Report 288

EVALUATING THE GROUND-WATER RESOURCES OF THE HIGH PLAINS OF TEXAS

Volume 1

TEXAS DEPARTMENT OF WATER RESOURCES

May 1984

TEXAS DEPARTMENT OF WATER RESOURCES

REPORT 288

EVALUATING THE GROUND-WATER RESOURCES OF THE HIGH PLAINS OF TEXAS

VOLUME 1

By

Tommy Knowles, Phillip Nordstrom,
and William B. Klemt

Prepared by the Texas Department of Water Resources in cooperation with the U.S. Geological Survey, High Plains Underground Water Conservation District No. 1, North Plains Ground Water Conservation District No. 2, Panhandle Ground Water Conservation District No. 3, and Texas Tech University

May 1984

Published and distributed
by the
Texas Department of Water Resources
Post Office Box 13087
Austin, Texas 78711

ABSTRACT

A regional ground-water study of the High Plains aquifer was initiated in 1978 by the Texas Department of Water Resources. The study, partially funded by the U.S. Geological Survey, is to be included in that agency's eight-state study of the High Plains aquifer. Two primary purposes of the study were to improve the data base describing the aquifer and to develop a computer model capable of predicting future conditions. The High Plains of Texas covers about 35,000 square miles (91,000 km^2) and includes all or parts of 46 counties. The High Plains aquifer consists primarily of the Ogallala Formation, and includes all water-bearing units, mainly Cretaceous and Triassic sediments, with which it is in hydraulic continuity.

Approximately 14,000 data points were used to construct a detailed altitude to base of High Plains aquifer map. Water levels in over 3,800 wells were measured to provide a detailed 1980 water-level map. The comprehensive nature of these two maps provided a more accurate saturated thickness map than had previously been attained. Maps depicting specific yield and permeability were constructed based on lithologic descriptions and the values derived were used in the digital model. The High Plains aquifer was determined to have an average specific yield of 16 percent and an average permeability of 400 gallons per day per square foot [16,300(l/d)/m^2]. An average annual natural recharge rate of 0.2 inch (0.5 cm), or 371,910 acre-feet (457 hm^3), was applied to the entire aquifer.

A two-part digital model of the aquifer was constructed and calibrated for the period 1960 through 1980. In 1980, the aquifer contained 420.58 million acre-feet (519,000 hm^3) of water, 91.5 percent recoverable. The model was applied to predict the future conditions of the aquifer, with several runs made while varying the degree to which management practices reduce irrigation application rates. The following is a comparison between a model run with the largest reduction in application rates, showing improved management practices in force, and a run without a reduction of application rates.

For the year 2000, results of the model application which used reduced application rates are as follows: 363.46 million acre-feet (448,000 hm^3) of water in storage, 2.348 million acre-feet (2,900 hm^3) of annual net withdrawals, and 4.249 million acres (17,200 km^2) under irrigation. These values represent reductions from 1980 levels of 13.6, 50.4, and 7.4 percent, respectively. The year 2000 results of the model application that did not use reduced irrigation rates are 341.66 million acre-feet (421,000 hm^3) of water in storage, 3.913 million acre-feet (4,820 hm^3) of net withdrawals, and 3.940 million acres (15,900 km^2) under irrigation. The corresponding reductions from 1980 levels are 18.7, 17.4, and 14.1 percent, respectively.

Fcr the year 2030, results of the model application which used reduced application rates are as follows: 310.66 million acre-feet (383,000 hm^3) of water in storage, 2.097 million acre-feet (2,590 hm^3) of annual net withdrawals, and 3.803 million acres (15,400 km^2) under irrigation. These values represent reductions from 1980 levels of 26.1,55.7, and 17.1 percent, respectively. The results for the year 2030 of the model application that did not reduce application rates are 259.89 million acre-feet (320,000 hm^3) of water in storage, 2.385 million acre-feet (2,940 hm^3) of annual net withdrawals, and 2.628 million acres (10,600 km^2) under irrigation. The corresponding reductions from 1980 levels are 38.2, 49.6, and 42.7 percent, respectively.

TABLE OF CONTENTS

TABLE OF CONTENTS—Continued

TABLE OF CONTENTS—Continued

TABLES

TABLE OF CONTENTS—Continued

FIGURES

TABLE OF CONTENTS—Continued

TABLE OF CONTENTS—Continued

TABLE OF CONTENTS—Continued

EVALUATING THE GROUND-WATER RESOURCES OF THE HIGH PLAINS OF TEXAS

INTRODUCTION

Purpose and Scope

The Texas Department of Water Resources initiated a regional ground-water study of the High Plains aquifer in August 1978. The study was conducted by the Department with assistance from the High Plains water districts and Texas Tech University and was partially funded by the U.S. Geological Survey. The study was in support of the Geological Survey's eight-state study of the High Plains aquifer. The purposes of the Department's study were to improve the data base describing the aquifer; to better describe the occurrence, operation, and use of the aquifer; and to develop a computer model of the aquifer.

The scope of the project included the following activities: (1) research files and published reports to obtain data related to the aquifer; (2) construct detailed maps depicting the elevation of the base of High Plains aquifer; (3) measure depth to water in wells currently in the water-level observation network and in wells which were added to the network to provide adequate coverage; (4) obtain data related to specific yield, permeability, and current ground-water pumpage; (5) construct lithofacies maps of the Ogallala Formation south of the Canadian River; (6) construct 1980 water-level and saturated thickness maps based on the intensive water-level measuring effort and on the detailed base of aquifer maps; and (7) construct and calibrate a computer model with the capability of predicting future water levels and saturated thicknesses based on the physical parameters describing the aquifer and on future levels of pumpage.

This report is prepared in four volumes. Volume 1 contains interpretive information presented as text and related tables and regional figures. Volumes 2 through 4 contain supporting basic data including records of wells and county maps depicting well locations, elevation of base of aquifer, elevation of water levels in 1980, and saturated thicknesses in 1980. The areas covered in Volumes 2 through 4 are shown on Figure 1. They are:

Volume 2. Approximately the northern third of the study area, to include Armstrong, Carson, Dallam, Donley, Gray, Hansford, Hartley, Hemphill, Hutchinson, Lipscomb, Moore, Ochiltree, Potter, Roberts, Sherman, and Wheeler Counties.

Volume 3. Approximately the middle third of the study area, to include Bailey, Briscoe, Castro, Crosby, Deaf Smith, Dickens, Floyd, Hale, Lamb, Motley, Oldham, Parmer, Randall, and Swisher Counties.

Volume 4. Approximately the southern third of the study area, to include Andrews, Borden, Cochran, Dawson, Ector, Gaines, Garza, Glasscock, Hockley, Howard, Lubbock, Lynn, Martin, Midland, Terry, and Yoakum Counties.

Four additional reports were published during the course of this study. The reports discuss results of test hole drilling (Ashworth, 1980), results of surface electrical resistivity surveys (Muller, 1980), results of neutron-probe measurements (Klemt, 1981) and program documentation and user's manual for GWSIM-Ill computer program (Knowles, 1981).

Description of Project Area

The High Plains of Texas is the southernmost extension of the Great Plains physiographic province of North America which extends from the southern Texas Panhandle northward into South Dakota and includes parts of Colorado, Kansas, Nebraska, New Mexico, Oklahoma, and Wyoming. The High Plains of Texas covers about 35,000 square miles (91,000 km^2), and includes the Canadian River basin and the upper parts of the Red, Brazos, and Colorado River basins within the state. The study area, which averages about 300 miles (480 km) from north to south, and about 120 miles (190 km) from east to west, includes all or parts of Andrews, Armstrong, Bailey, Borden, Briscoe, Carson, Castro, Cochran, Crosby, Dallam, Dawson, Deaf Smith, Dickens, Donley, Ector, Floyd, Gaines, Garza, Glasscock, Gray, Hale, Hansford, Hartley, Hemphill, Hockley, Howard, Hutchinson, Lamb, Lipscomb, Lubbock, Lynn, Martin, Midland, Moore, Motley, Ochiltree, Oldham, Parmer, Potter, Randall, Roberts, Sherman, Swisher, Terry, Wheeler, and Yoakum Counties. The extent of the High Plains aquifer study is shown in Figure 1.

The Texas High Plains is essentially a flat plateau. A remarkable characteristic of the region is the great number of shallow depressions, or playas, which dot its surface. During periods of rainfall the playas accumulate drainage from local watershed areas ranging in size **from** less than one square mile to several square miles. Only a very small portion of the rainfall drains into the streams which traverse the plateau.

