Texas Water Development Board

Report 330

Evaluation of Ground-Water Resources in the Southern High Plains of Texas

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ABSTRACT

The evaluation of ground-water resources in the southern High Plains of Texas is in response to the 1985 passage of House Bill 2 by the Sixty-ninth Texas Legislature, which called for the identification and study of areas in the State that are experiencing or are expected to experience critical underground water problems within the next 20 years. Primary emphasis is placed on Andrews, Gaines, Lynn, and Terry Counties, and parts of Borden, Ector, Garza, Howard, and Midland Counties. The region is characterized by a flat to gently rolling, treeless plateau with a semi-arid Continental Steppe climate. Oil and gas production, raising cattle, and irrigated farming are the mainstays of the local economy. Water needs for the area are supplied mostly from the Ogallala aquifer with lesser amounts pumped from underlying Cretaceous and Triassic aquifers.

Water-level declines of up to 50 feet have occurred from predevelopment to 1980 in the heavily irrigated areas of western Gaines and Martin Counties. Additional declines of up to 30 feet have occurred in western Gaines County from 1980 to 1990. However, a net water-level rise during the past decade was experienced over most of the study area.

The chemical quality of the Ogallala aquifer is generally poorer in the southern part of the Texas High Plains than it is to the north, with dissolved solids ranging from less than 1,000 to over 3,000 milligrams per liter. The quality of the aquifer may be substantially influenced by upward leakage and subsequent mixing of water from the underlying Cretaceous aquifers. Numerous chemical analyses indicate that fluoride, nitrate, and selenium concentration levels are often in excess of recommended maximum safe drinking water standards. High sodium-chloride concentration and high chloride/bromide ratios in some Ogallala aquifer samples suggest contamination from brine sources.

In 1985, the total pumpage of ground water from the High Plains aquifer system within Andrews, Gaines, Lynn, and Terry Counties was about 446,000 acre-feet, of which 96 percent was used for agricultural irrigation. The total annual demand for ground water within this area is projected to decrease by 36 percent by the year 2010 as a result of an expected decline in irrigation pumpage. By the year 2010, approximately 19 percent of the recoverable ground water presently held in storage in the entire study area will have been used, with approximately 24 million acre-feet remaining. Although there appears to be a reasonable quantity of ground water available for all uses in the area through the year 2010, the continued deterioration of the chemical quality could limit the usefulness of some of this water.

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INTRODUCTION

In 1985, the Sixty-ninth Texas Legislature recognized that certain areas of the State were experiencing or were expected to experience, within the next 20 years, critical ground-water problems. House Bill 2 was enacted which, in part, directed the Texas Department of Water Resources to identify critical ground-water areas, conduct studies in those areas, and submit its findings and recommendations on whether a ground-water conservation district should be established in the respective areas to address the ground-water problems (Subchapter C, Chapter 52, Texas Water Code). This study in the southern High Plains of Texas was conducted to address the problems of overdraft and quality deterioration with respect to the Ogallala, Edwards-Trinity, and Dockum aquifers.

The study area is located in the southern part of the Texas High Plains which is the lower extent of the Great Plains physiographic province of North America (Figure 1). Primary emphasis is placed on Andrews, Gaines, Lynn, and Terry Counties. Also included are parts of Borden, Ector, Garza, Howard, and Midland Counties that are underlain by the Ogallala aquifer. However, in order to more completely describe the aquifer, several of the maps in the report extend into Dawson, Glasscock, Martin, and Yoakum Counties which are currently served by underground water conservation districts.

Numerous reports have been written concerning the ground-water resources of the Texas High Plains. For a more detailed description of the geology and hydrology of the area, a partial list of studies is included in the Selected References section of this report.

Basic data used to construct the High Plains aquifer water-level and saturated thickness maps and to project ground-water availability to the year 2010 was generated by Darrell Peckham during the 1990 recalibration of the Texas Water Development Board's High Plains aquifer model. Graphic and statistical illustrations for this report were prepared by Steve Gifford and Marc Berryman.

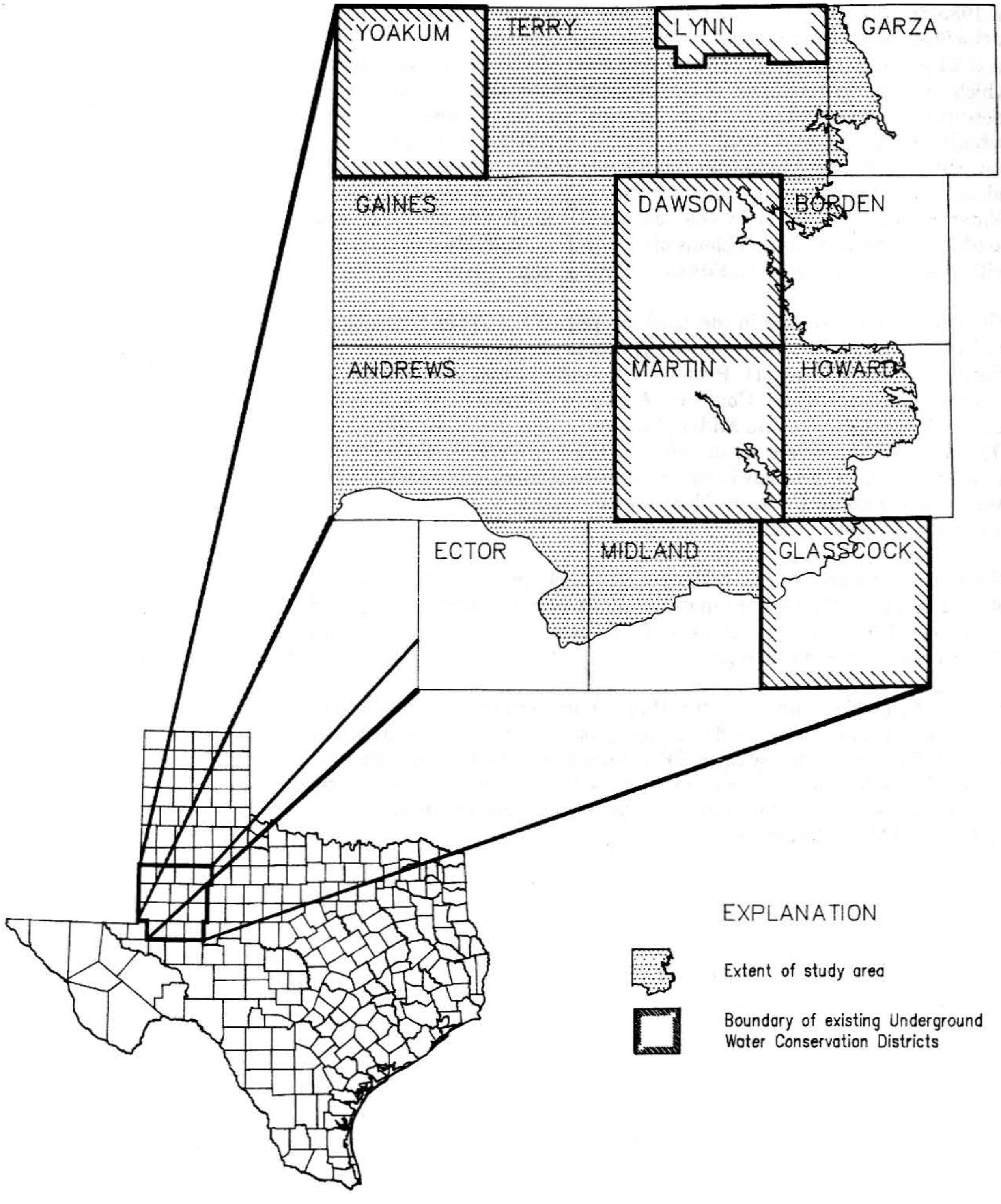


Figure 1

LOCATION OF STUDY AREA

GEOGRAPHIC SETTING

The southern High Plains of Texas is a flat to gently rolling, treeless plateau that slopes imperceptibly to the southeast and is generally devoid of major drainage systems. Shallow playa depressions and windblown sand commonly occur on the surface and are often underlain by hard indurated caliche layers known as the caprock. Approximately 16 evaporative saline lakes also occur within the study area.

The semi-arid Continental Steppe climate of the Texas High Plains is characterized by large extremes in daily temperature ranges, low relative humidity, and irregularly-spaced rainfall events of moderate amounts (Larkin and Bomar, 1983). Rainfall, ranging from 13 to 18 inches annually, is usually light during winter months and increases in the late spring and early fall. The average annual gross lake evaporation is about 78 inches, or five times the average annual rainfall.

Oil and gas production, raising cattle, and irrigated farm production, all of which primarily depend on ground water for their operation in the study area, are the mainstays of the regional economy.

GEOHYDROLOGY

Regional Setting

The most prominent geologic structures underlying the study area are the Central Basin Platform, a structural high in western Andrews and Gaines Counties, and the Midland Basin, a structural depression throughout the rest of the area. Both features are subdivisions of the more extensive Permian Basin and influenced the deposition of the Triassic Dockum. Overlying units of Cretaceous, Tertiary, and Quaternary age are not significantly affected by these structural features; however, both Trinity and Ogallala sediments were initially deposited in existing erosional valleys.

Hydrogeologic Units

Geologic units in the study area that contain ground water range in age from Paleozoic to Tertiary (Figure 2). Permian and older formations produce very saline (10,000 to 35,000 milligrams per liter (mg/l) dissolved solids) to brine (greater than 35,000 mg/l dissolved solids) water as a byproduct of oil and gas wells. Triassic aquifers contain slightly saline (1,000 to 3,000 mg/l dissolved solids) to very saline water, whereas Cretaceous and Tertiary aquifers generally contain fresh (less than 1,000 mg/l dissolved solids) to slightly saline water. A minor amount of water may occur in shallow alluvial and windblown sediments but is very limited in quantity. In the chemical quality characterization of each aquifer, the hydrochemical signature is named after the constituents that make up more than 50 percent of the total milliequivalents per liter (meq/l) concentration. A mixed cation or anion signature indicates a lack of any prevailing cation or anion. Figure 3 shows the location of wells with available chemical analyses used in this report.

The following discussion is limited to those stratigraphic units that contain ground water of economic importance and to their extent within the study area. The "High Plains aquifer system," as used in this report, refers to the saturated intervals of the Ogallala Formation and underlying formations of Cretaceous (Edwards-Trinity) and/or Triassic (Dockum) that are in hydraulic continuity and contain potable water (Knowles and others, 1984). The High Plains aquifer system is used in the section addressing the availability of ground water.

Triassic Dockum

The Triassic Dockum overlies strata of Permian age and is composed of 1,000 to 2,000 feet of sandstone, siltstone, mudstone, and shale sediments that were formed in a lacustrine and fluvial depositional system (McKee and others, 1959; and McGowen and others, 1979). These continental sediments were deposited within the Midland Basin and generally dip toward a central axis in Terry, eastern Gaines, and western Dawson Counties.

Of particular interest is the occurrence of a sandy unit commonly referred to as the Santa Rosa Sandstone. This unit is 150 to 300 feet thick and generally yields less than 200 gallons per minute to wells. Total dissolved solids concentrations increase from 3,000 mg/l with a sodium-sulfate (Na-SO4) hydrochemical signature in the southwest part of the study area to over 30,000 mg/l with a sodium-chloride (Na-Cl) hydrochemical signature in the northeast (Dutton and Simpkins, 1986)(Figures 4 and 9-C). Within the study area, water from the Dockum is used principally as a supply for secondary recovery processes in the extraction of oil and gas.

Cretaceous

Lower Cretaceous (Comanchean Series) strata, consisting of up to 250 feet of sandstone, limestone, and shale formations belonging to the Trinity, Fredericksburg, and Washita Groups, unconformably overlie Triassic Dockum "redbeds" and occur in two separate subcrops within the study area (Figure 2). In the northern half, the Cretaceous units are a part of the Edwards-Trinity (High Plains) aquifer, while to the south, the Cretaceous is a part of the Edwards-Trinity (Plateau) aquifer.

Edwards-Trinity (High Plains) Aquifer

Two distinct ground-water zones occur in the Edwards-Trinity (High Plains) aquifer (Fallin, 1989). One occurs in the basal sand and sandstone deposits of the Antlers Formation and is almost always under artesian pressure. The other water-bearing zone occurs primarily in joints, solution cavities, and along bedding planes in limestones of the Comanche Peak and Edwards Formations. In much of the area this zone is hydrologically connected to the overlying Ogallala Formation.

Recharge to the aquifer occurs directly from the bounding Ogallala Formation along northern and western parts of the subcrop, and by downward percolation from overlying ground-water units at other locations (Fallin, 1989). Nativ and Gutierrez (1988) also indicate upward movement of ground water from the Triassic Dockum into the Cretaceous in the northeastern half of Lynn County. Ground-water movement is generally to the east-southeast in conformance with hydraulic head distribution and regional structure. Discharge is to well heads, to spring flow along the eastern High Plains escarpment, and to surrounding formations. In many places the potentiometric surface of ground water in the Cretaceous aquifer is higher than in the Ogallala aquifer, resulting in the upward leakage from the Cretaceous aquifer (Nativ and Gutierrez, 1988). Water quality in the Ogallala aquifer in these areas is thus influenced by Cretaceous water.

