIA FOR PUBLIC WATER SUPPLIES [128]

Constituent or Characteristic	Permissible[a] Criteria	Desirable[b] Criteria
Physical:		
Color (color units)	75	<10
Microbiological:		
Coliform organisms	10,000/100 ml[c]	<100/100 ml[c]
Fecal coliforms	2,000/100 ml[c]	< 20/100 ml[c]
Inorganic Chemicals:	mg/l	mg/l
Ammonia	0.5 (as N)	<0.01
Arsenic	0.05	Absent
Barium	1.0	Absent
Boron	1.0	Absent
Cadmium	0.01	Absent
Chloride	250	<25
Chromium, hexavalent	0.05	Absent
Copper	1.0	Virtually absent
Dissolved Oxygen	4 (monthly mean) 3 (indiv. sample)	Near Saturation
Iron (filterable)	0.3	Virtually Absent
Lead	0.05	Absent
Manganese (filterable)	0.05	Absent
Nitrates plus nitrites	10 (as N)	Virtually Absent
pH (range)	6.0 to 8.5	Variable
Selenium	0.01	Absent
Silver	0.05	Absent
Sulfate	250	<50
Total dissolved solids, (filterable residue)	500	<200
Uranyl ion	5	Absent
Zinc	5	Virtually absent

[a]Permissible criteria--Those characteristics and concentrations of sub-substances in raw surface water which will allow the production of a safe, clear, potable, aesthetically pleasing, and acceptable public water supply which meets the limits of Drinking Water Standards after treatment.

[b]Desirable criteria--Those characteristics and concentrations of substances in the raw surface waters which represent high-quality water in all respects for use as public water supplies. Water meeting these criteria can be treated in the defined plants with greater factors of safety or at less cost than is possible with waters meeting permissible criteria.

Table A-1 (cont'd) SURFACE WATER CRITERIA FOR PUBLIC WATER SUPPLIES 128/

Constituent or Characteristic	Permissible[a] Criteria	Desirable[b] Criteria
Organic Chemicals:	(mg/l)	(mg/l)
Carbon chloroform extract (CCE)	0.15	<0.04
Cyanide	0.20	Absent
Methylene blue active substances	0.5	Virtually Absent
Oil and Grease	Virtually Absent	Absent
Pesticides:		
Aldrin	0.017	Absent
Chlordane	0.003	Absent
DDT	0.042	Absent
Dieldrin	0.017	Absent
Endrin	0.001	Absent
Heptachlor	0.018	Absent
Heptachlor epoxide	0.018	Absent
Lindane	0.056	Absent
Mathoxychlor	0.035	Absent
Organic phosphates plus Carbamates	0.1[d]	Absent
Toxaphene	0.005	Absent
Herbicides:		
2, 4-D plus 2, 4, 5-T plus 2, 4, 5-TP	0.1	Absent
Phenols	0.001	Absent
Radioactivity:	(pc/l)	(pc/l)
Gross beta	1,000	<100
Radium-226	3	<1
Strontium-90	10	<2

[a]See Previous page.

[b]See Previous page.

[c]Microbiological limits are monthly arithmetic averages based upon an adequate number of samples. Total coliform limit may be relaxed if fecal concentration does not exceed the specified limit.

[d]Expressed as parathion in cholinesterase inhibition. It may be necessary to resort to even lower concentrations for some compounds or mixtures.

Table A-2. CHEMICAL STANDARDS OF DRINKING WATER 129/

Category A -- Maximum allowable concentrations where other more suitable supplies are, or can be made available:

Substance	Concentration in mg/l
Alkyl Benzene Sulfonate (ABS)	0.5
Arsenic (As)	0.01
Chloride (Cl)	250
Copper (Cu)	1
Carbon Chloroform Extract (CCE)	0.2
Cyanide (CN)	0.01
Iron (Fe)	0.3
Manganese (Mn)	0.05
Nitrate (NO_3)[a]	45
Phenols	0.001
Sulfate (SO_4)	250
Total Dissolved Solids (TDS)	500
Zinc (Zn)	5

Category B -- Maximum concentrations which shall constitute grounds for outright rejection of the supply:

Substance	Concentration in mg/l
Arsenic (As)	0.05
Barium (Ba)	1.0
Cadmium (Cd)	0.01
Chromium (Hexavalent) (Cr^{+6})	0.05
Cyanide (CN)	0.2
Fluoride (F)	0.6 to 1.7[b]
Lead (Pb)	0.05
Selenium (Se)	0.01
Silver (Ag)	0.05

[a] In areas in which the nitrate content of water is known to be in excess of the listed concentration, the public should be warned of the potential dangers of using the water for infant feeding.

[b] Varies with water temperature.

Table A-3. GUIDES TO THE QUALITY OF WATER FOR LIVESTOCK 130/

Quality Factor mg/l	Threshold[a] Concentration	Limiting[b] Concentration
Total Dissolved Solids (TDS)[c]	2500	5000
Cadmium	5	-
Calcium	500	1000
Magnesium	250	500
Sodium	1000	2000
Arsenic	1	-
Bicarbonate	500	500
Chloride	1500	3000
Fluoride	1	6
Nitrate as NO_3	200	400
Nitrite	None	None
Sulfate	500	1000
Range of pH	6.0 to 8.5	5.6 to 9.0

[a] Threshold values represent concentrations at which poultry or sensitive animals might show slight effects from prolonged use of water. Lower concentrations are of little or no concern.