The Ogallala Formation of late Miocene to Pliocene age unconformably overlies Cretaceous, Jurassic, Triassic, and Permian rocks and consists primarily of sand, silt, clay, and gravel derived from the southern Rocky Mountains to the west. The Ogallala is the major water-bearing unit of the High Plains of Texas. Hydraulic continuity occurs between the Ogallala Formation and both the underlying Cretaceous, Jurassic, and Triassic rocks in many areas of the High Plains, and the Quaternary deposits, where present. Therefore, for the purpose of this study, the High Plains aquifer will be considered to consist of the saturated sediments of the Ogallala Formation and those geologic units which contain potable water and are in hydraulic continuity with the Ogallala.

Pleistocene and recent soils form a thin mantle over the Ogallala Formation. Caliche horizons, at depths ranging from 1 to 6 feet (0.30 to 1.80 m), underlie the top and subsoil zones over most of the Texas High Plains. These caliche zones are generally 1 to 2 feet (0.30 to 0.60 m) thick and grade downward into the lower Pleistocene subsoils or into hard indurated caliche layers (caprock) at the top of the Ogallala. The caprock in many cases separates the Pleistocene sediments from the Ogallala Formation. The topsoils consist of three major textural types: (a)fine sandy and silty loams, (b) clay and clay loams, and (c) fine sandy loams.

The High Plains consists of about 22 million treeless acres (91,000 km^2). A large part of this area is used for irrigation farming; the region is noted for its production of cotton, grain sorghums, and wheat.

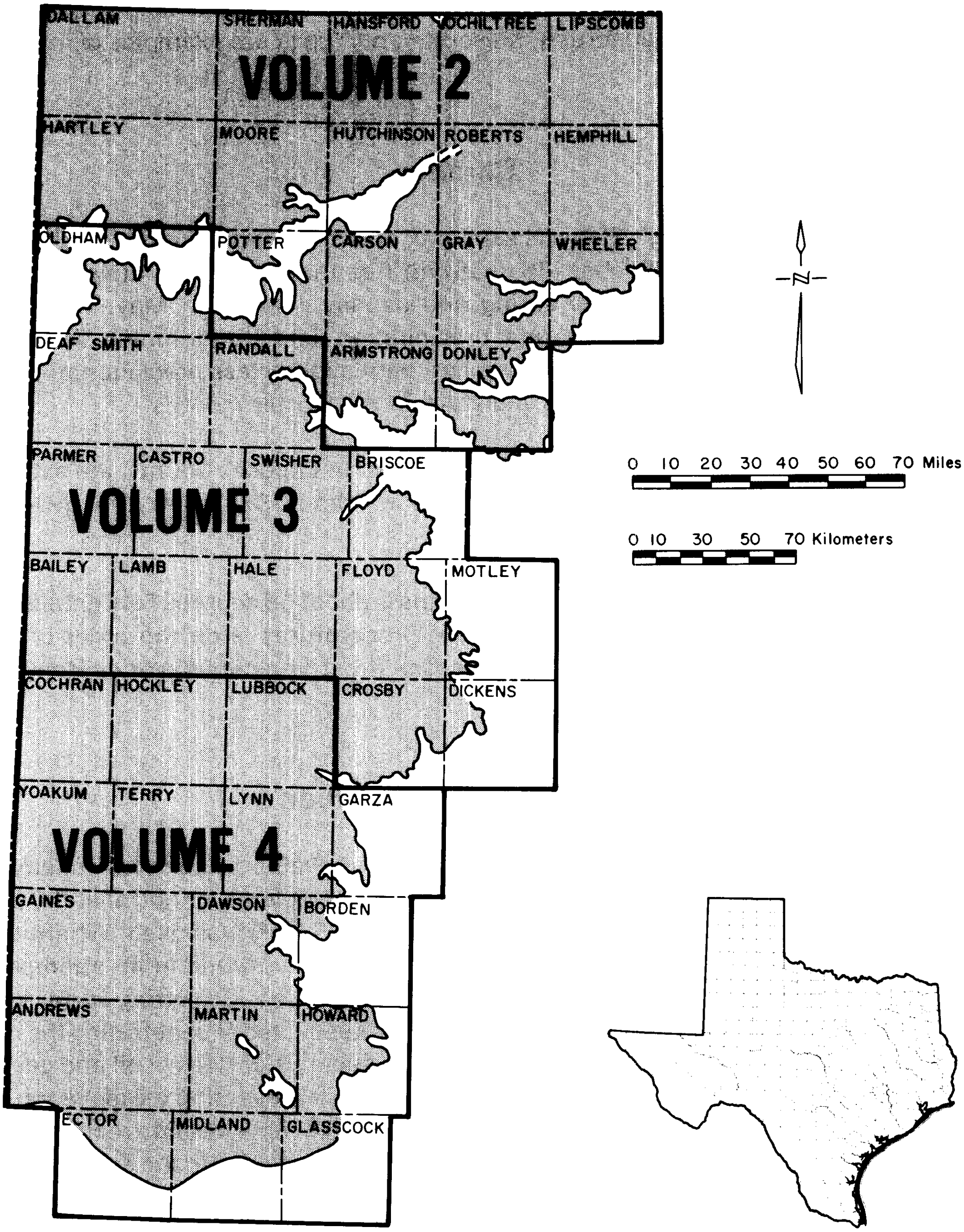


Figure 1

Extent of the High Plains Aquifer in Texas and Index to Volumes 2, 3, and 4

About one-half of the High Plains remains in grassland. Buffalo grass and Blue Grama are found on the clay and clay loam soils. On the sandy loam soils Little Bluestem, Western Wheat, Indian, Switch, and Sand Reed grasses are found. In other areas, the deep sands support thick growths of Shinoak and Sand Sagebrush. Mesquite and Yucca are examples of invading brushy plants.

Climate

The climate in the Texas High Plains is semiarid, and the mean annual precipitation over the area ranges from about 14 to 23 inches (36 to 58 cm). Rainfall is usually relatively light during the winter months, increasing during the spring and usually peaking in May. The average May precipitation is about three times the normal precipitation for a winter month. Average monthly precipitation reaches a second peak in September, with slightly less precipitation than the May peak. Snowfall is an important source of moisture in the winter months.

Evaporation is greatest during the summer months. In Lubbock County, the average annual evaporation potential for an open-water surface is about 3 1/2 times the average annual precipitation.

The mean annual temperature for the High Plains is about 59 degrees Fahrenheit (15°C). The average difference between summer and winter temperatures is on the order of 40 degrees Fahrenheit (22°C). The length of the growing season (frost free period) varies from year to year but on the average is about 200 days.

Method of Investigation

The map showing the elevation of the base of the High Plains aquifer was constructed using drillers' logs and geophysical logs of water wells which completely penetrated the aquifer. For most of the study area, one data point per 2 square miles (5 km^2) was used. Where this density could not be attained with existing well logs, other data were utilized in an attempt to provide coverage. This supplemental work included (1) drilling test holes, (2) plotting surface contacts of the formation's outcrop, (3) geophysical logging of wells suspected of penetrating the base but for which drillers' logs were not available, and (4) utilizing geophysical logs of oil and gas test wells. The base map is a State of Texas Highway map and the lines representing the elevation of the base of the aquifer were drawn using a contour interval of 20 feet (6 m). A location map and a tabulation of all wells and data points used in the study were made and included in the study. Approximately 14,000 data points are included in the tabulation; however, thousands of supplemental points were also used in the base construction. The cooperating ground-water conservation districts developed the base of aquifer map, well-location map, and tabulation of all data used within their respective areas.

Water-level elevation maps for the years 1960, 1965, 1970, 1975, and 1980 were constructed utilizing measurements made from water-level observation wells in the High Plains area. The network presently contains over 3,800 wells, representing an average density of one well per 9 square miles (23 km^2). The coverage, however, is not uniform. The water-level measurements are usually taken during the winter months to minimize the effect of pumpage. The regional maps for 1960 through 1980 were prepared by Department personnel. Detailed county maps for 1980 were prepared by Department personnel except for those prepared by district personnel for areas within their respective boundaries. The districts also provided tabulations of data used in the construction of their portions of the maps.

The ability of an aquifer to yield water to wells is dependent on saturated thickness. Saturated thickness equals the interval between the water table and the base of the aquifer. The Department, with the aid of the districts, developed 1980 saturated thickness maps based on detailed base of High Plains aquifer maps and the winter 1979-80 altitude of water-level maps. The maps were used to identify areas containing sufficient amounts of water to support irrigation in the future.