Ground water in the aquifer is generally fresh to slightly saline and exhibits a mixed cation - mixed anion hydrochemical signature (Nativ and Gutierrez,1988; and Fallin, 1989)(Figures 5 and 9-B). Water quality deteriorates in areas where Cretaceous formations are overlain by saline lakes and the gypsiferous Tahoka and Double Lakes Formations.

The majority of wells completed in the Edwards-Trinity (High Plains) aquifer provide water for irrigation. However, the aquifer also provides ground water for domestic, stock, industrial, and public supply use. Well yields generally range between 50 and 200 gallons per minute.

Edwards-Trinity (Plateau) Aquifer

The southern Cretaceous subcrop contains ground water in the sands and sandstones of the Antlers Formation that is generally under water-table conditions. Recharge occurs laterally from the Ogallala aquifer along the northern edge of the subcrop and vertically from downward percolation where the Ogallala overlies the Cretaceous. Well depths are generally

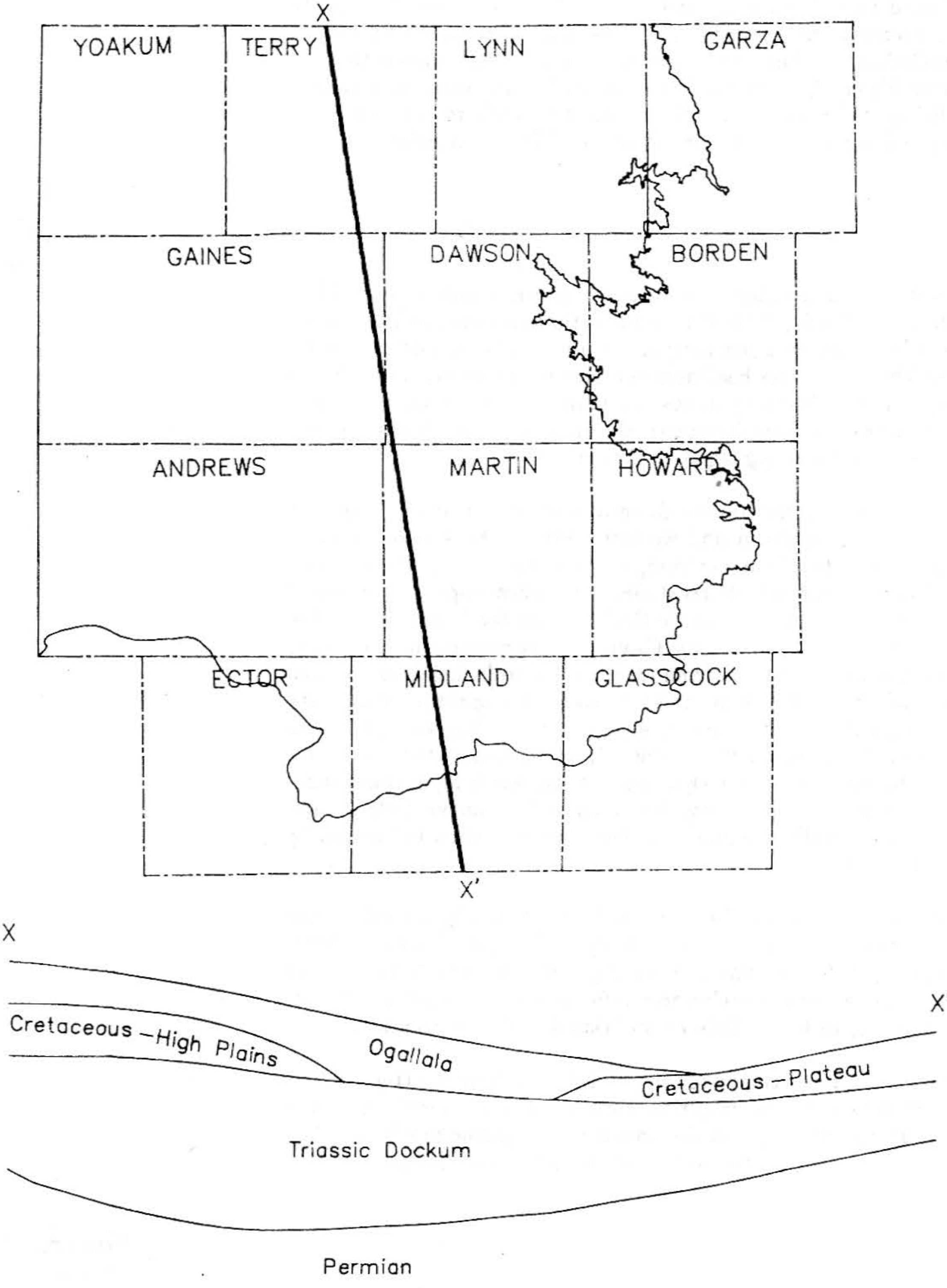


Figure 2

GEOLOGIC SECTION X–X'