[b] Limiting concentrations based on interim criteria, South Africa studies. Animals in lactation or production might show definite adverse reaction.

[c] Total magnesium compounds plus sodium sulfate should not exceed 50 percent of the total dissolved solids.

Table A-4. SUGGESTED GUIDELINES FOR SALINITY IN IRRIGATION WATER 131/

Crop Response	TDS in mg/l	EC[a]
Water for which no detrimental effects will usually be noticed	less than 500	less than 0.75
Water which can have detrimental effects on sensitive crops	500-1000	0.75-1.50
Water that may have adverse effects on many crops and requiring careful management practices	1000-2000	1.50-3.00
Water that can be used for salt-tolerant plants on permeable soils with careful management practices	2000-5000	3.00-7.50

[a]Electrical Conductivity expressed in millimhos per centimeter.

Table A-5. TRACE ELEMENT TOLERANCES FOR IRRIGATION WATER 131/

Element	For Water Used Continuously on All Soils mg/l	For Short-term Use on Fine-Textured Soils Only mg/l
Aluminum	1.0	20.0
Arsenic	1.0	10.0
Beryllium	0.5	1.0
Boron	0.75	2.0
Cadmium	0.005	0.05
Chromium	5.0	20.0
Cobalt	0.2	10.0
Copper	0.2	5.0
Lead	5.0	20.0
Lithium	5.0	5.0
Manganese	2.0	20.0
Molybdenum	0.005	0.05
Nickel	0.5	2.0
Selenium	0.05	0.05
Vanadium	10.0	10.0
Zinc	5.0	10.0

Table A-6. LEVELS OF HERBICIDES IN IRRIGATION WATER AT WHICH CROP INJURY HAS BEEN OBSERVED 131/

Herbicide	Crop Injury Threshold in Irrigation Water, expressed in mg/l
Acrolein	Flood or Furrow: beans-60, corn-60, cotton-80, soybeans-20, sugar beets-60. Sprinkler: corn-60, soybeans-15, sugar beets-15.
Aromatic Solvents (Xylene)	Alfalfa >1600, beans-1200, carrots-1600, corn-3000, cotton-1600, grain sorghum >800, oats-2400, potatoes-1300, wheat >1200.
Copper Sulfate	Apparently, above concentrations used for weed control.
Amitrole-T	Beets (rutabaga) >3.5, corn >3.5.
Delapon	Beets >7.0, corn <0.35
Dequat	Beans-5.0, corn 125.0.
Enothall Na and K salts	Corn-25, field beans <1.0, alfalfa >10.0.
Dimethylamines	Corn >25, soybeans >25. sugar beets-25.
2, 4-D	Field Beans >3.5 <10. grapes-0.7-1.5, sugar beets-3.5.
Dichlobenil	Alfalfa-10, corn >10, soybeans-1.0, sugar beets-1.0-10.
Fenac	Alfalfa-1.0, corn-10, soybeans-0.1, sugar beets-0.1-10.
Picloram	Corn >10, field beans-0.1, sugar beets <1.0.

Note: Where the symbol ">" is used, the concentrations in water cause no injury. Data are for furrow irrigation unless otherwise specified.

Table A-7. PREFERRED LIMITS FOR SEVERAL CRITERIA OF WATER FOR USE IN INDUSTRIAL PROCESSES 132/

Process	Turbidity Max. ppm	pH Min.	pH Max.	TDS Max. mg/l
Aluminum (hydrate Wash)				low
Baking	10			
Boiler Feed:				
0 to 150 psi	80	8.0		3000
150 to 250 psi	40	8.4		1500
250 to 400 psi	5	9.0		2500
400 to 1000 psi	2	9.6		50
Over 1000 psi				0.5
Brewing	10	6.5	7.0	1500
Carbonated beverages	2			
Confectionery		7.0		100
Dairy				500
Electroplating and finishing, rinse				low
Fermentation	low			
Food Canning and Freezing	10	7.5		850
Food Processing, general	10			
Ice Manufacturing				170 to 1300
Laundering		6.0	6.8	
Oil Well Flooding		7.0		
Photographic process	low			
Pulp and Paper:				
Groundwood paper	50			500
Solda and Sulfate pulp	25			250
Kraft paper, bleached	40			300
Kraft paper, unbleached	100			500
Fine paper	10			200
Sugar Manufacture				low
Tanning Operations	20	6.0	8.0	
Textile Manufacture	0.3			

Note: The values in this table are taken from summaries in the comprehensive review by McKee and Wolf, cited in the ASTM report 131/, and are presented here only as a general guide. They should be used only after study of the original references cited in the ASTM report.

SECTION XII

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A study was conducted to determine the ground-water pollution problems in the states of Arkansas, Louisiana, New Mexico, Oklahoma, and Texas. Information was obtained through review of the literature and through interviews with engineers, scientists, and governmental officials concerned with water pollution in the five states of the project area.

Natural salinity was the greatest factor affecting the quality of ground water of the region. Disposal of oil-field brines was the most widespread source of man-made pollution. Other causes of ground-water pollution included poor well construction and abandonment procedures, over-pumping, irrigation return flows and land disposal of solid and liquid wastes.

17a. Descriptors

*Ground water, *water pollution, water resources, natural pollution, oil-field brines, over-pumping

17b. Identifiers

*South-Central United States, Arkansas, Louisiana, New Mexico, Oklahoma, Texas

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