Hydraulic parameters studied were specific yield and permeability. Since the Ogallala in Texas is a water-table aquifer which is being mined, specific yield will govern its useful life. Specific yield varies from one area to the next and also from one vertical interval to the next. The Department employed a varied approach to determine the distributions of specific yield and permeability. A weighted mean specific yield and permeability value was assigned to selected wells by examining the vertical distribution of different lithologic types in the saturated zone as described on drillers' logs and assigning average specific yield and permeability values to each type-layer. Regional maps of specific yield and permeability were then constructed using an average data point density of one per model cell (about 9 square miles or 23 km^2). Values derived from these regional maps were incorporated into a digital model from which computer-generated maps for specific yield and permeability were created (see section on the "Results of Model Operation"). Other approaches used to support the specific yield and permeability map construction included lithofacies mapping, test-hole drilling, laboratory testing, electrical resistivity soundings, geophysical logging, literature research, and computer modeling.

New regional lithofacies maps of the southern portion of the Ogallala Formation were prepared by personnel of Texas Tech University under the supervision of Dr. C. C. Reeves, Jr. The maps indicate distribution of sand, clay, and gravel in the Ogallala Formation. A map describing the distribution of basal Ogallala gravel zones was also produced. All field-determined specific yield and permeability values are representative of only a relatively small area. Since specific yield and permeability are affected by lithology, the lithofacies maps were developed to better estimate regional trends.

Forty-one test holes were drilled to aid in determining the hydraulic characteristics of the aquifer. This was accomplished during drilling operations by collecting undisturbed formation samples from different depths within the aquifer using the Shelby tube or Christensen core barrel. The cores were analyzed to determine porosity, vertical and horizontal permeabilities, specific yield, and grain size distribution. The holes also provided additional data utilized in preparing the base of aquifer map.

Electrical resistivity soundings were conducted to determine any variations in lithology between test holes and to attempt to correlate these soundings to porosity and specific yield values obtained through laboratory analysis of the cores retrieved from nearby test holes. The soundings were also used to determine variations in lithology where neutron soil moisture studies were conducted in an effort to better define the natural recharge and irrigation recirculation to the aquifer.

For the electrical subsurface investigation, the "Barnes Layer Method," which uses the Wenner array, was employed for the selection of electrode spacing to electrically evaluate the water-bearing zones of the aquifer. Following proper site selection, field procedures used in conducting the surface electrical resistivity surveys included selecting the proper electrode spacing, conducting actual soundings, and plotting the field VES (vertical electrical sounding) curve. Field data on apparent resistivity were interpreted by utilization of computer programs. Qualitative variations in hydrologic properties such as permeability and specific yield are shown in terms of the aquifer's apparent formation factor and computer-calculated resistivity.

Neutron soil moisture surveys were conducted in an attempt to determine the amount of natural recharge and irrigation recirculation to the aquifer. Twenty-two widely separated sites were established in carefully selected locations throughout the study area. Considerations for site selection included soil type, method of irrigation, and subsurface structure. At least two boreholes were installed at each site, the first to measure moisture in an irrigated, cultivated field and the second to measure moisture in a nonirrigated field. The boreholes were cased with 2-inch (5-cm) diameter aluminum tubing, sealed at the bottom to exclude moisture. The boreholes were constructed approximately 30 feet (9 m)deep to monitor the movement of moisture below the root zone and zone of evaporation. It was assumed that moisture passing below this depth reaches the water table. Weekly measurements were taken with the neutron moisture tools. These measurements were recorded in the form of a log which registered any moisture build-up. A recording rain gage was also installed at each site to measure precipitation, and the amount of water applied for irrigation was obtained by monitoring the nearby wells being pumped. By monitoring the movement of moisture through the soil profile, an estimate was made of the amount of water percolating to the water table. This estimate was compared to the amount of water applied to the surface to determine the proportional amount of irrigation water that becomes recharge and recirculation.

The High Plains Underground Water Conservation District No. 1 and the North Plains Ground Water Conservation District No. 2 serviced 17 of the sites using their equipment while the Department monitored the remaining 5 sites. Site monitoring began in November 1978 and continued for 12 months. This period generally corresponds to crop year 1979.

The construction of the digital model utilized data developed from this study and other investigations. The model used the finite difference technique to simulate water levels. The model was calibrated by reproducing water-level changes during the period 1960 through 1980. The model calculated water-level changes based on predicted pumpage through the year 2030. The pumpage prediction procedure accounts for reduced water availability due to dewatering of the aquifer.

Acknowledgements

Acknowledgement is extended to the following sources of valuable information and expertise within the study area: Mr. Edwin D. Gutentag, Mr. Richard R. Luckey, and Mr. Edwin P. Weeks of the U.S. Geological Survey, and the Southwestern Public Service Company.

The authors appreciate the cooperation extended by the property owners in the High Plains who supplied information concerning their wells and, in many instances, also allowed access to their property and the use of their wells to monitor water-level changes. Acknowledgement is also

extended to the water well drillers of the area for the use of their drillers' logs provided to the Department. Special thanks are given to the Texas State Department of Highways and Public Transportation for allowing test holes to be drilled on highway right-of-way.

Personnel

Principal investigators for the High Plains aquifer study were Dr. Tommy R. Knowles, P.E., Chief, Data Collection and Evaluation Section, and geologists Phillip L. Nordstrom and William B. Klemt. Contributing authors include John B. Ashworth, Celeste Zouzalik, Bernard Baker, Howard Taylor, and Daniel A. Muller, geologists with the Texas Department of Water Resources. Mr. Klemt served as co-principal investigator for the first part of the study. Also assisting in the completion of this study were personnel of the High Plains Underground Water Conservation District No. 1 (A. Wayne Wyatt, Manager; Don Smith and Don McReynolds, geologists), the North Plains Ground Water Conservation District No. 2 (J. W. Buchanan, former Manager; Orval Allen, Manager; Mike Crawford, geologist), the Panhandle Ground Water Conservation District No. 3 (Felix Ryals, former Manager; Richard Bowers, Manager), and the Department's Data and Engineering Services Division. The study was conducted under the general supervision of C. R. Baskin, P.E., Director, Data and Engineering Services Division. Lithofacies maps of the Ogallala Formation south of the Canadian River were prepared under the supervision of Dr. C. C. Reeves, Jr., of Texas Tech University. Test hole drilling and laboratory testing of samples were conducted by the Department's Geotechnical Services Unit.

Metric Conversions

For those readers interested in using the International System (SI) of Units, the metric equivalents of English units of measurements are given in parantheses in the text. The English units used in this report may be converted to metric units by the following conversion factors:

From English units	Multiply by	To obtain metric units
inches (in)	2.540	centimeters (cm)
feet (ft)	.3048	meters (m)
miles (mi)	1.609	kilometers (km)
acres	.4047	square hectometers (hm^2)
	.004047	square kilometers (km^2)
square miles (mi^2)	2.590	square kilometers (km^2)
gallons per minute (gal/min)	.06309	liters per second (l/s)
acre-feet	.001233	cubic hectometers (hm^3)

From English units	Multiply by	To obtain metric units
feet per mile (ft/mi)	0.189	meters per kilometer (m/km)
gallons per day per foot [(gal/d)/ft]	12.418	liters per day per meter [(l/d)/m]
gallons per day per square foot [(gal/d)/ft^2]	40.74	liters per day per square meter [(l/d)/m^2]

To convert degrees Fahrenheit (°F) to degrees Celsius (°C) use the following formula:

$$°C = (°F-32)(0.556)$$

STRATIGRAPHY OF THE OGALLALA AND ASSOCIATED WATER-BEARING FORMATIONS

Pre-Ogallala Rocks

Triassic System

The Dockum Group of Triassic age was named in 1890 by Cummins for the community of Dockum in Dickens County, Texas (Sellards and others, 1932, p. 242). Dockum and underlying Permian strata are red, but are readily differentiated by contrasting depositional environments. In some areas, Permian and Triassic strata are separated by an unconformity. Elsewhere, sedimentation was probably continuous from Permian into Triassic time (McGowen and others, 1979, p. 3), resulting in a gradational contact. Dockum beds are overlain unconformably by strata of Tertiary, Cretaceous, or Jurassic age and are exposed at the surface along the High Plains escarpment, in the "breaks", and in outcrops of small areal extent. Table 1 shows the stratigraphic relationship of these systems. The regional dip of Triassic strata is towards the center of the Southern High Plains. As uplifting occurred to the west, the basin was tilted to the southeast (Fink, 1963, p. 7).