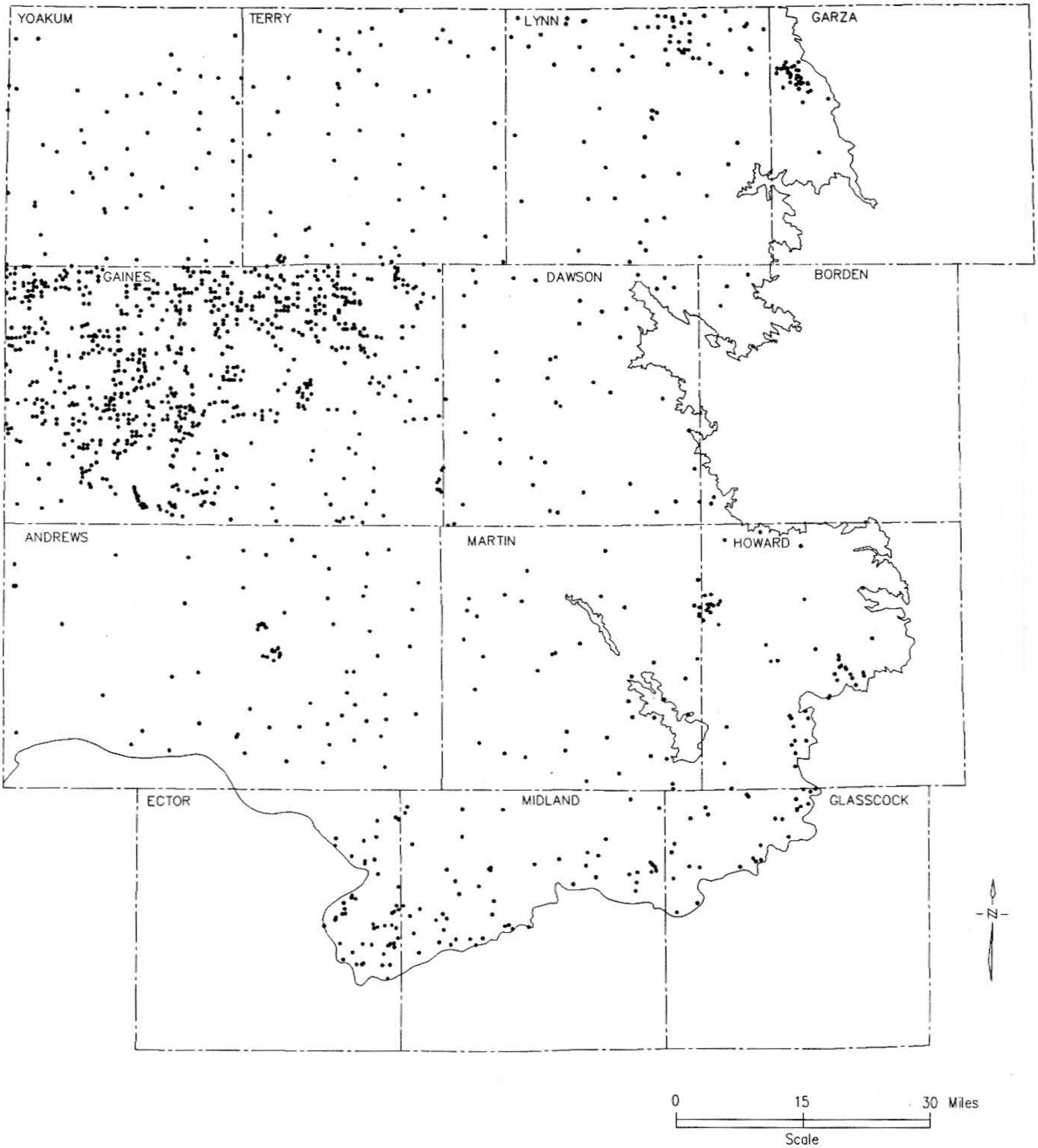


Figure 3

LOCATION OF WELLS WITH AVAILABLE CHEMICAL ANALYSES

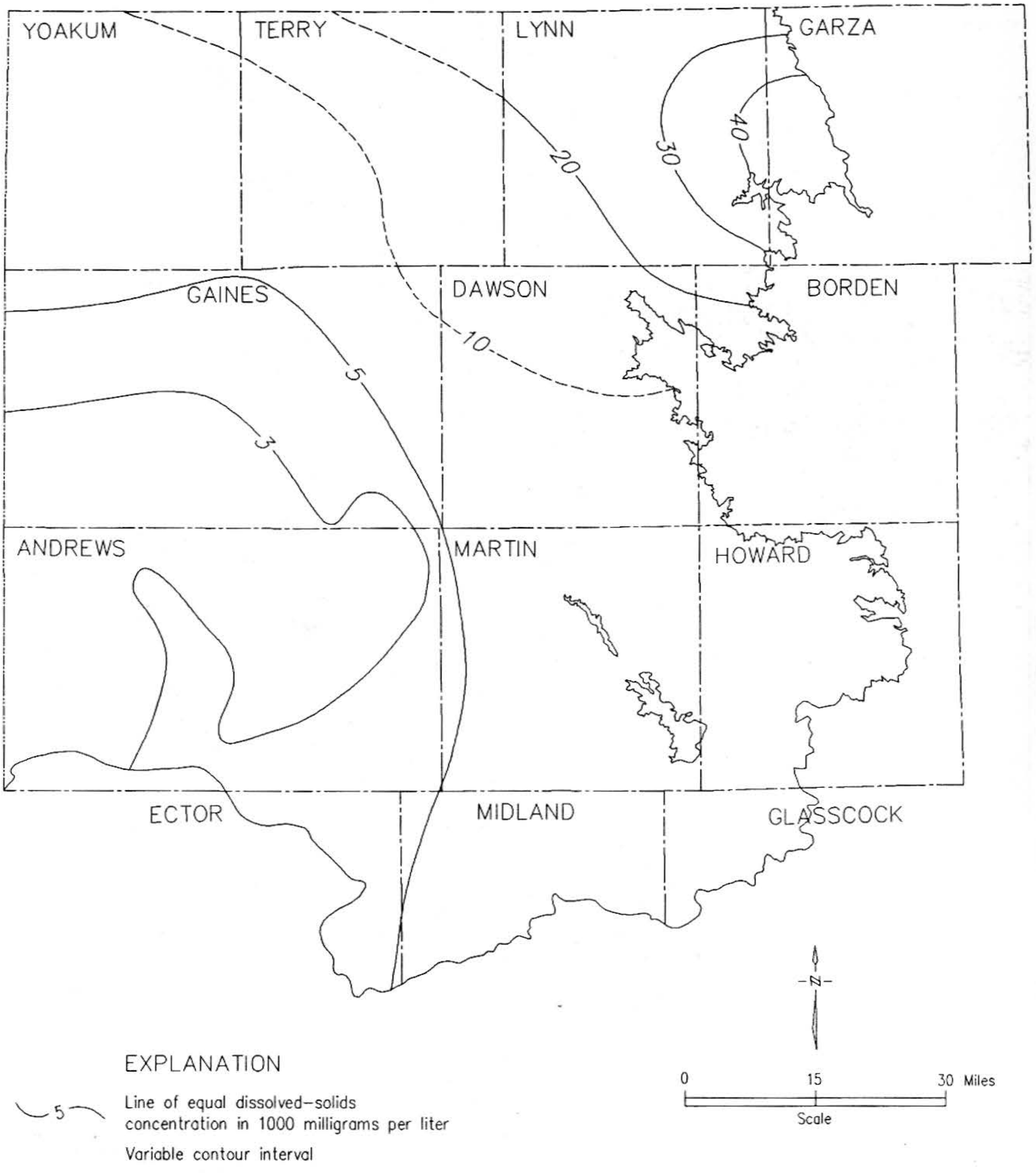


Figure 4

DISSOLVED–SOLIDS CONTENT OF WATER IN THE TRIASSIC DOCKUM AQUIFER

Modified from: Dutton and Simpkins, 1986

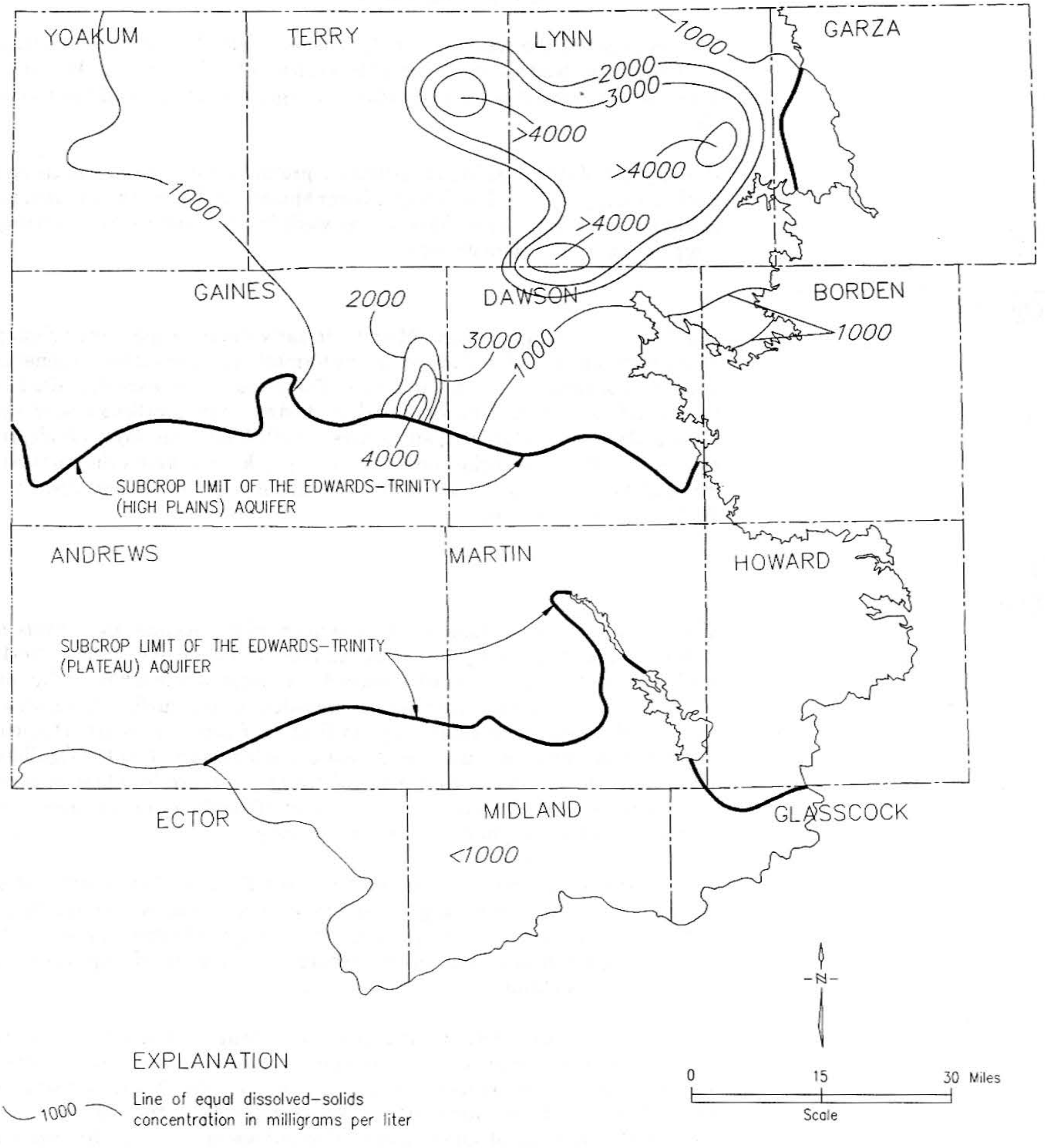


Figure 5

DISSOLVED–SOLIDS CONTENT OF WATER IN THE EDWARDS–TRINITY (HIGH PLAINS) AND EDWARDS–TRINITY (PLATEAU) AQUIFERS

Modified from: Nativ and Gutierrez, 1988; and Fallin, 1989 less than 200 feet below the land surface with water levels commonly of less than 100 feet. In the southern part of this area, the Ogallala is not easily discernable from the underlying Antlers; the two units are therefore generally considered as a single hydrologic unit.

Ground water in the southern aquifer characteristically contains less than 2,000 mg/l dissolved solids and exhibits a calcium-bicarbonate (Ca-HCO3) to mixed cation - mixed anion hydrochemical signature (Nativ and Gutierrez, 1988).

Primary use of Edwards-Trinity (Plateau) ground water is for domestic and public supply purposes. The Colorado River Municipal Water District provides ground water to the City of Odessa from wells in northeastern Ector County completed in the Antlers Formation.

Ogallala

The Ogallala Formation of late Miocene to early Pliocene age is the primary water-bearing unit in the study area. The formation consists of heterogeneous sequences of clay, silt, sand, and gravel. These sediments were deposited by eastward flowing aggrading streams that filled and buried valleys eroded into pre-Ogallala rocks (Gutentag and others, 1984). A resistant layer of calcium carbonate-cemented caliche known as the "caprock" occurs near the surface of much of the area. This distinctive unit typically marks the eastern edge of the High Plains escarpment.

Aquifer Occurrence

Water levels in the Ogallala aquifer are primarily influenced by the rate of recharge to and discharge from the aquifer (Knowles and others, 1984). Recharge to the aquifer, which generally is under water-table conditions, occurs primarily by infiltration of precipitation on the surface. To a lesser extent, recharge may also occur by upward leakage from underlying Cretaceous units that in places have a higher potentiometric surface than the Ogallala. Generally, only a small percentage of water from precipitation actually reaches the water table due to a combination of small annual precipitation, high evaporation rate, and slow infiltration rate.

Ground-water movement in the aquifer generally flows from northwest to southeast normally at right angles to the water-level contours shown in Figure 6. Velocities of less than 1 foot per day are typical, but higher velocities may occur along filled erosional valleys where coarser grained deposits have greater permeabilities.

Discharge from the Ogallala aquifer occurs naturally through seeps and springs mostly along the eastern escarpment, and by downward movement into underlying formations especially in the southern Cretaceous subcrop area. However, the greatest withdrawal of water from the aquifer occurs through the discharge of pumping wells. Ground-water pumpage often exceeds recharge, especially in heavily irrigated regions, and results in water-level declines.

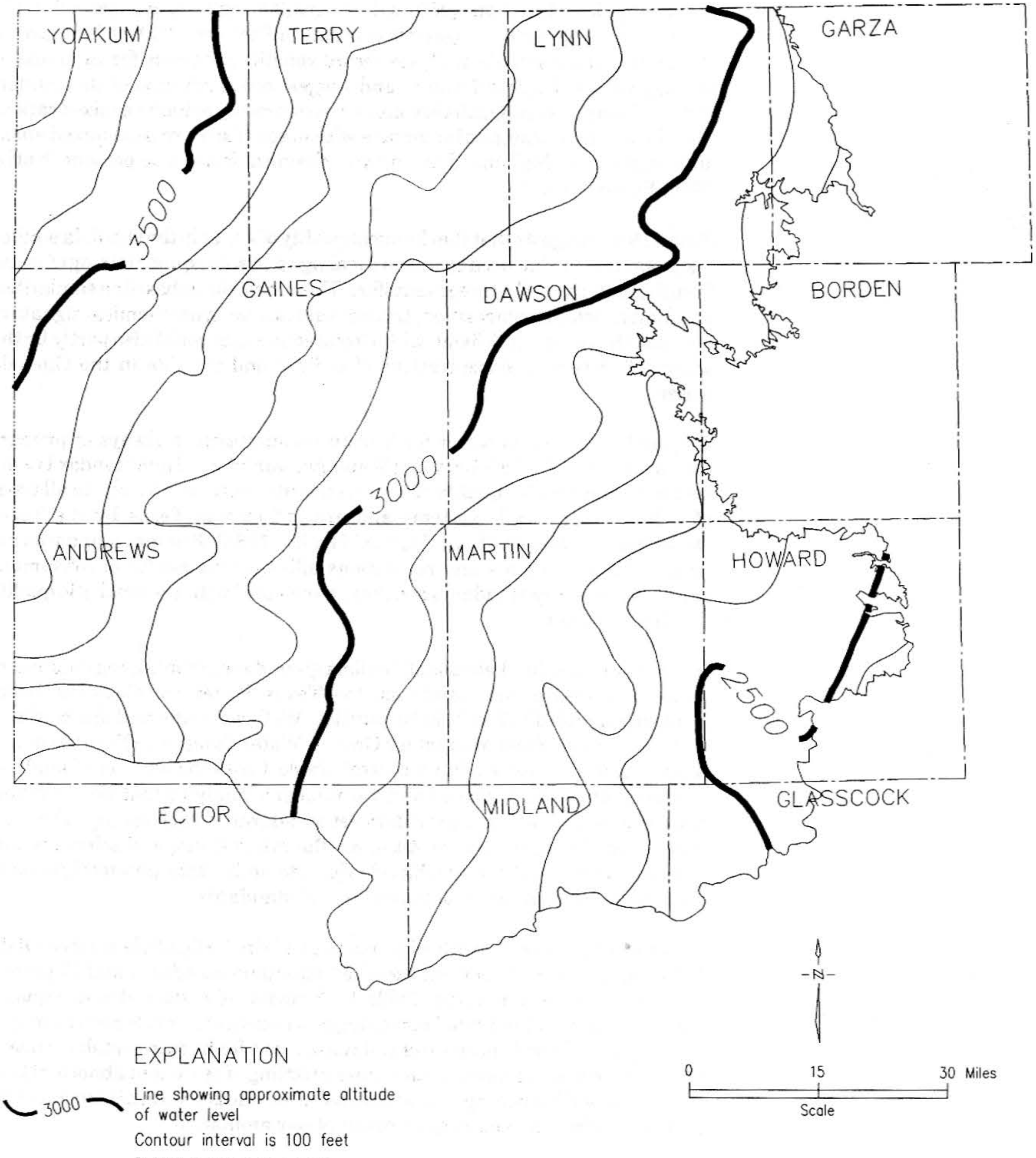


Figure 6

APPROXIMATE ALTITUDE OF WATER LEVELS IN THE OGALLALA AQUIFER, 1990

Aquifer Quality

The chemical quality of the Ogallala aquifer is generally poorer in the southern part of the Texas High Plains than it is to the north. In the study area, dissolved solids range from less than 1,000 mg/l to over 3,000 mg/l (Figure 7) and chloride concentrations typically range from less than 300 to over 1,000 mg/l (Figure 8). Numerous water sample analyses record constituent levels far in excess of average values (Figures 7 and 8) and suggest contamination of the aquifer. Within the study area, Ogallala water most commonly exhibits a mixed cation-mixed anion hydrochemical signature with areas of sodium (Na)-mixed anion and magnesium (Mg)-mixed anion hydrochemical facies also present (Nativ, 1988)(Figure 9-A).

Nativ (1988) suggests that the chemical quality of water in the Ogallala aquifer is substantially influenced by upward leakage and subsequent mixing of water from the underlying Cretaceous aquifers. This conclusion is based on similarities in salinity, isotopic composition, tritium values, and hydrochemical signature between the two units. Mixing with Cretaceous water could also partly be the source of increased concentrations of sodium and chloride in the Ogallala water.

The quality of ground water for human consumption is always of primary concern. In 1974 the Safe Drinking Water Act was adopted and standards were set for drinking water quality. These standards apply, selectively, to all types of public water supply systems and are enforced in Texas by the Texas Department of Health (Texas Dept. of Health, 1988). Primary standards are devoted to constituents and regulations affecting the health of consumers, whereas secondary standards are those which deal with the aesthetic quality of drinking water.

In order to assess the likelihood of Ogallala ground water containing constituent levels in excess of set standards, the Texas Water Development Board randomly sampled 137 wells in 10 counties. Wells were sampled in accordance with the Board's Field Manual for Ground Water Sampling (Nordstrom and Adidas, 1990) to insure quality control. Table 1 lists the number of analyses conducted on each constituent and the number of analyses that were in excess of maximum primary and secondary set standards in each county. The table shows that three primary constituents (fluoride, nitrate, and selenium) and three secondary constituents (chloride, fluoride, and sulfate) plus total dissolved solids were often in excess of maximum set standards.

Fluoride content is commonly high, particularly in the Ogallala aquifer. Of the 137 samples taken, 74 percent exceeded secondary standards and 47 percent exceeded primary standards (Table 1). A review of historical water-quality data suggests that the overall percentages of excessive fluoride content may be even higher. Fluoride is an essential constituent for human metabolic needs; however, excessive amounts may cause mottling of teeth and abnormal bone thickening and hardening (osteosclerosis). Fluoride is a natural element in the Ogallala Formation and is not a result of contamination.

Nitrate levels in excess of maximum primary standards were found in 26 percent of the samples taken and were most extensively found in Dawson, Howard, and Lynn Counties (Table 1). Excessively high concentrations of nitrate have been reported to be the cause of methemoglobinemia, an often fatal disease in infants. The main sources for the occurrence of nitrogen in ground water are decaying organic matter, human and animal wastes, and fertilizers. A minor amount of nitrate is normal in Ogallala water, however, areas having a shallow water table are more susceptible to surface contamination.