The Triassic strata portrayed on Figure 2, showing the geologic units underlying the Ogallala Formation, represents the limit of preserved Triassic in the High Plains. A substantial outlier of Dockum not shown on Figure 2 exists to the east of this limit in the Northern High Plains (McKee and others, 1959, Pl. 4); it provides up to 135 feet (41 m) of water-bearing strata to irrigation wells in portions of Hansford, Hutchinson, Moore, and Sherman Counties and is included in the High Plains aquifer.

The Dockum Group can be subdivided into two or three formations depending on the location within the High Plains and on the authors of the many publications treating the Triassic rocks in this area. Fink (1963, p. 7) subdivides the Dockum in the northern part of the Southern High Plains into three formations. A basal member, the Tecovas Formation, consists of variegated shales and

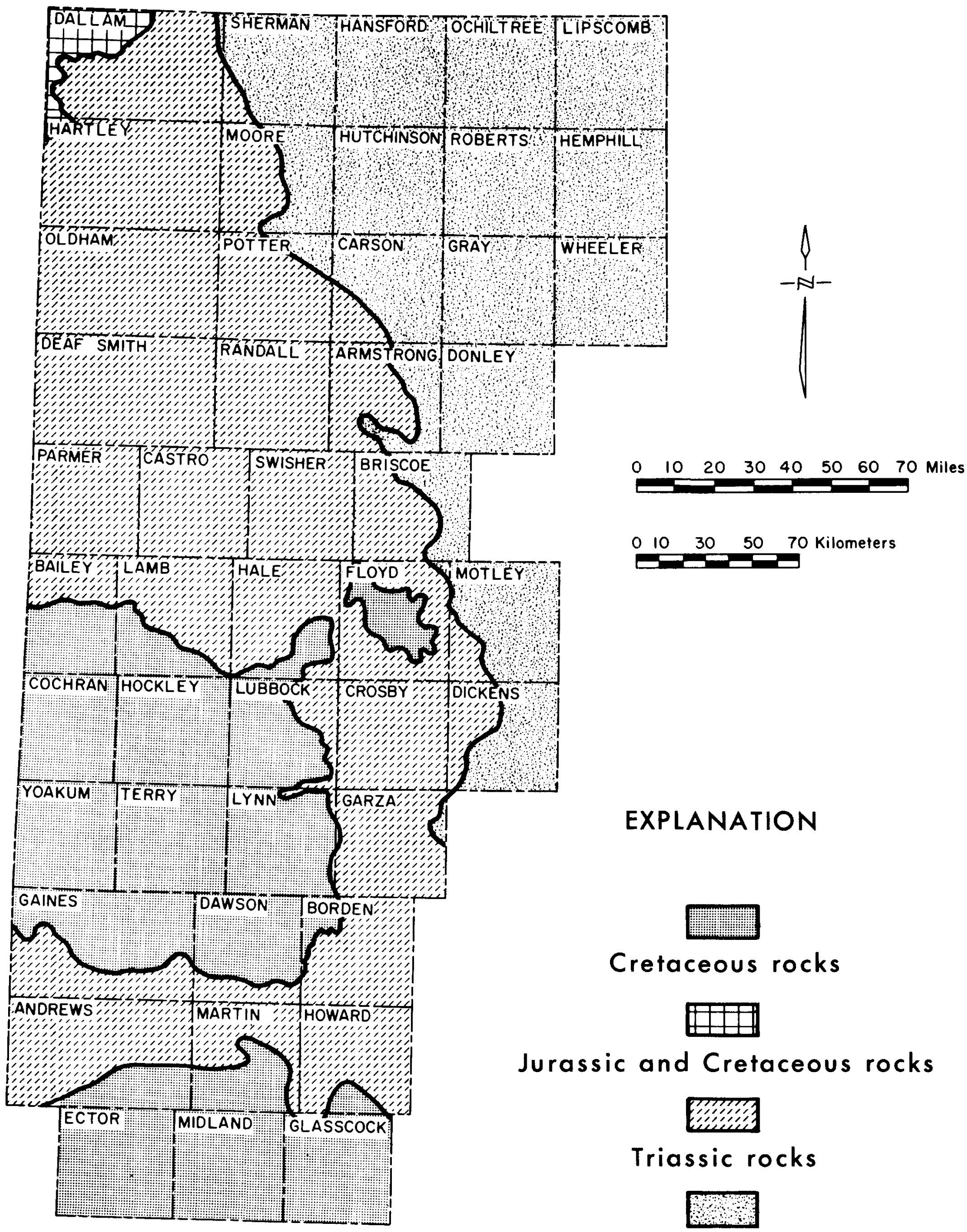


Figure 2

Geologic Units Underlying the Ogallala Formation

Table 1.—Geologic Units and Their Water-Bearing Characteristics

System	Series	Group	Formation	Approximate maximum thickness (ft)	Physical character of rocks	Water-bearing characteristics
Quaternary	Pleistocene to Recent		Alluvium, eolian and lacustrine deposits	150	Windblown sand and silt, fluvial flood plain deposits, and silt and clay playa lake deposits.	Yields small amounts of water to wells.
Tertiary	Late Miocene to Pliocene		Ogallala	900	Tan, yellow, and reddish-brown, silty to coarse-grained sand mixed or alternating with yellow to red silty clay and variable sized gravel. Caliche layers common near surface.	Yields moderate to large amounts of water to wells. The principal aquifer in the study area with yields of some wells in excess of 1,000 gal/min.
Cretaceous	Gulf	Colorado	Graneros Shale	45	Dark-gray shale.	Not known to yield water to wells.
		Dakota	Dakota Sandstone	190	Tan to yellowish-brown, fine to medium-grained, thin to massive-bedded sandstone with interbedded gray shale.	Yields as much as 150 gal/min to irrigation wells in the northwest part of Dallam County.
	Comanche	Washita	Purgatoire	100	Upper member a dark-gray shale. Lower member a massive, buff to white, fine to coarse-grained, poorly cemented sandstone.	Yields as much as 500 gal/min to irrigation wells in the northwest part of Dallam County.
			Duck Creek	35	Yellow, sandy shale and thin gray to yellowish-brown, argillaceous limestone beds.	Not known to yield water to wells.
		Fredericksburg	Kiamichi	100	Thinly laminated, sometimes sandy, gray to yellowish-brown shale with interbeds of thin, gray, argillaceous limestone and thin, yellow sandstone.	Yields small amounts of water locally to wells.
			Edwards Limestone	40	Light-gray to yellowish-gray, thick bedded to massive, fine to coarse-grained limestone.	Locally yields moderate to large amounts of water to wells from fractures and crevices. Yields small amounts of water to wells.
			Comanche Peak Limestone	55	Light-gray to yellowish-brown, irregularly bedded, argillaceous limestone and thin interbeds of light-gray shale.	Yields small amounts of water to wells.
			Walnut	25	Light-gray to yellowish-brown, fine to medium-grained, argillaceous sandstone; thin bedded, gray to grayish-yellow, calcareous shale; and light-gray to grayish-yellow, argillaceous limestone.	Not known to yield water to wells.
		Trinity	Antlers	125	White, gray, yellowish-brown to purple, fine to coarse-grained, argillaceous, loosely cemented sand, sandstone, and conglomerate with interbeds of siltstone and clay.	Yields small to moderate amounts of water to wells in the southern quarter of the study area.
Jurassic	Upper		Morrison	550	Grayish-green to red shale; white to brown, fine to coarse-grained sandstone; some clay, conglomerate, and limestone; brown-silt member at base.	Yields small amounts of water to livestock wells in north-central Dallam County.
			Exeter Sandstone	50	White to brown, massive, fine to medium-grained sandstone.	Yields as much as 20 gal/min to wells.
Triassic	Upper	Dockum	Undivided	2,000	Upper unit, Trujillo Formation, varicolored siltstone, claystone, conglomerate, fine-grained sandstone, and limestone. Lower unit, Tecovas Formation, varicolored, fine to medium-grained sandstone with some claystone and interbedded shale. Includes units equivalent to Chinle Formation and Santa Rosa Sandstone.	Yields small to moderate amounts of water to wells. Water quality variable with stratigraphic position and depth.
Permian	Upper		Undivided	1,000+	Very fine to fine-grained, red sandstone and shale; white to brown gypsum, anhydrite, and dolomite.	Yields small amounts of water to wells near the outcrop. Water quality generally slightly saline.

clays, sometimes sandy or silty. Colors and predominately maroon, reddish brown, blue, yellow, and white. In localized areas, the Tecovas also contains fine-grained sandstone and conglomerate lenses. Tecovas beds are up to 200 feet (60 m) thick and are not known to yield water to wells. Occupying the middle unit is the Santa Rosa Sandstone, the major water-bearing unit of the Triassic in this area. Beds may exceed 200 feet (60 m) in thickness and consist of gray, tan, white, and brown, fine- to coarse-grained, crossbedded sandstone and conglomerate with interbedded red, blue, and gray shale and clay. Petrified wood and mica are common with local areas of mudstone and siltstone. The upper unit is the Chinle Formation and consists of up to 600 feet (180 m) of red, blue, and reddish brown clays and shales. Thin beds of micaceous sandstone, conglomerate, and sandy green clays occur locally. Sand zones rarely exceed 30 feet (9 m) and yield small quantities of water to domestic and livestock wells.

Matthews' (1969, p. 24) guidebook on the geologic story of Palo Duro Canyon labels the Triassic deposits as the Trujillo Formation, consisting primarily of fine-grained and massive-bedded sandstones. The basal sandstone is gray to greenish gray and contains channel deposits of coarse sand and an abundance of mica. The middle portion consists of red, maroon, and gray shales overlain by a coarse-grained, cross-bedded sandstone. An upper unit of red and green shale tops the section. The Trujillo is the approximate equivalent to the Santa Rosa as described by Fink (1963).

Hart and others (1976, p. 17) divide the Dockum Group in the Oklahoma Panhandle into an upper and lower sandstone. The lower unit consists mostly of varicolored, fine- to medium-grained sandstone with some clay and interbedded shale. Sufficient quantities of water are available from this unit for irrigation purposes in some areas. Usually the aquifer is used to supplement more productive aquifers that overlie the Dockum. The upper unit of the Dockum is composed mainly of red and green shale with occasional thinly bedded, fine-grained, pink to red shaly sandstone and siltstone. Adequate water for livestock and domestic supplies is usually available from this upper unit.

In wells in the north-central area of Hansford County, the occurrence of red, blue, and yellow clay near the base is common, suggesting the presence of Triassic deposits in the lower section of these wells. Since the base of the High Plains aquifer (Figure 20) was picked solely on generalized drillers' log descriptions, an areal distribution of the Triassic outlier could not be accurately delimited. If the basal material as described in the drillers' logs seemed to contribute to the High Plains aquifer and be hydraulically connected with the Ogallala Formation, then it was included as part of the aquifer.

Logs in the northwestern corner of Hutchinson County indicate a persistant brown clay bed above the traditionally accepted Permian "red bed", sometimes in direct contact with the red bed but more often separated from it by a series of fine, muddy sand and clay layers. The brown clay is often associated with red and blue clay. This lower section seems to be also of Triassic age as seen from color, sand grain size, and areal extent of the clay layer.

Moore County presents the most difficult situation in determining the base of the aquifer. Wells in approximately one-half of the county obtain water from both Tertiary and Triassic(?) rocks. This relationship can be visualized by referring to geologic section B-B' (Figure 23) where the section passes through Moore County. Based on the presence of carbonized wood, mica, pyrite, and the distinctive colors exhibited by both the sands and clays in the lower section, these basal strata are considered to be of Triassic age. Clay colors range from yellow to red and blue.

Sand colors include red, yellow, gray, and a very fine-grained white sand referred to locally as "sugar sand". Similar sections may be seen in outcrops in extreme south-central Moore County where the Canadian River incises the Dockum Group. The developed Triassic sands occur principally in the western, north-central, and northeastern parts of the county. The steep submerged escarpment in the western portion of Moore County, denoted by a line and hatchure symbol on both county and regional base of aquifer maps, represents the western area of the developed Triassic sands. The line begins in the northwest corner of the county and continues south to a point just southwest of Dumas. The lower sand is overlain by a massive red and blue clay layer which abuts the higher red beds to the west. The entire lower section thins rapidly to the east and is not as continuous. The southern area of Moore County was treated separately in view of the low permeability and the development of a separate piezometric surface in the lower sands with the implied lack of permeability. An arbitrary line, based primarily on specific capacity, was extended from the point southwest of Dumas eastward to near the county boundary in order to include erosional remnants not shown on Figure 2. The aquifer base south and east of this line is mapped on top of the highest significant red clay layer. The area north of the line includes the Dockum sands since they do contribute significantly to the water resources of the local area.

The boundary line of Ogallala and Ogallala plus Dockum water-bearing strata ends in the northwest corner of Moore County, where further differentiation was not attempted. Potential for extending the delineation can be seen in Dallam County along the eastern side where closely spaced contour lines occur on both county and regional base of aquifer maps.

In a small area of northeast Randall County, as depicted on the county elevation of base map (Volume 3), wells are completed in both the Ogallala Formation and the Santa Rosa Sandstone of Triassic age, Insufficient water for irrigation is characteristic of the Ogallala in northeastern Randall and northwestern Armstrong Counties. In some parts of this area, even domestic and livestock wells are completed in Triassic sands. In all of Randall County except the above designated area, the base of Ogallala Formation was considered to be the base of High Plains aquifer. Many other counties had areas with water wells completed in Triassic rocks, such as Castro, Deaf Smith, Hale, Oldham, and Swisher Counties, but a lack of hydraulic continuity with the Ogallala or small areal extent excluded these areas from the High Plains aquifer designation.

One other area had dual Ogallala and Triassic water-well completions and was included in the High Plains aquifer. This area parallels the eastern extent of the study and is located in all or parts of Crosby, Dickens, Garza, and Motley Counties. Drillers' logs describe sand, gravel, and broken sandstone below the Ogallala Formation, separated from it by a section of blue clay and "boulders".

In general, the Dockum provides small amounts of water to wells for livestock and domestic use, with isolated areas yielding as much as 500 gal/min (32 l/s) for irrigation. Ground water from the Triassic varies considerably in chemical quality over the High Plains, but generally is more mineralized than water from overlying water-bearing units.

Jurassic System

Exeter Sandstone

Lying unconformably on tilted beds of the Dockum Group of Triassic age, the Exeter Sandstone is the basal unit of the Jurassic System in the study area (Table 1). The Exeter is primarily a massive sandstone with a maximum thickness of approximately 50 feet (15 m). It grades up into the brown-silt member of the Morrison Formation.

The Exeter is a massive, white to buff, fine- to medium-grained sandstone which grades into a brown color near the contact with both the Morrison and Dockum beds. Locally, lenses of clay and gravel are present (Hart, Hoffman, and Goemaat, 1976, p. 17).

Yields of as much as 20 gal/min (1.3 l/s) can be obtained from wells in north-central Dallam County. Water quality is better when overlain directly by Tertiary deposits, but quality decreases as the overlying Morrison Formation thickens.

Morrison Formation

Underlying Tertiary or Cretaceous units in Dallam and Hartley Counties, as delineated by the Jurassic limit depicted on Figure 21, is the Morrison Formation of the Upper Jurassic Series. The Morrison overlies the Exeter Sandstone disconformably. Forming the basal unit of the Morrison is the brown-silt member, into which the underlying Exeter may grade (Baldwin and Muehlberger, 1959, p. 46). Sandstone beds occurring in the upper part of the Morrison contribute some water to wells where these beds are in direct contact with the Cretaceous Purgatoire Formation or the Tertiary Ogallala Formation. The relationship of the Ogallala, Cretaceous, and Jurassic strata in Dallam County can be seen on geologic section B-B’ (Figure 23).

The Morrison Formation consists of varicolored shale dominated by gray-green and red, interbedded with white to brown, fine- to coarse-grained sandstone beds, locally thick. A persistent bed of brown silt occurs at the base of the Morrison. Strata of clay, marl, and conglomerate also occur at some locales.

Only small quantities of ground water are produced from domestic and livestock wells completed in the Morrison, and locations of most such wells are restricted to the north-central part of Dallam County. Chemical quality of ground water from Jurassic beds generally limits its usefulness. Thicknesses of up to 550 feet (168 m) have been documented in test holes drilled through the Jurassic into Triassic rocks.

Cretaceous System

Antlers Formation

The Trinity Group is represented by the Antlers Formation in the southern part of the High Plains study area. These rocks are considered to be equivalent to the Paluxy Sand of Central Texas, and are generally referred to as the “Trinity Sand” in the High Plains. The north-south limits of the Cretaceous occur where the sequence of Cretaceous rocks thins markedly or is absent in the subsurface due to erosion. In the Southern High Plains, isolated Cretaceous remnants occur north and south of these boundaries (Figure 2). The Antlers is underlain by an eroded surface of Triassic strata and overlain by Tertiary or other Cretaceous formations. Both boundaries exhibit an unconformable relationship.