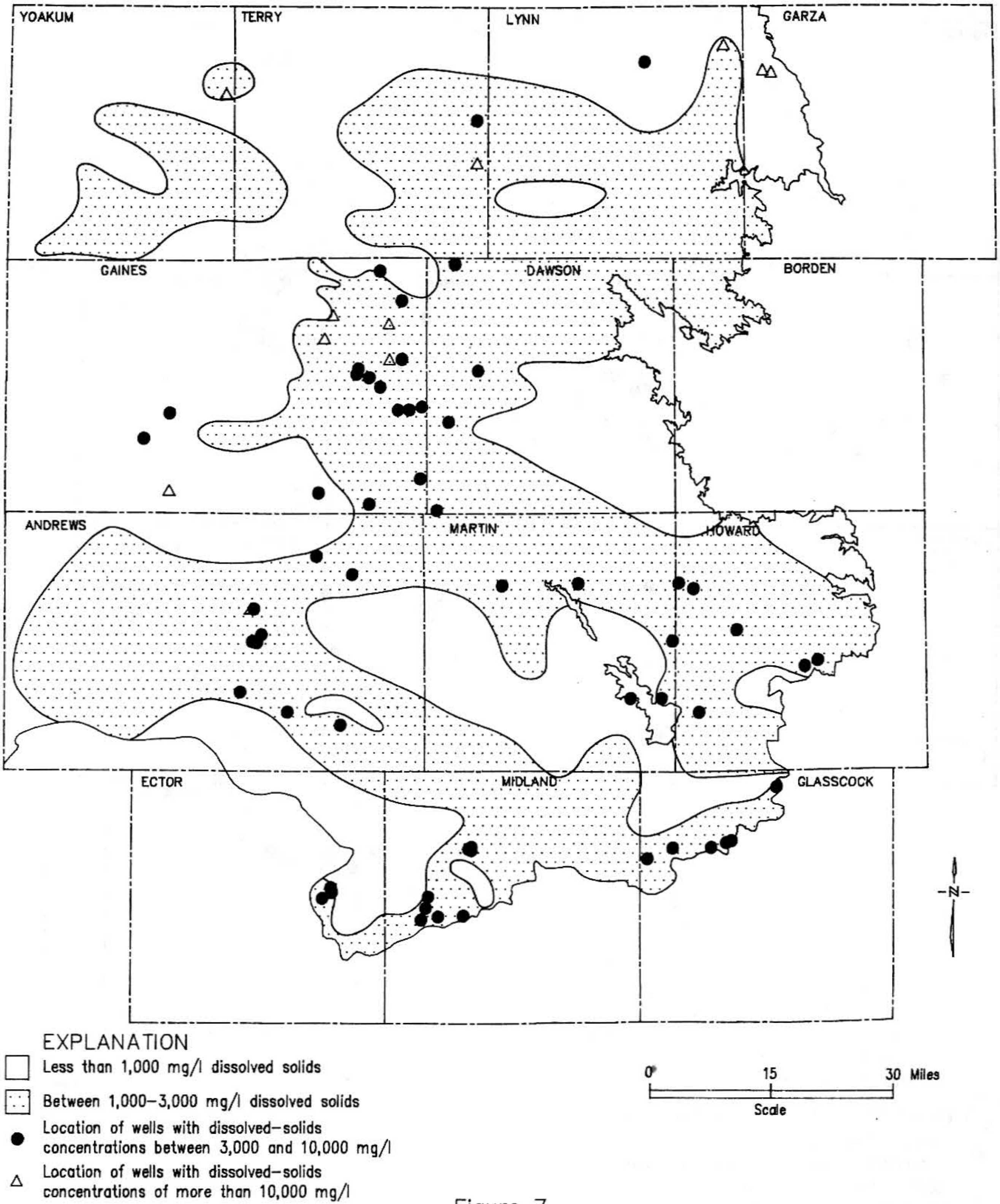


Figure 7

DISSOLVED–SOLIDS CONTENT OF WATER
IN THE OGALLALA AQUIFER

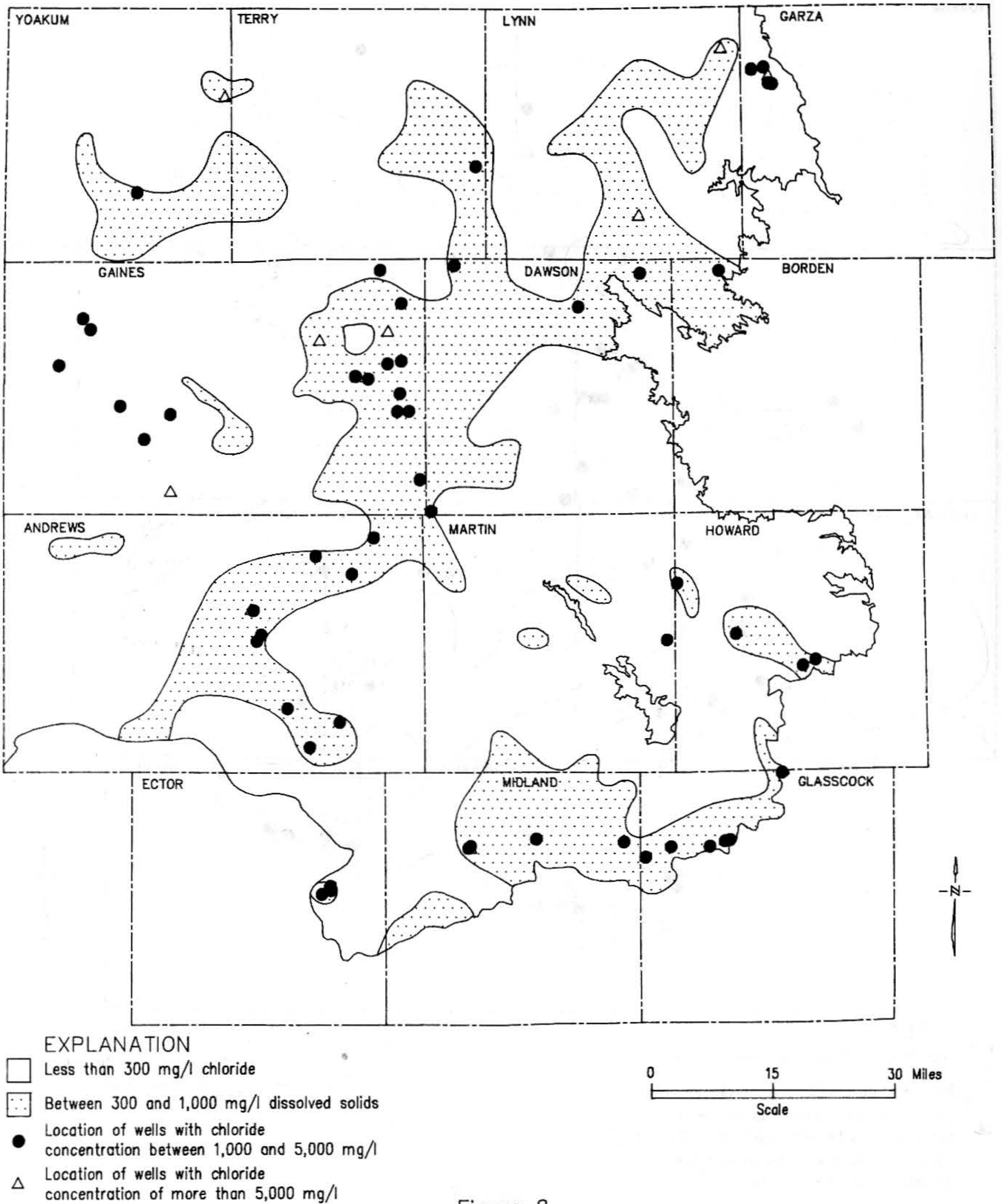
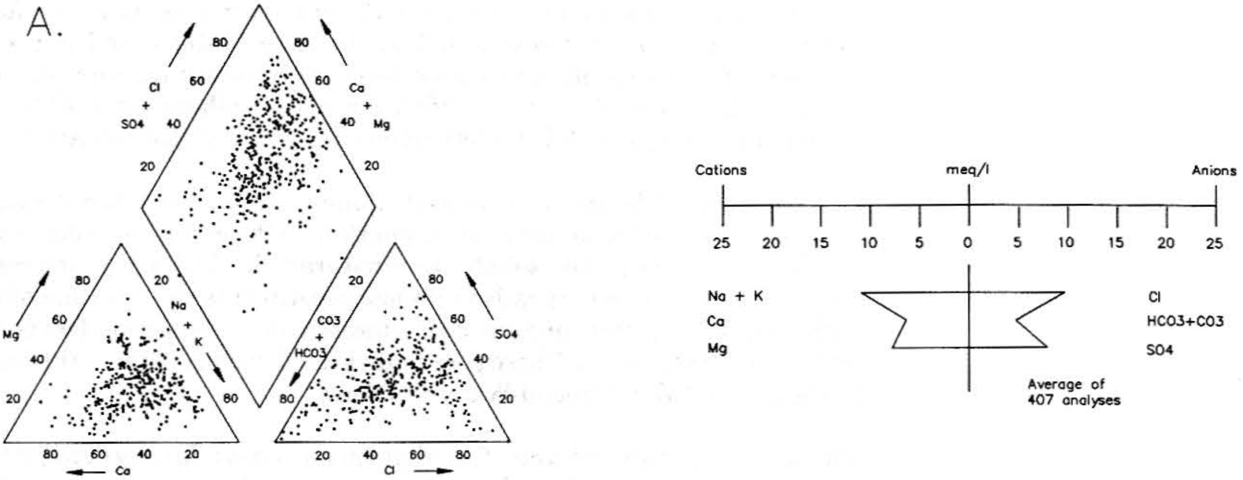
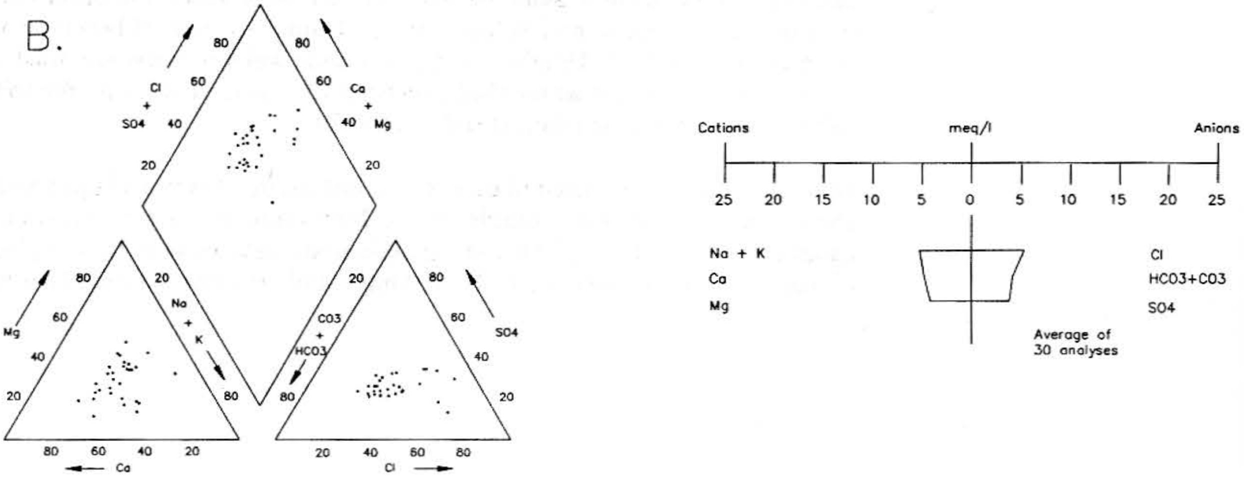


Figure 8

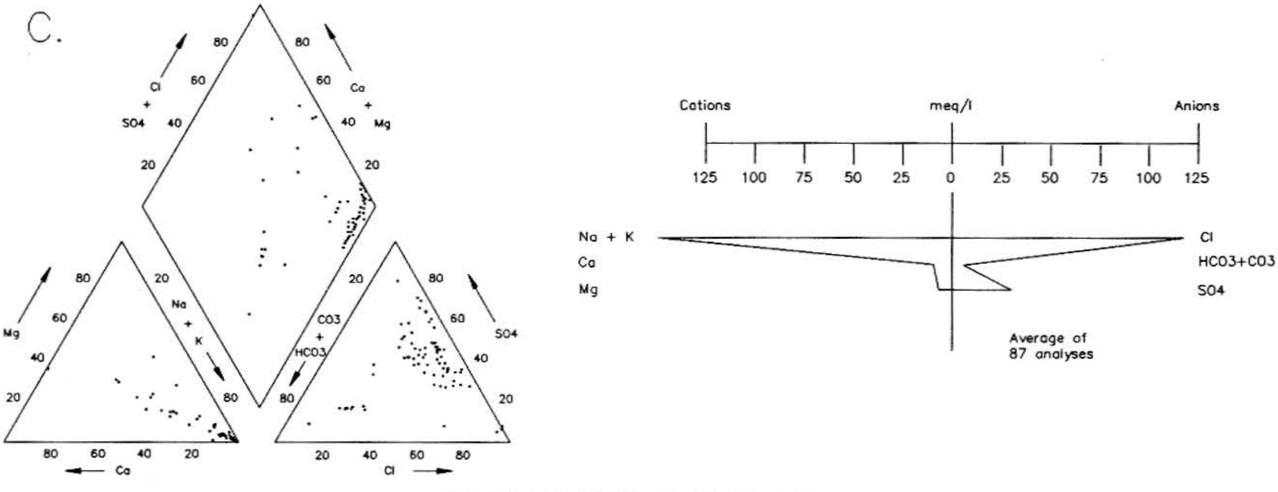
CHLORIDE CONTENT OF WATER
IN THE OGALLALA AQUIFER



OGALLALA WATER QUALITY



CRETACEOUS WATER QUALITY



DOCKUM WATER QUALITY

Figure 9

PIPER AND STIFF DIAGRAMS OF GROUND WATER FROM OGALLALA, CRETACEOUS, AND DOCKUM AQUIFERS

Selenium concentrations in excess of maximum primary standards were found in 60 percent of the samples collected for this study (Table 1) and 39 percent of historical water-quality data. Adverse effects from excessive concentrations may include growth inhibition, liver damage, and an inflammation of the skin. Selenium occurs naturally in the formation and is not a result of contamination.