Although absent in places, the Antlers forms a basal sand unit in the Cretaceous system in the southeastern and southern portions of the High Plains. It is a white to purple, loosely consolidated, fine- to coarse-grained, quartz sandstone, locally hard, and commonly interbedded with fine-grained yellow sand, green clay, and gray to pink siltstone. Scattered lenses of gravel occur throughout the unit, but a more persistent, basal conglomeratic unit with interbedded coarse sand is present in most sections. Ferruginous and calcareous cementation is common.

Small to moderate amounts of water can be pumped from wells completed in the Antlers Formation. Where a sufficient saturated thickness of Ogallala sediments overlies the Antlers, the well completion interval usually encompasses both formations. In Ector, Midland, and part of Glasscock Counties, the Antlers sand yields more water of acceptable quality than any other water-bearing formation, but because of relatively thin saturated thickness and low permeability, only moderate quantities of water can be obtained from individual wells. Well yields are usually less than 100 gal/min (6.3 l/s). Water from Cretaceous wells is only slightly more mineralized than water pumped from wells completed in the Ogallala. The High Plains aquifer includes the Trinity Group in Ector, Midland, and parts of Gaines, Andrews, Martin, and Glasscock Counties.

Locally, large quantities of water can be pumped from wells tapping fractures and crevices in the Fredericksburg Group limestones (Table 1) overlying the Antlers, but the dissimilar hydraulic characteristics and localized nature of this water source kept these formations from being included as part of the High Plains aquifer. Such large capacity wells were found in several areas, but were most extensive in Hale and Floyd Counties.

Purgatoire Formation

The Purgatoire Formation of the Washita Group underlies the Dakota Sandstone and unconformably overlies the Morrison Formation of Jurassic age (Table 1). Where the upper shale unit in the Purgatoire is absent, the Dakota and Purgatoire sandstones are contiguous and difficult to differentiate. For the purpose of this study, the Dakota Sandstone and Purgatoire Formation are referred to as Cretaceous rocks. In localized areas, water-bearing sandstone units of Upper Jurassic age in contact with the basal Purgatoire unit contribute sufficient quantities of ground water so as to be included in well completion intervals. The resulting Jurassic and Cretaceous rock combination shown on Figure 2 constitutes part of the High Plains aquifer, and all maps and sections of text referring to the High Plains aquifer make use of geologic and hydrologic data derived from wells completed in the Ogallala, Dakota, Purgatoire, Upper Jurassic, or any combination thereof. The extent of Purgatoire coincides with the extent of Dakota in Dallam County. The approximate thickness of the Purgatoire is 100 feet (30 m). Geologic section B-B’ (Figure 23) further shows the subsurface position and net thickness of the Cretaceous and Jurassic rocks which contain the Purgatoire.

The upper unit of the Purgatoire consists of dark gray shale with thin sandstone ledges and is not water bearing. The lower unit is a buff to white, fine- to coarse-grained, poorly cemented, massive sandstone. Conglomerate beds are sometimes present in the basal part of the lower unit. The Purgatoire-Morrison contact is occasionally difficult to pick from geophysical logs in areas where sandstone beds occupy the upper interval of the Jurassic.

The primary source of water for irrigation wells in northwest Dallam County is the Purgatoire, with younger stratigraphic units (Ogallala and Dakota) also being included in well completions.

Yields of up to 500 gal/min (32 l/s) can be obtained from wells completed in the Purgatoire, and yields exceeding 800 gal/min (50 l/s) are realized when all water-bearing strata are included in the completion interval.

Dakota Sandstone

The Dakota Sandstone lies below the Graneros Shale (Table 1) and rests disconformably on the Purgatoire Formation, both of which are of Cretaceous age. Where the Graneros Shale has been removed by erosion, the Dakota is overlain by Ogallala sediments. The Dakota crops out along several creek beds in the northwest part of Dallam County and the weathered surface exhibits an iron oxide veneer ranging in color from yellow to orange to brown-black. The thickness of the Dakota approaches 190 feet (58 m) and the extent is restricted to a part of northwest Dallam County, falling within the boundary shown on Figures 2 and 20.

Tan to brown, thin to massive-bedded sandstones of the Dakota locally contain a middle interval of lenticular to parallel-bedded gray shale to dark gray mudstone. The upper interval is mainly a shaly sandstone grading into a massive-bedded basal unit. The sandstones are fine- to medium-grained and exhibit intense crossbedding.

Many irrigation wells are completed in the Dakota, usually in conjunction with water-bearing formations above or below which increase well yields. Quantities of ground water up to 150 gal/min (9.5 l/s) can be obtained from the Dakota Sandstone. Where the Graneros or basal Ogallala clays are present, the water in the Dakota is confined under artesian pressure.

Ogallala Formation

Depositional History

The Ogallala Formation in Texas is the southernmost extension of the major water-bearing unit underlying the Great Plains physiographic province of North America. It was named by Darton (1898) for the town of Ogallala, Nebraska, near the type locality.

Following the Laramide revolution in which the southern Rocky Mountains were uplifted and the Cretaceous seas retreated, rivers flowing east and southeastward cut valleys into the pre-Ogallala surface. This erosional pattern continued until late Miocene or early Pliocene (Neogene) time when the climate became progressively more arid (Leonard and Frye, 1974). Sediments transported from the unstable southern Rocky Mountains began to accumulate in the valleys and basins formed on the Permian, Triassic, Jurassic, and Cretaceous surfaces. As the valleys and basins filled, sediments overflowed to form coalescing aprons fed by braided streams that spread across a generally level plain. Throughout the time when Ogallala sediments were being deposited, the southern Rocky Mountains remained tectonically active, providing source material for the Ogallala Formation.

Seni (1980) has described a deltaic system of deposition of the Ogallala Formation in Texas consisting of three overlapping fan lobes of which only the medial and distal fan facies occur in Texas. Each lobe contains distinct lithologic systems identified as channel, inter-channel, and inter-fan lobe.

At its maximum areal range, the Ogallala Formation in Texas may have extended as far as 175 miles (282 km) east of its present location (Walker, 1978, p. 23). Earlier studies have suggested areal extents as far east as the Dallas area (Byrd, 1971, p. 29; and Menzer and Slaughter, 1971).

Aggradation continued until late Pliocene time when climate change and upwarping of the High Plains area caused alluviation to cease and erosion to begin. Pleistocene time followed with extensive erosion laterally along the eastern escarpment and along major river valleys. Vertical erosion has been limited due to the resistant caliche “caprock” that formed over much of the surface of the Ogallala.

During Pleistocene time the southward flowing Pecos River captured eastward flowing streams thus isolating most of the Texas High Plains from the source from which it was derived.

Stratigraphy

The Ogallala Formation consists primarily of fluvial elastics which unconformably overlie Permian, Triassic, Jurassic, and Cretaceous strata. In the Northern High Plains the formation has been divided into three subdivisions, the Valentine, Ash Hollow, and Kimball, based on fossil vertebrates and flora. The subdivisions, often referred to as floral zones, are less distinguishable in the Southern High Plains although Frye and Leonard (1957, 1959) have identified distinctive fossil seeds which correlate to the three floral zones as far south as Howard County, Texas. Evans and Meade (1948) have suggested subdividing the Ogallala of Texas into the Couch Formation consisting of coarse-grained valley fill material, and the Bridwell Formation consisting of the finer grained material deposited by coalescing streams. For this report, the Ogallala will be treated as a single unit although different depositional facies will be discussed. Lithologic descriptions are based on observations made on the 41 test holes (Ashworth, 1980) and on previous works.

Basal Ogallala sediments consist primarily of fine- to coarse-grained elastics. The sands are generally tan, yellow, or reddish brown, medium- to coarse-grained, moderately to welt sorted, unconsolidated quartz grains, interbedded with thin layers of clay and occasionally sandstone. Gravel commonly occurs in layers in the basal section and ranges in size from boulders to pea size. The gravel is usually associated with sand, silt, and clay and is occasionally cemented. Quartzite is the predominant rock type in the gravel, although a high percentage of limestone boulders and cobbles occur in the southern third of the study area along with weathered Cretaceous invertebrate fossils. The occurrence of limestone gravel and Cretaceous fossils indicate that a local source possibly contributed to the Ogallala sediments in the southern third of the study area.

Basal Ogallala sediments occupy previously eroded drainage valleys and thus are not everywhere present. Grain size and condition of sorting is an indication of the high energy involved-in the depositional process of these sediments. As expected, sand grain and gravel size decreases and sorting improves eastward.

Above the basal segment of initially deposited coarse-grained elastics are fine- to medium-grained, well to poorly sorted sand, silt, clay, marl, and occasional stringers of small gravel. The sand is generally poorly consolidated to unconsolidated, although local cementation by calcium carbonate and silica occurs. These sediments completed filling the valleys and overflowed onto a flat alluvial plain.

Near the surface of much of the Texas High Plains are layers of resistant caliche known as “caprock”. Caliche occurs in both Ogallala and post-Ogallala sediments and is formed by the leaching of carbonate and silica from surface soils and the redeposition of the dissolved minerals in layers below the surface. Although caliche layers occur primarily near the surface, deeper zones of caliche are also present. These deeper layers represent older soil horizons.

Reeves (1970, p. 355) has classified the caliche “calcrete,” profiles as young, mature, and old based on age, physical factors, and chemistry. The caliche ranges from crumbly to very hard and is almost impermeable although secondary porosity has been observed in many samples. Figure 3 (by Ries, 1981) shows the number and classification of calcrete horizons, and Figure 4 shows the thickness of calcrete horizons overlying Ogallala calcrete. The effect of caliche layers on infiltration rates will be discussed in another section.

Thickness of the Ogallala Formation is primarily controlled by the morphology of the eroded pre-Ogallala surface. The greatest Ogallala thickness occurs where sediments have filled previously eroded drainage channels. These channels generally trend east or southeast. Other areas of large Ogallala thickness occur in the northeast quadrant of the Texas High Plains where sediments have filled collapsed basins formed by dissolution of Permian evaporites. Positive structures beneath the Ogallala result in a thinning of the formation and exist where Cretaceous remnants occur in Floyd and Hale Counties. These structures are shown on the elevation of the base of aquifer map, Figure 20, and on the generalized geologic sections, Figures 21 through 27. Thickness of the Ogallala Formation, which is generally greater in the northern part of the study area and thins toward the south as it overlaps Cretaceous rocks, ranges from 0 to approximately 900 feet (0 to 274 m).

Sedimentary Zonation of the Ogallala Formation

The hydraulic properties of the Ogallala aquifer are dependent on its lithology. Therefore, to accurately estimate the future potential and limitation of the Ogallala Formation, it is necessary to possess a thorough knowledge of the distribution of sediments of various types. As the principal investigator of sedimentary zonation, Dr. C. C. Reeves of Texas Tech University provided maps showing percentage distribution and thickness of sand, gravel, basal gravel, and clay. In addition, a sand and gravel to clay ratio map was supplied. Paul H. Buika and Randall K. Smelley, research assistants for Dr. Reeves, produced the following discussion and associated maps concerning sedimentary zonation of the Ogallala Formation south of the Canadian River in Texas and New Mexico.

Method of Study

Water well logs, test hole logs, and measured sections from the outcrops of the Ogallala Formation were studied. The total thickness and percentage of sand, clay, and gravel within the Ogallala section was calculated for each log.

The thickness of the gravel at the base of the Ogallala section as well as total gravel through the entire Ogallala section was determined. The positions of ancient (pre-Ogallala) stream channels were established by examining structural maps of the base of the Ogallala section. Wells located in most channels were excluded when calculating the basal gravel map, but were included in calculating total gravel thickness.

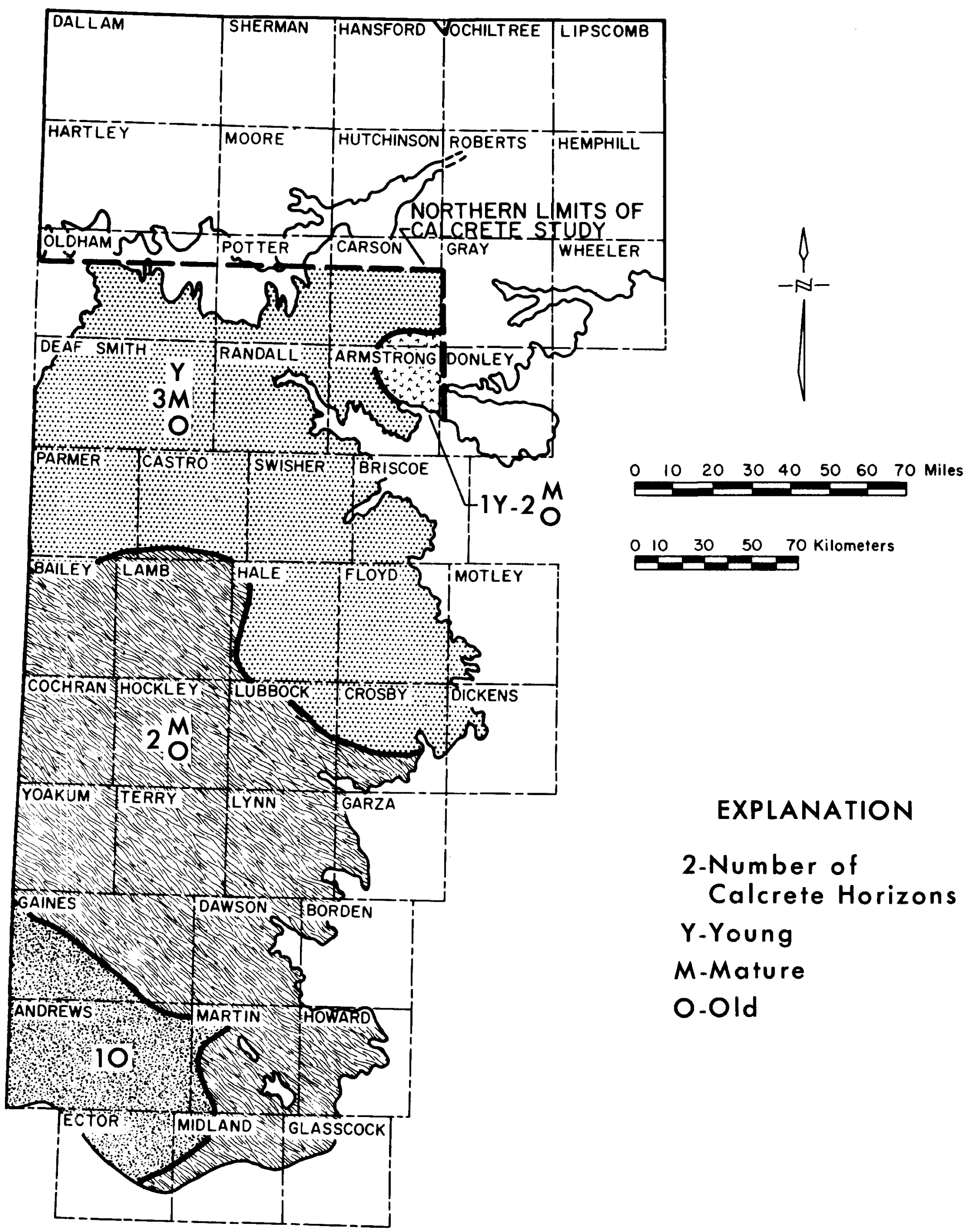


Figure 3

Number and Classification of Calcrete Horizons, Southern High Plains (After Ries, 1981)