Concentrations of chloride, fluoride, and sulfate in excess of secondary standards (Table 1) may result in salty taste, mottled teeth, and objectionable odor respectively. Chloride and sulfate occur naturally in Ogallala ground water; however, excessive concentrations of these constituents may indicate mixing with ground water from underlying Cretaceous and Triassic aquifers or with oil field produced brines. These possibilities are discussed later in this report in the section titled "Ground-Water Problems."

The suitability of ground water for irrigation purposes is largely dependent on the chemical composition of the water and is determined by the total concentration of soluble salts, relative proportion of sodium to other cations (magnesium, calcium, and potassium), and concentration of boron or other toxic elements. Of 128 Ogallala and Cretaceous wells recently sampled, only one percent contained water that exceeded recommended limits for soluble salts and relative proportion of sodium (SAR).

Boron is necessary for good plant growth, but rapidly becomes highly toxic at concentrations above acceptable levels. Maximum levels for various crops range from 1.0 to 3.0 mg/l. Of 134 Ogallala and Cretaceous wells sampled, 20 exceeded 1.0 mg/l, three exceeded 2.0 mg/l, and only one exceeded 3.0 mg/l.

Table 1.
Well Samples With Constituent Levels Above Maximum Standards Set by the Safe Drinking Water Act*

County	Primary Standards										Secondary Standards							
	Arsenic	Barium	Cadmium	Chromium	Fluoride	Lead	Mercury	Nitrate (N)	Selenium	Silver	Chloride	Copper	Fluoride	Iron	Manganese	Sulfate	TDS	Zinc
Andrews	0	0	0	0	4	0	0	2	7	0	5	0	10	0	1	5	7	0
	18	18	18	18	18	18	18	18	18	18	18	18	18	18	18	18	18	18
Borden	1	0	0	0	1	0	0	3	2	3	4	0	4	0	0	2	4	0
	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4
Dawson	0	0	0	0	9	0	0	5	10	0	9	0	9	0	0	8	11	0
	15	15	15	15	15	15	15	15	15	15	15	15	15	15	15	15	15	15
Ector	0	0	0	0	0	0	0	1	1	0	0	0	1	0	0	1	1	0
	6	6	6	6	6	6	6	6	6	6	6	6	6	6	6	6	6	6
Gaines	1	0	0	0	10	0	0	1	9	0	5	0	17	0	0	3	4	0
	21	21	21	21	21	21	21	21	21	21	21	21	21	21	21	21	21	21
Howard	1	0	0	0	4	0	0	9	6	0	3	0	9	0	0	6	7	0
	13	13	13	13	14	13	13	14	13	13	14	13	14	13	13	14	14	13
Lynn	0	0	0	0	10	0	0	6	7	0	3	0	11	0	0	4	6	0
	11	11	11	11	11	11	11	11	11	11	11	11	11	11	11	11	11	11
Midland	0	0	0	0	2	0	0	1	5	0	3	0	7	0	0	4	7	0
	9	9	9	9	10	9	9	10	9	9	10	9	10	9	9	10	9	9
Terry	1	0	0	1	6	0	0	4	11	0	4	0	9	1	0	6	7	0
	13	13	13	13	13	13	13	13	13	13	13	13	13	13	13	13	13	13
Yoakum	0	0	0	0	19	0	0	4	22	0	12	0	24	0	1	17	19	0
	25	25	25	25	25	25	25	25	25	25	25	25	25	25	25	25	25	25

* Top number indicates the number of samples with constituent levels above the maximum primary or secondary standard level set by the Federal "Safe Drinking Water Act," revised April 16, 1988 and effective May 9, 1988. Bottom number indicates the total number of samples collected for each constituent. All samples collected in 1990.

GROUND-WATER PROBLEMS

Water-Level Change

Declining water levels have been of concern for many years in the region. The water level in the Ogallala is primarily influenced by the rate of recharge to and discharge from the aquifer. Average low rainfall and high evaporation rates in the area usually result in less water entering the aquifer than is being pumped out. Lower water levels result in decreasing well yield and higher pumping cost; they may also contribute to deteriorating water quality.

Water-level declines of up to 50 feet have occurred in the study area from predevelopment to 1980 (Luckey and others, 1981). The greatest amount of decline occurred in western Gaines and Martin Counties. Texas Water Development Board water-level monitoring records show that over the past 10 years (1980 to 1990) the water levels in western Gaines County have continued to decline by as much as an additional 30 feet (Ashworth, 1991)(Figure 10). In addition, an area in eastern Andrews and western Martin Counties, in the vicinity of the City of Midland's Paul Davis well field, has experienced a 10 year water-level decline of up to 20 feet.

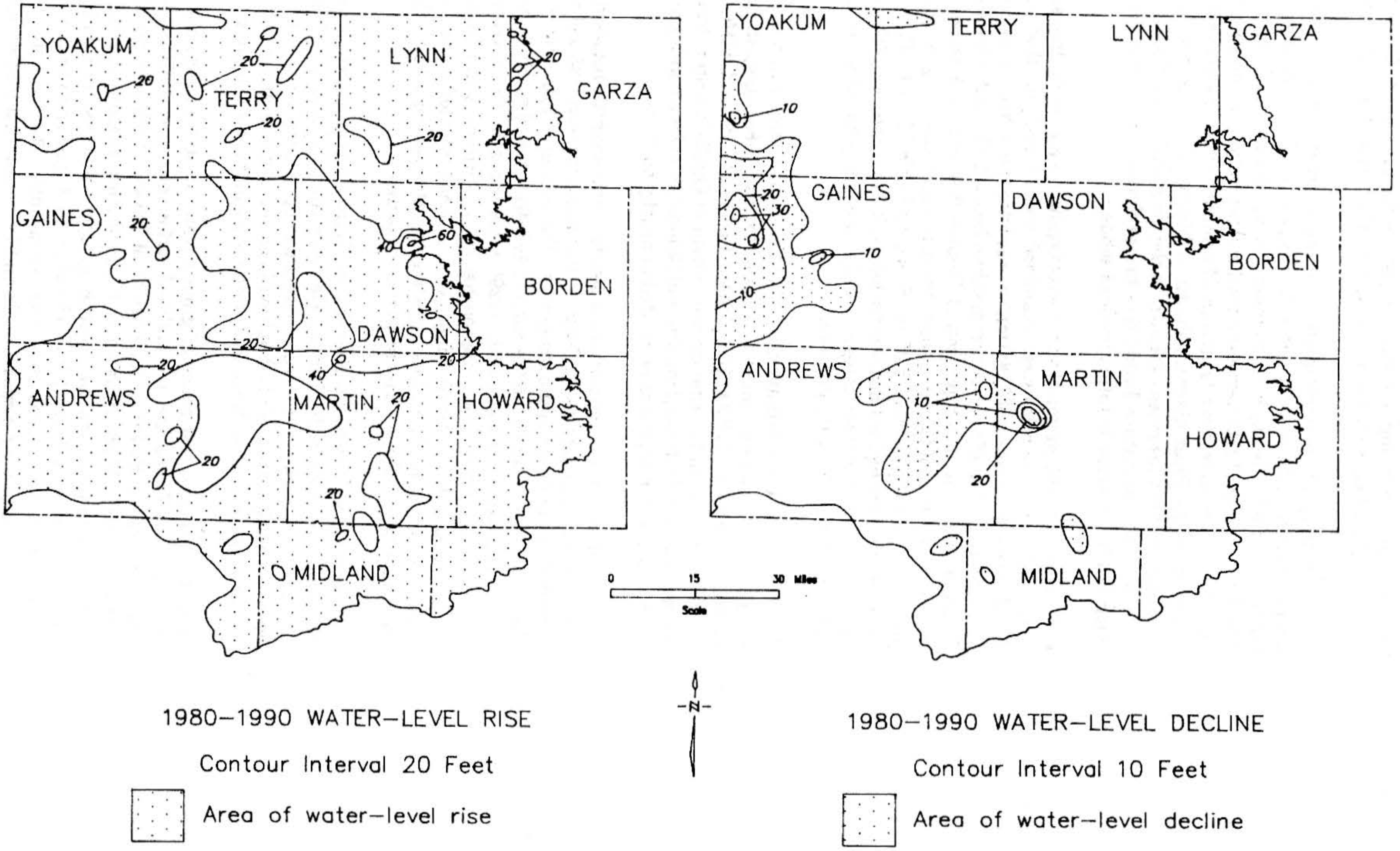
From 1980 to 1990 the water table experienced a net rise over a large part of the study area (Ashworth, 1991) which resulted in some flooding and shallow ground-water problems (Figure 10). A rise of over 20 feet was common in most of Dawson and eastern Gaines Counties. The greatest amount of rise, approximately 60 feet, was measured in an area northeast of the City of Lamesa in Dawson County. The net rise was the result of a decline of irrigation pumpage, especially during the years 1985 through 1987 when the region experienced above average precipitation. The water level at the conclusion of the 1980-1990 decade was probably near or possibly even above the average predevelopment static level, especially in the Dawson and eastern Gaines County area. With the resumption of average rainfall and pumpage, water levels will again probably trend in a downward direction.

Water-Quality Deterioration

The natural chemical quality of the ground water in the Ogallala aquifer is generally poorer in the study area than it is to the north primarily as the result of mixing with underlying Cretaceous ground water. However, certain areas have experienced a definite deterioration in quality as a result of human activities. Figure 7 shows locations of wells with dissolved-solids concentrations in excess of 3,000 and 10,000 mg/l. This quality deterioration is primarily the result of petroleum industry activities, but irrigation practices and the existence of saline lakes may also have an effect.

Petroleum Industry Activities

Chemical characteristics of Ogallala ground water with increasingly high salinity suggests that the greatest cause of contamination to ground water in the study area is by oil field brines (water containing greater than 35,000 mg/l dissolved solids). The recovery of oil and gas has historically, and continues to be today, a major industry in the region with well fields located



1980–1990 WATER–LEVEL RISE

Contour Interval 20 Feet

▒ Area of water–level rise

1980–1990 WATER–LEVEL DECLINE

Contour Interval 10 Feet

▒ Area of water–level decline

Figure 10

WATER–LEVEL CHANGES IN THE HIGH PLAINS AQUIFER 1980–1990 in virtually every county (Figure 11). As of November 1990 approximately 11 thousand surface casing recommendations, within Andrews, Gaines, Lynn, and Terry Counties, have been processed by the Texas Water Commission.

The probability of contamination by brine sources can be identified by comparing chemical characteristics of locally produced brine water and ground water suspected of being contaminated. Numerous chemical analyses from Core Laboratories (1972) were examined and seven typical analyses of brines from the three most commonly produced Permian formations were selected for inclusion on the Piper diagram shown in Figure 12-C. The hydrochemical characteristics of the brines as shown on the diagram have a distinct sodium-chloride (Na-Cl) signature. In addition, brines show an increase in sodium and chloride with increase in total dissolved solids.

For comparison, 407 chemical analyses of Ogallala water in Andrews, Gaines, Lynn, and Terry Counties were examined and 27 analyses that contained dissolved solids in excess of 3,000 mg/l were plotted on a Piper diagram (Figure 12-A). Similar plots of analyses from saline lakes (12-B) and brine water (12-C) are also shown. A comparison of Figures 9-A and 12-A shows that for increasing salinity of Ogallala water there is a corresponding increase in the proportion of sodium (Na), sulfate (SO4), and chloride (Cl). Five of seven analyses with the highest dissolved solids (4,833 to 6,340 mg/l) fall within the sodium-sulfate (Na-SO4) category. Only one analysis indicated a strong sodium-chloride (Na-Cl) signature.

Another type of analysis that is useful in identifying brine contamination is the comparison of various constituent ratios. Nativ (1988) suggests that high salinities, low ratios of HCO3/Cl and SO4/Cl, and high ratios of Ca/(HCO3+SO4) could serve to identify brine contamination of Ogallala water. Nativ found several places in Andrews, Howard, and Gaines Counties where high salinities in Ogallala water appear to be related to nearby oil fields.

To substantiate these conclusions a similar ratio analysis between chloride (Cl) and bromide (Br) was conducted using analyses from 133 wells recently sampled by the Board in the study area. The average Cl/Br ratio of 150 from these analyses is similar to the ratio of 140 determined by Nativ and Smith (1987). The ratio of sea water is about 290, while the ratio of brines representing extensive halite dissolution approaches 900 (Whittemore and Pollock, 1979; and, Wood and Jones, 1990). Nine of the 133 wells sampled for this study had Cl/Br ratios greater than 300, suggesting that the water quality of these wells may have been influenced by nearby brine sources.

This evaluation of available chemical analyses suggests a lack of widespread contamination from oil field brines. However, this conclusion is not necessarily valid because wells that were sampled were primarily irrigation wells that were currently active. Wells that have been severely contaminated by oil field brines have been abandoned and were not available for sampling.

Probably the greatest cause of ground-water contamination has been the disposal of oil-field brines into unlined surface pits prior to the statewide "no pit" order of the Railroad Commission of Texas, which became effective on January 1, 1969. Much of the water discharged into these pits probably seeped into the ground and eventually into the ground-water system. Additional brine contamination could result from abandoned oil, gas, and injection wells and wells with broken or poorly cemented casings. The location of currently permitted salt-water disposal wells and brine solution mining stations are shown in Figure 13.

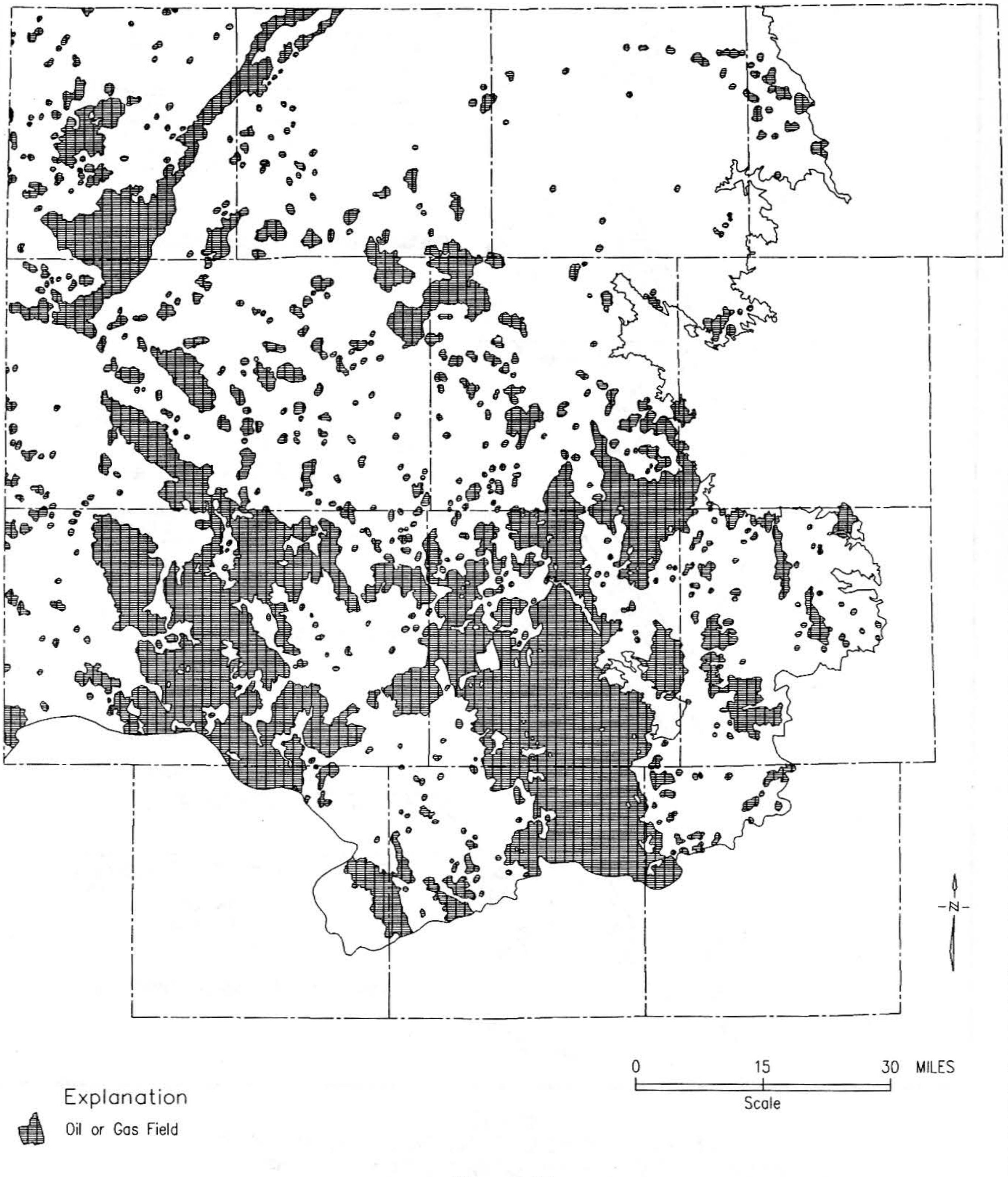
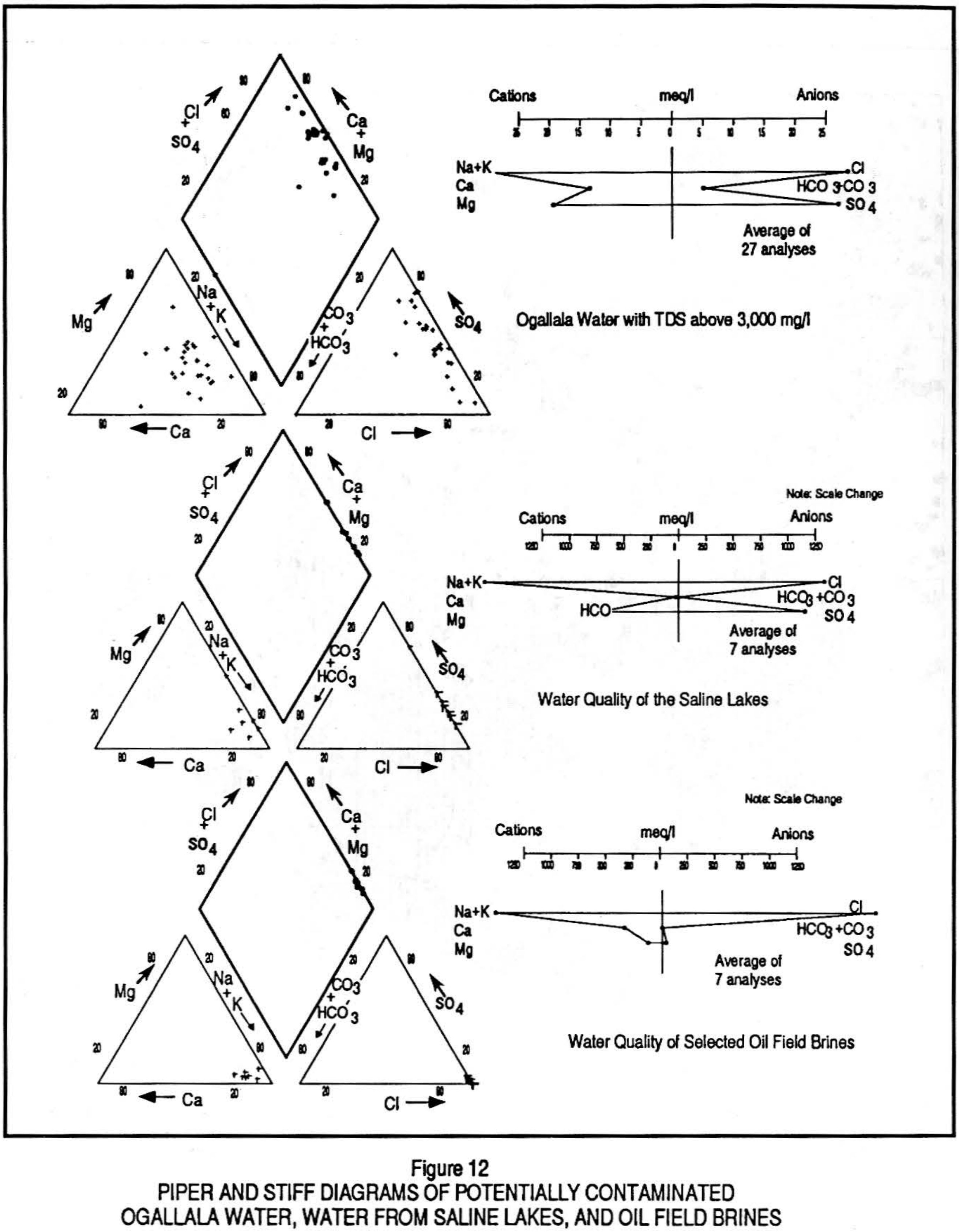


Figure 11

OIL AND GAS FIELDS

Adapted from: 1985 Producing Zone Map, Midland Map Company



Ogallala Water with TDS above 3,000 mg/l

Water Quality of the Saline Lakes

Water Quality of Selected Oil Field Brines

Figure 12
PIPER AND STIFF DIAGRAMS OF POTENTIALLY CONTAMINATED
OGALLALA WATER, WATER FROM SALINE LAKES, AND OIL FIELD BRINES

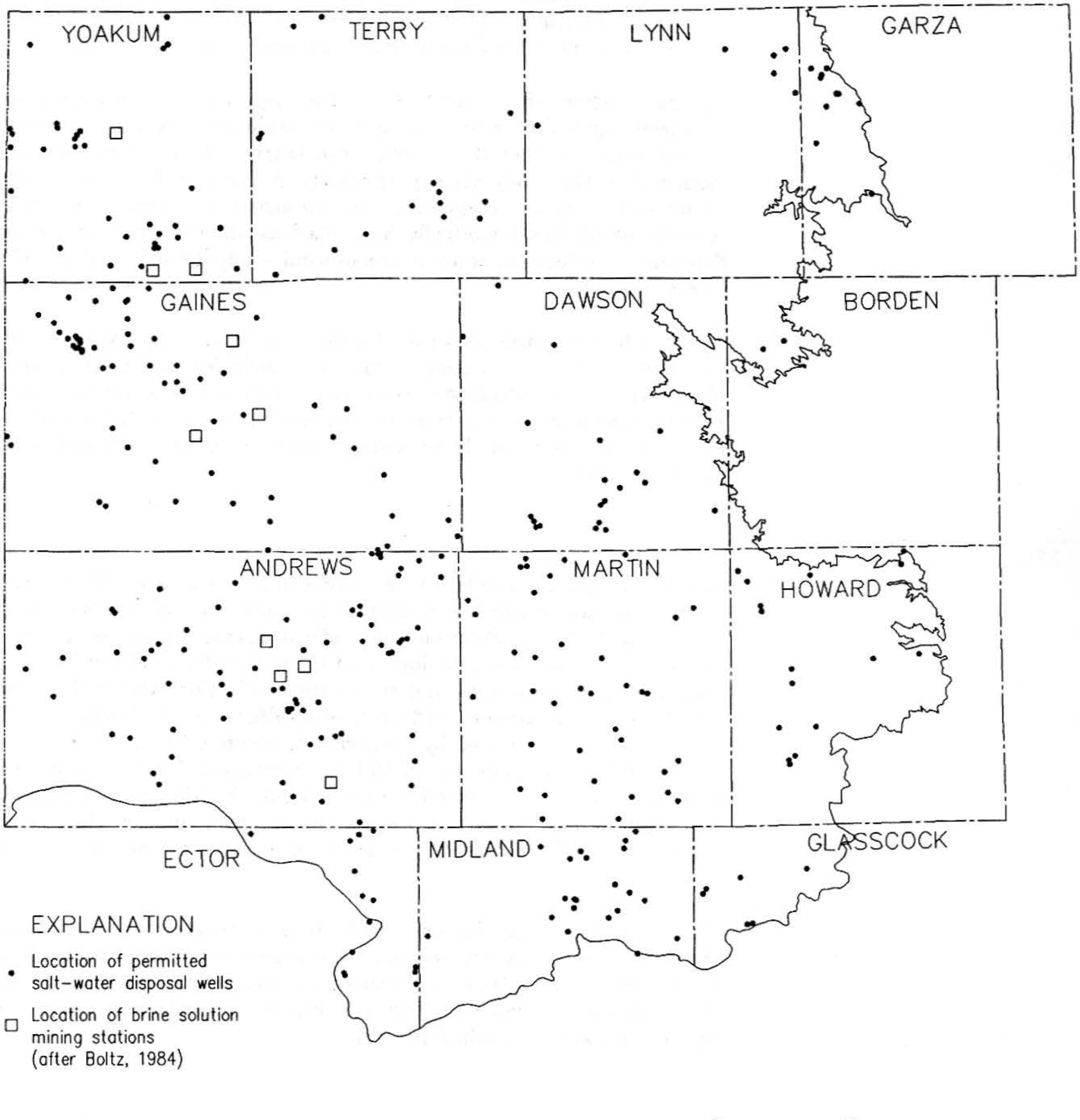


Figure 13

LOCATION OF PERMITTED SALT-WATER DISPOSAL WELLS AND BRINE SOLUTION MINING STATIONS

Agricultural Practices

Although irrigation pumpage does not appear to have had a significant effect on the chemical quality of the aquifers, it could be responsible for increasing the spread of existing contamination by increasing the rate of ground-water movement. Continued pumpage in areas of declining water levels may eventually result in the encroachment of poorer quality water into the area.

Especially where the water level is relatively shallow, the application of fertilizers containing ammonia may result in elevated levels of nitrate in the ground water. Higher than normal concentrations of nitrates have been identified in the study area, particularly in Dawson, Howard, and Lynn Counties; however, no tests have been conducted to determine their source. Arsenic, which has historically been used as an insecticide and a cotton defoliant, was detected at above recommend safety levels in four of 137 well samples tested.

In order to detect the presence of agriculturally derived chemicals in the Ogallala aquifer, an extensive scan of insecticides and chlorinated acid phenoxy herbicides was made on 87 water samples with a gas chromatograph. Also, an organic screen was conducted on the samples with a gas chromatograph and mass spectrometer. The results showed no pesticides above laboratory detection limits.

Saline Lakes

Sixteen identified saline lake basins occur in the study area (Figure 14) and often retain water which may contain concentrations of dissolved solids in excess of 300,000 mg/l. Solution mining of hydrous sodium sulfate has occurred in several of the lake basins (Bluntzer, 1982 and 1984). Wood and Jones (1990) used hydraulic head data and solute ratios of chloride/bromide, chloride/sulfate, sodium/potassium, and isotopes of sulfur to conclude that the solutes in the lakes, concentrated by evaporation, originate from the High Plains aquifer and from overland runoff. Chloride/bromide ratios of water from saline lakes average about 160 (Wood and Jones, 1990) which is similar to the average of 150 determined in this study for ground water from the High Plains aquifer. Ratios from oil field brines differ significantly and are generally in excess of 290.

The saline lakes are thought to be areas of evaporative discharge and, therefore, probably do not have much influence on the chemical quality of the surrounding aquifer. However, extensive irrigation pumpage in the vicinity of these lakes could reverse the hydraulic gradient and allow the saline waters to travel toward the discharging wells.

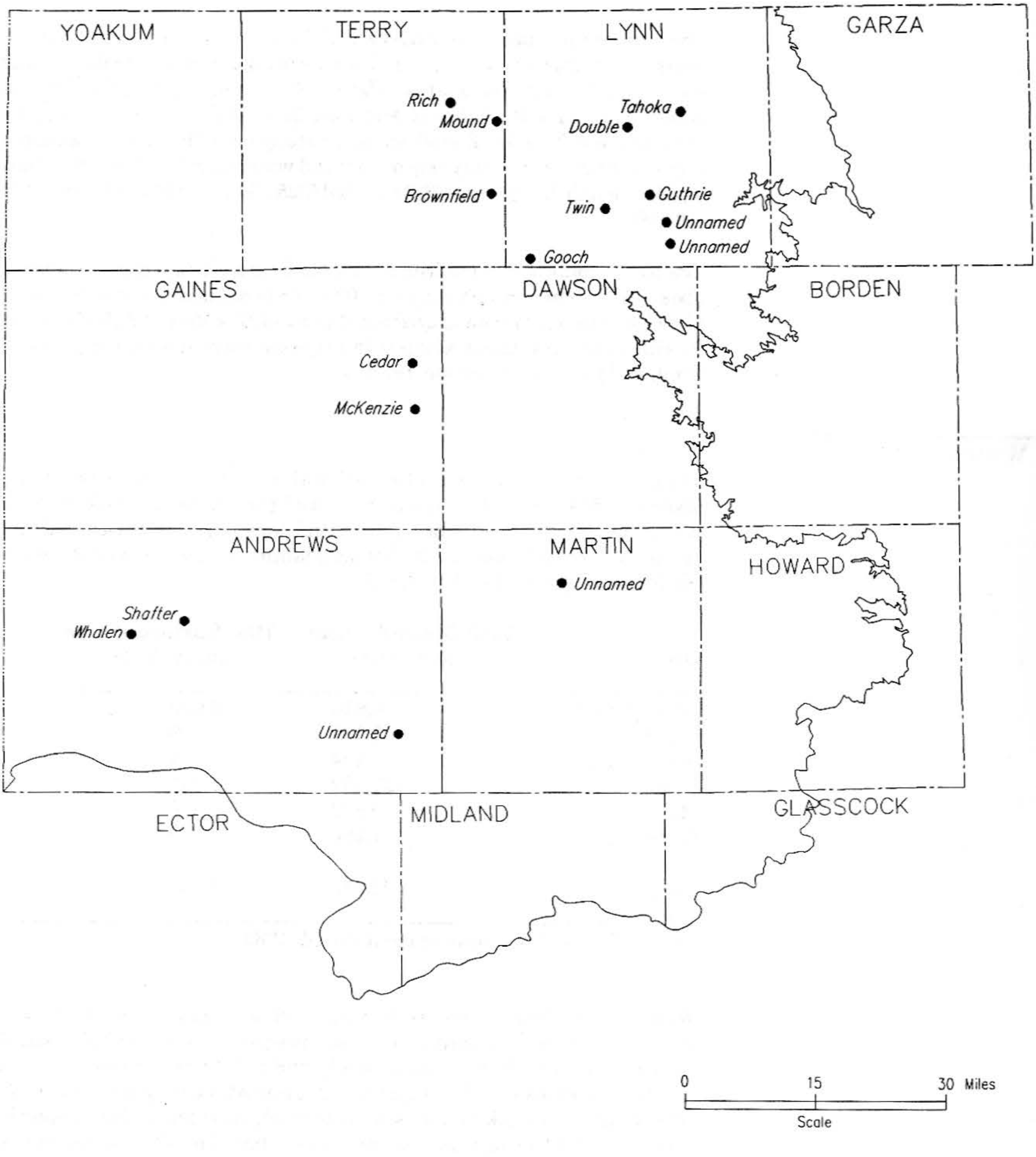


Figure 14

LOCATIONS OF SELECTED SALINE LAKES

Adapted from: Wood and Jones, 1990

WATER DEMAND

Population

The regional population of Andrews, Gaines, Lynn, and Terry Counties is sparse and depends heavily on both agriculture and petroleum related industries. In 1985, the total population of this area was 54,152. Sixty-nine percent resided in the Cities of Andrews, Brownfield, O'Donnell, Seagraves, Seminole, and Tahoka. Elsewhere in the study area, the cities that currently rely on, or potentially may rely on, ground water supplied from the Ogallala aquifer include Big Spring (26,813), Gail (225), Midland (94,336), and Odessa (101,165).

The total population of the four county study area is expected to increase by about 13 percent through the year 2010, while the additional four cities are, likewise, expected to expand by about 19 percent. The 1980 and 1985 population for cities and rural areas, along with projected estimates for the years 1990, 2000, and 2010, are shown in Table 2.

Water Use

The total amount of water used in 1985 within the four county study area was about 453,504 acre-feet. This amount is a 41 percent reduction from the 1980 water use and is the result of a substantial decrease in irrigation and mining operations. The following table lists the quantity of water by type of use within the four county area for the year 1985.

Use	1985 Ground Water (acre-feet)	1985 Surface Water (acre-feet)
Public Supply	4,816	2,090
Rural	2,339	8
Manufacturing	494	0
Irrigation	427,482	4,843
Mining	9,872	0
Livestock	1,250	310
Total	446,253	7,251

Source: Texas Water Development Board, 1989

Water use for 1985, as reported in this section, was compiled by the Texas Water Development Board and is documented in their 1989 Revised Data Series, revised 10-30-90. Public supply and rural use is based on amounts reported by cities or other suppliers and apportioned by population where appropriate. Livestock use is based on the rural geographical share apportioned to county total livestock use. All other use is based on site-specific computed use.

Public Supply

The municipal water needs of the various communities are supplied from ground-water sources and in some cases are supplemented by surface water supplied by the Canadian River Municipal Water Authority (CRMWA) or the Colorado River Municipal Water District (CRMWD). In 1985, 6,906 acre-feet

Table 2. Current and Projected Population [1]

	1980	1985	1990	2000	2010
Andrews County					
City of Andrews	11,061	13,305	13,265	14,281	15,465
Rural	2,262	3,225	3,100	3,610	3,953
Total	13,323	16,530	16,365	17,891	19,418
Gaines County					
City of Seagraves	2,596	2,596	2,560	2,665	2,861
City of Seminole	6,080	6,964	7,373	7,569	8,128
Rural	4,474	4,742	4,079	4,533	4,534
Total	13,150	14,302	14,012	14,767	15,523
Lynn County					
City of O'Donnell	1,200	1,011	936	1,067	1,189
City of Tahoka	3,262	3,015	2,928	3,338	3,708
Rural	4,267	3,874	3,393	3,871	4,299
Total	8,729	7,900	7,257	8,276	9,196
Terry County					
City of Brownfield	10,387	10,722	10,134	10,652	11,606
Rural	4,194	4,698	4,679	4,985	5,390
Total	14,581	15,420	14,813	15,637	16,996
City of Big Spring	24,804	26,813	25,436	27,346	30,329
City of Gail	172	225	228	233	233
City of Midland	70,525	94,336	98,862	111,586	119,716
City of Odessa	90,027	101,165	96,441	101,534	114,037

[1] 1980 and 1985 population is based on Bureau of Census statistics. 1990, 2000, and 2010 is based on the Texas Water Development Board 1990 Texas Water Plan High Series population projection. The term "rural" includes cities and unincorporated areas with a 1980 population of less than 1,000 and all rural population.

of ground and surface water was supplied to communities within the four county area which represents approximately 1.5 percent of the total water used. The following table lists the major communities within the entire study area and the quantity and source of water supplied to each in 1985.

City	Ground-Water (acre-feet)	Source	Surface Water (acre-feet)	Source
Andrews	2,449	Self Supplied	0	
Seagraves	570	Self Supplied	0	
Seminole	1,619	Self Supplied	0	
O'Donnell	0		123	CRMWA
Tahoka	143	Self Supplied	361	CRMWA
Brownfield	35	Self Supplied	1,606	CRMWA
Big Spring	103	CRMWD	6,655	CRMWD
Gail	44	Self Supplied	0	
Midland	11,547	Self Supplied	12,803	CRMWD
Odessa	6,499	CRMWD	12,984	CRMWD

Source: Texas Water Development Board, 1989

Rural

The rural population of the four county area is quite sparse, mostly concentrated around several small unincorporated communities. In 1985, 2,339 acre-feet of ground water and 8 acre-feet of surface water were supplied for rural use. Ground water for rural domestic use is pumped from private wells or provided through community systems such as those found at Loop, Grassland, New Home, Wilson, Meadow, and Wellman (Christian and others, 1990). The 8 acre-feet of surface water for rural domestic use occurs in Lynn County and is supplied from the Cities of O'Donnell and Tahoka.

Manufacturing and Mining

Manufacturing and mining represent the industrial use of water in the study area. In 1985 manufacturing use amounted to only 494 acre-feet of ground water which was partially supplied from municipal sources.

Mining is the second largest ground-water use category with 9,872 acre-feet of pumpage in 1985. Most of the pumpage was from the Ogallala aquifer with lessor amounts from the Edwards-Trinity and Dockum aquifers. Pumpage for mining purposes is almost exclusively related to the petroleum industry, including such operations as water flooding for secondary recovery, operation of gasoline plants and compressor stations, and drilling of oil and gas wells. Fresh water (primarily from the Ogallala aquifer), which is injected into oil- and gas-bearing zones for secondary recovery, is essentially eliminated from the hydrologic cycle.

Irrigation

Irrigation represents the largest use of water in the study area with ground water being the primary source. Table 3 shows the acre-feet of ground water pumped for irrigation and the number of acres irrigated with ground water

Table 3. Irrigation Development [1]

Year	Andrews	Gaines	Lynn	Terry
	Acre-Feet of Ground Water Pumped for Irrigation			
1958	1,699	153,467	79,501	135,586
1964	16,393	285,084	79,067	170,313
1969	1,198	146,835	23,294	57,897
1974	5,278	310,826	72,274	145,410
1979	8,882	413,032	37,815	57,645
1984	3,605	282,872	54,793	65,244
1989	2,724	368,881	23,442	152,282
	Acres Irrigated with Ground Water			
1958	1,200	108,000	65,000	136,034
1964	8,000	225,000	79,200	130,000
1969	2,389	319,820	91,640	169,500
1974	5,353	350,500	72,355	173,030
1979	8,957	359,670	63,959	166,136
1984	4,871	261,920	80,980	146,449
1989	4,344	211,815	46,332	129,356

[1] Data from Texas Water Development Board Report 329.

since 1958. In 1985, approximately 427,482 acre-feet of ground water was pumped for irrigation use, which represents about 96 percent of all ground water pumped in the four county study area. In addition, 4,843 acre-feet of surface water was supplied for irrigation use from recovered wastewater from the Cities of Brownfield and Lubbock wastewater treatment plants. The largest amount of irrigation pumpage, 66 percent, occurs in Gaines County. The following table lists the 1985 irrigation water use by county.

County	**Ground Water (acre-feet)**	**Surface Water (acre-feet)**
Andrews	4,345	0
Gaines	283,916	0
Lynn	52,746	3,970
Terry	86,475	873

Source: Texas Water Development Board, 1989

Livestock

Water used for livestock in the study area in 1985 amounted to 1,250 acre-feet of ground water and 310 acre-feet of surface water.

Projected Water Demand, 1990-2010

The total annual water requirement for the four county study area is expected to decrease by approximately 36 percent from 1985 to the year 2010. Irrigation pumpage, the primary use of water in the area, is projected to decline by approximately 38 percent as a result of a reduction in irrigated acreage, increasingly efficient water conservation management irrigation practices, and declining water levels. The total use of water for mining purposes is also expected to decline.

All other category users are projected to increase their demand for water between 1985 and 2010. Public supply demand within the four county study area is expected to increase by 30 percent, while the demand by the Cities of Midland and Odessa is expected to increase by 20 percent. Table 4 lists the current and projected total water demand by use for the four county study area.

Projections of future public supply and rural water requirements are based on Texas Water Development Board projected high per capita water use with conservation, dated October 1989, revised 10-30-90. All other water use projections are based on Texas Water Development Board high series projected demands, dated October 1989, revised 10-30-90, and the apportioned share of total county demands. High series projections take into account the demands that are likely to occur during periods of less than normal rainfall conditions.

Table 4. Projected Water Demand by Use[1]

(Units in Acre-Feet)

County	Year	Public Supply[2]	Rural[3]	Manufacturing	Irrigation	Mining	Livestock	Total
Andrews	1990	3,260	751	64	6,271	6,046	343	16,735
	2000	3,329	799	89	5,925	3,141	398	13,681
	2010	3,410	817	114	5,767	2,531	398	13,037
Gaines	1990	2,654	598	375	166,402	4,539	623	175,191
	2000	2,592	630	536	147,684	5,430	721	157,593
	2010	2,632	596	710	144,432	3,852	721	152,943
Lynn	1990	674	565	29	49,403	85	235	50,991
	2000	730	612	37	40,478	88	272	42,217
	2010	767	642	45	40,259	91	272	42,076
Terry	1990	2,103	685	142	91,506	968	218	95,622
	2000	2,097	693	207	81,213	440	251	84,901
	2010	2,161	709	278	79,424	300	251	84,123
Total by Use	1990	8,691	2,599	610	313,582	11,638	1,419	338,539
	2000	8,748	2,734	869	275,300	9,099	1,642	298,392
	2010	8,970	2,764	1,147	269,882	6,774	1,642	291,179

[1] Projected water demand includes both surface and ground water and is based on Texas Water Development Board Revised October 1989 Data Series, Revised 10-30-90.

[2] Public Supply includes projected demand for the Cities of Andrews, Seagraves, Seminole, O'Donnell, Tahoka and Brownfield. Projected total demand for the City of Midland is 26,453; 28,326; and 28,748 and for the City of Odessa is 22,540; 23,179; and 23,919.

[3] Rural includes towns and unincorporated areas with a 1980 population of less than 1,000 and all rural population.

AVAILABILITY OF WATER

Current Availability of Ground Water

The recoverable volume of fresh to slightly saline ground water in storage in the High Plains aquifer system within the four county study area was approximately 28 million acre-feet in 1990. The volume of water in storage in the entire study area, less the amount in counties already served by underground water conservation districts, was approximately 35 million acre-feet in 1990. The Texas Water Development Board's computer model of the High Plains aquifer calculated these amounts using 1990 measured data. The computer calculates storage based on aquifer depth, water level, and specific yield. Recoverable storage, however, does not include the bottom 10 feet of the aquifer because this amount of saturated thickness is not sufficient to allow significant yield to wells. The 1990 recoverable volume of water in storage by county is shown in Table 5, and the 1990 approximate saturated thickness is illustrated in Figure 15.

Table 5. Projected Ground-Water Availability Through the Year 2010 [1] (Units in millions of acre-feet)

County	Year		
	1990	2000	2010
Andrews	3.84	3.69	3.61
Borden	.12	.11	.10
Ector	1.88	1.84	1.80
Gaines	12.26	10.90	9.78
Garza	.58	.54	.51
Howard	1.53	1.46	1.41
Lynn	2.83	2.47	2.23
Midland	1.62	1.52	1.42
Terry	4.64	3.73	3.02

[1] Availability is the volume of recoverable ground water in storage as simulated by the 1990 run of the Texas Water Development Board's computer model of the High Plains aquifer which was computed from 1990 measured data. Calculations do not include the bottom 10 feet of saturated material.

Potential for Conjunctive Use of Ground and Surface Water

Due to the arid climate and lack of established drainage, there is little surface water locally available for use in the study area. Ground water is, therefore, relied upon heavily. However, there are three sources of surface water that are in use; (1) water supplied from lakes outside the study area for public supply use, (2) water supplied for irrigation use from recovered wastewater, and (3) a minor amount of water in playa lakes and stock tanks for livestock use. The recently completed O. H. Ivie Reservoir, operated by the Colorado RiverMunicipal Water District, will provide additional water to its member cities (Odessa and Big Spring along with purchased supplies for Midland). All other sources are at, or near, full capacity and additional surface-water supplies are not anticipated.

Potential for Additional Ground-Water Development

Areas most favorable for additional ground-water development are dependent on the saturated thickness, specific yield, history of water-level decline, and chemical quality of the aquifer. Additional ground-water development, in the form of irrigation pumpage, is possible in Dawson and eastern Gaines Counties where saturated thickness is in excess of 50 feet and, in some places, of 100 feet (Figure 15). Water level declines in this area have thus far been minimal; and, particularly in Dawson County, the water level has recently been significantly rising (Figure 10).

Ground water in the Edwards-Trinity (High Plains) aquifer has not been fully developed. The northern half of the study area is underlain by Cretaceous sandstones and limestones that are capable of producing up to 200 gallons per minute to wells but more typically about 50 gallons per minute. Although
Edwards-Trinity ground water is generally acceptable for irrigation use, it is usually of poorer quality than the water in the overlying Ogallala and will not meet public supply drinking water standards. Moreover, it does not exist in sufficient quantities to prevent overdrafts of the aquifer in heavily pumped areas.

Ground water in the Triassic Dockum aquifer is similarly underdeveloped. It is of too poor-quality for most uses; however, it is quite usable as a water source for secondary recovery procedures in the petroleum industry and should be used rather than depleting fresh water in overlying aquifers.

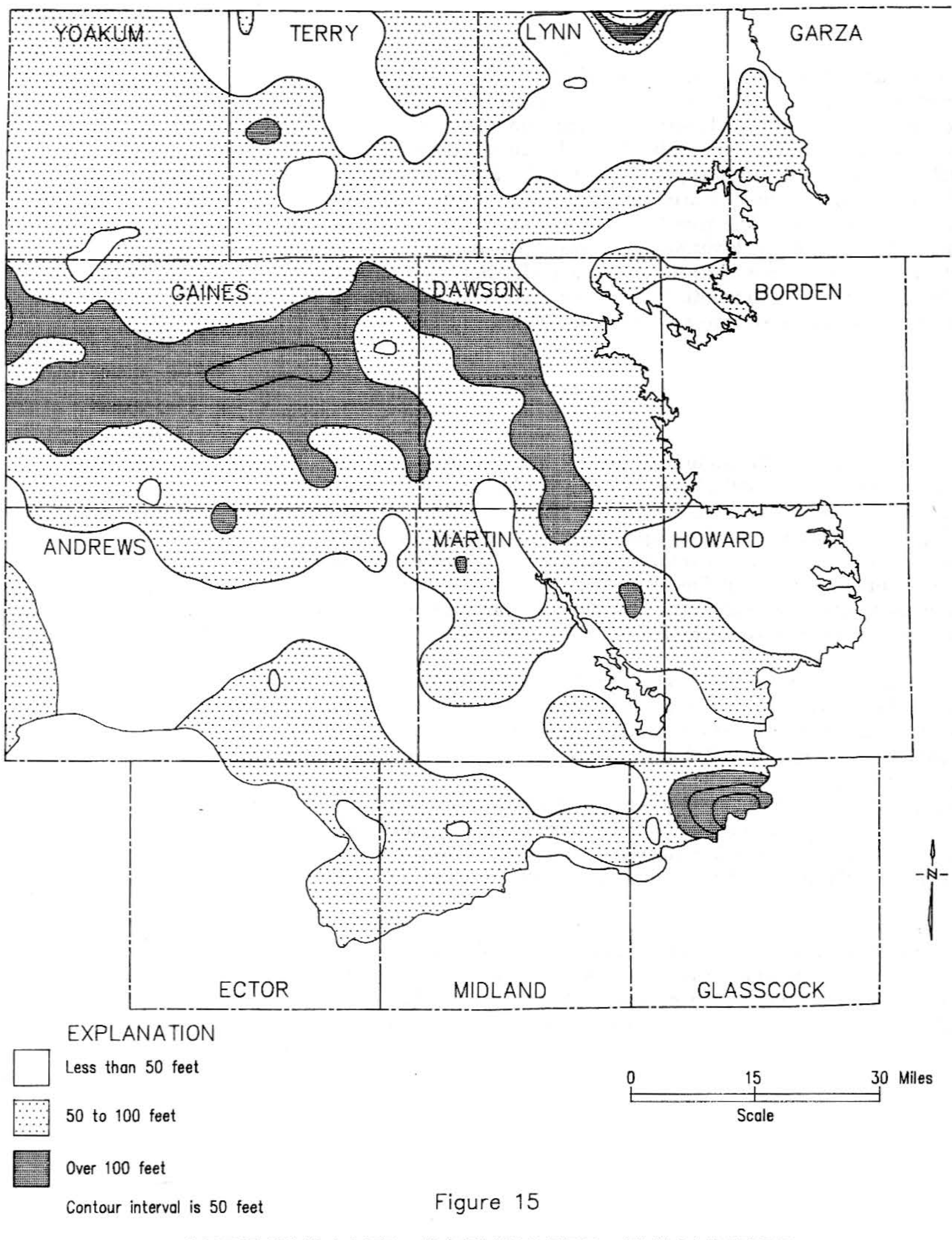


Figure 15

APPROXIMATE SATURATED THICKNESS OF HIGH PLAINS AQUIFER, 1990

Modified from: Peckham, unpublished

Potential Methods of Increasing Aquifer Recharge

Recharge is both a natural and artificial process by which water is absorbed and added to the zone of saturation. As described earlier, natural recharge to the aquifer primarily occurs as water, derived from precipitation, percolates downward from the surface. Any activity by man, either intentional or unintentional, that increases or supplements the rate of replenishment to the aquifer, is called artificial recharge. Increased aquifer recharge within the study area is best achieved by two methods; modification of playa lake bottoms and injection through wells.

The majority of the precipitation that falls on the land surface in the study area drains into playa lakes. Water that collects in these shallow depressions tends to evaporate faster than it can percolate downward through the fine-grained sediments that line the bottom of these features. The vertical permeability, or infiltration rate, of these lake beds can be improved by digging a trench in the basin which will not only remove a portion of the clay soil, but will also concentrate the water such that less surface area is exposed to evaporation. Precaution should be taken to avoid depressions that were historically used as salt-water disposal pits. These basins usually contain a high salt content in their soil which can leach out and percolate downward into the aquifer. Also, playas should be avoided in which concentrated levels of pesticides and fertilizers have collected by drainage from nearby fields.

Recharge wells have successfully been used to inject water directly into underground water-bearing zones. The nature of the water source and an understanding of the geohydrological characteristics of the formation into which the water will be injected determines the technology necessary to construct the recharge wells (O'Hare and others, 1986). In the study area, water collected in playa lakes and storm-runoff structures represents the most viable source for injection. Precaution must be given to injecting only water that is silt free and chemically fresh.

Projected Availability Through the Year 2010

The amount of ground water needed to supply projected demands through the year 2010 is in excess of the estimated annual effective recharge to the aquifer which should result in declining water levels. Although some of the water pumped in the study area will be replaced by recharge, a portion will continue to be drawn from storage within the aquifer. Based on the amount of projected recoverable storage in the High Plains aquifer (Table 5), by the year 2010 approximately 19 percent of the recoverable ground water presently held in storage in the entire study area will have been used with approximately 24 million acre-feet remaining.

With the completion of O.H. Ivie Reservoir by the Colorado River Municipal Water District, all member cities and cities with purchase contracts with the district are expected to meet their future water needs through the year 2010. Other cities within the study area are also expected to have adequate supplies to meet their water needs for the next 20 years.

CONCLUSIONS

An adequate quantity of ground water for all projected uses should be available through the year 2010 although heavy pumpage in a concentrated area, especially during periods of less than normal rainfall, will result in significant water-level declines. While there appears to be a reasonable quantity of ground water available for the area through the year 2010, the continued deterioration of the chemical quality could limit the usefulness of some of this water.

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