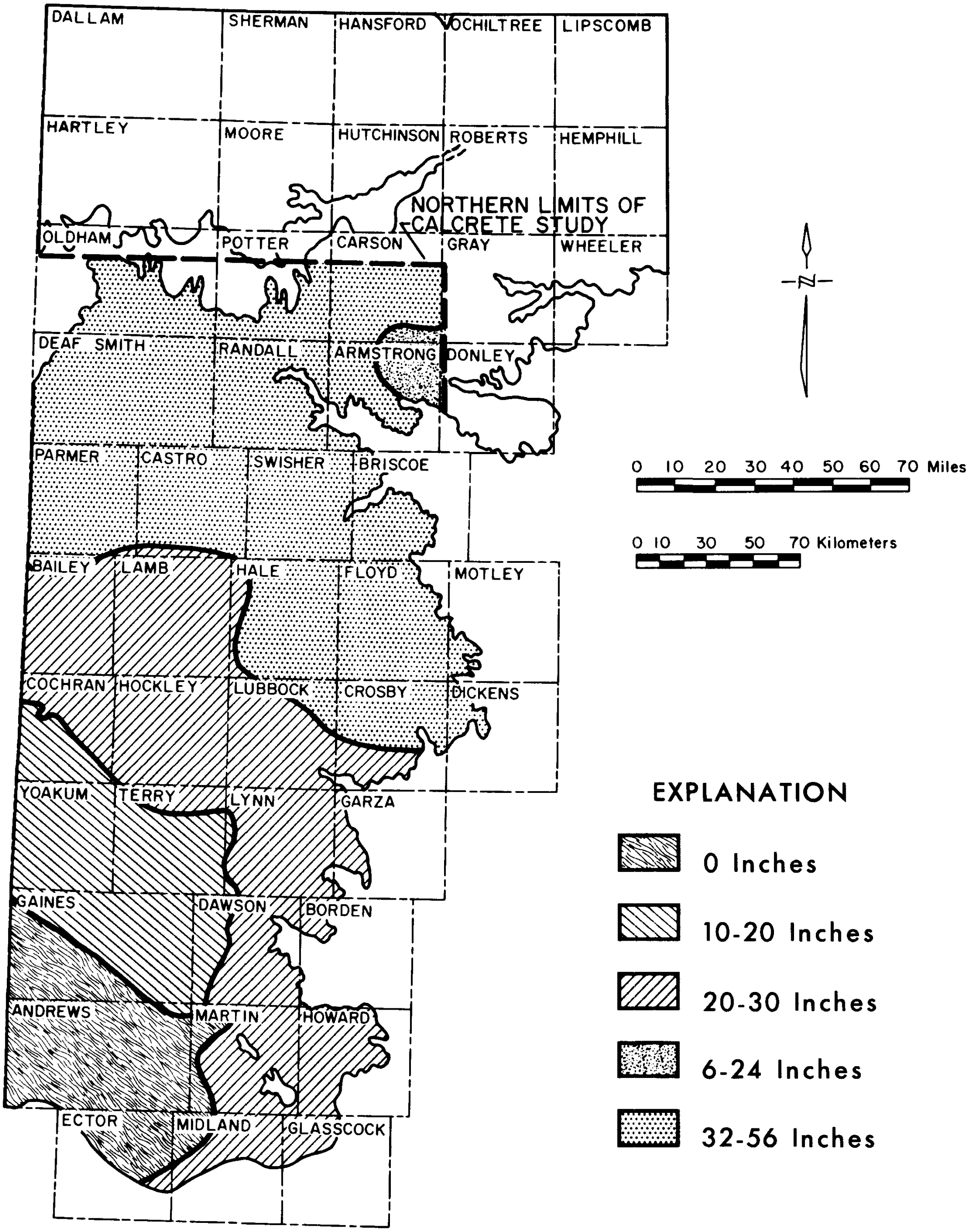


Figure 4

Thickness of Calcrete Horizons
Overlying Ogallala Calcrete
(After Ries, 1981)

Because of inconsistent and vague lithologic descriptions of well logs written by some drillers, certain guidelines were established. Lithologic sections ambiguously described as “rock” were excluded from individual calculations of sand, clay, or gravel thicknesses. “Caliche” was classified as sand, because sand was the parent material in most cases for calcrete development. Sections described as limestone were classified as sand, because limestones in the Ogallala section are principally calcrete. Sections described as “shale” were classified as clay.

A 1O-mile (16-km) square grid was established using the Texas-New Mexico state line as the “base line”. Data were gathered for each grid area, with an approximate well density of no more than 1 square mile (2.6 km^2). Only wells which completely penetrated the Ogallala section were used. The selection of each well log was determined by the completeness of the log and comparison of the log to adjacent wells. Unfortunately, in many grids there was not enough available data to insure representative figures. To eliminate skewness, the highest and lowest values within each grid were dropped if they were considerably higher or lower than most of the other values. The remaining figures were then averaged, and the mean value plotted at the center of each grid.

Sand Distribution

Sand accumulations within the Ogallala section of the Southern High Plains exhibit regional thinning to the southeast (Figures 28 and 29), ranging in thickness from 20 to over 360 feet (6 to over 110 m).

Through most of the Southern High Plains, the percentage of sand within the Ogallala section consistently ranges from 50 to 60 percent. However, due to large amounts of clay in localized areas, sand values (thickness and percent) are low. Sand percentages remain high through the northern part of the Southern High Plains (60 to 90 percent), thinning both to the east and west from Curry County, New Mexico, where sand accumulations comprise over 90 percent of the Ogallala section. Sand percentages increase to the south through Andrews, Dawson, Gaines, and Martin Counties.

Clay Distribution

Clay distribution of the Southern High Plains thickens regionally to the north and northeast. The thickness of the clay ranges from O feet in Lea and Roosevelt Counties, New Mexico, to over 300 feet (91 m) in Carson County (Figure 31) where clay exceeds 50 percent of the total section (Figure 30). Excessive accumulations of reddish to reddish-brown clays indicative of lacustrine lakes are found in Castro, Cochran, Crosby, Dawson, Deaf Smith, Floyd, Hale, Hockley, Lamb, Lea (New Mexico), Parmer, Swisher, Terry, and Yoakum Counties.

Gravel Distribution

Figures 32 and 33 show regional trends of thick gravel accumulations indicative of pre-Ogallala drainage channels where initial Ogallala sediments were deposited. Figure 34 exhibits relatively high basal gravel values extending east-southeastward from Parmer to Floyd County, and from southern Roosevelt (New Mexico) eastward to southern Lubbock County. Basal gravel values from southern Lea County (New Mexico) eastward through Martin County suggest the presence of a minor pre-Ogallala drainage (from relatively thin, but continuous, gravel accumulations in Lea County, New Mexico). However, thick localized gravel accumulations in Martin County combined with lack of sufficient data in Andrews County (Figure 33) discourage the assumption of a drainage system flowing eastward through the southern region of the study area from the Rocky Mountains.

Low gravel values of 0 to 5 feet (O to 1.5 m) through the southwestern (Andrews, Gaines, Lea, and Yoakum Counties) and northern (Deaf Smith, Oldham, Potter, and Randall Counties) regions of the Southern High Plains represent broad upland areas lying between pre-Ogallala drainage systems. Thin gravel accumulations are also present in Briscoe, Howard, Lynn, and Swisher Counties.

Gravel thickness diminishes to less than 5 feet (1.5 m) in the northwest corner of the Southern High Plains (Quay County, New Mexico). An anomalous high value in southwestern Quay County, New Mexico, indicates the presence of either a pre-Ogallala drainage system or a sink filling. The gravel distribution within Carson County exhibits a wedge which thickens to the northeast (Figure 33). Inconsistent values calculated within Carson County are attributed to numerous logs which show high thicknesses of basal gravel. This anomaly may indicate an ancient drainage channel which flowed eastward from the Rocky Mountains north of the sedimentary zonation study area, a northeast source supplying sediment to the Southern High Plains, or a complex of sink fills. A gravel wedge thickening to the west in southern Roosevelt County, New Mexico, is related to initial Ogallala sediments deposited in a pre-Ogallala drainage channel. Thick gravel accumulations within the Slaton Channel are prominent through southern Lubbock and northern Lynn Counties.

Figure 32 shows gravel comprising from 5 to 10 percent of the Ogallala section in the central Southern High Plains. High percentage values in the western region (Roosevelt and Lea Counties, New Mexico) are evidence of pre-Ogallala drainage.

Ratio of Sand and Gravel to Clay

Attempts to recharge the aquifer will be more favorable in areas which contain high percentages of permeable and porous sediments. The peripheral distance that recharged water will flow through an aquifer from an isolated recharge site is principally dependent on permeability of the rock, while storage capacity of the aquifer is controlled by porosity. Therefore, the average ratio of sand and gravel (high permeability) to clay (low permeability) within the Ogallala section was determined for each grid based on percentage values.

Figure 35 shows that the ratio of sand and gravel to clay is between 1 and 4 for most of the central Southern High Plains. The ratio increases sharply (up to 100) along the western Southern High Plains (Curry, Lea, Quay, and Roosevelt Counties) as a result of thick channel gravels (Figures 32,33, and 34). The ratio remains high (4 to 10) through the northern region (Deaf Smith, Parmer, and Randall Counties), but drops considerably to the east in Carson County where thick accumulations of clay occur (Figures 30, 31, and 35). Moderately high values (4 to 6) are found throughout the southern region of the study area (Andrews, Dawson, Gaines, Martin, and Yoakum Counties).

Conclusions

Conclusions inferred from the percentage distribution, thickness, and ratio maps (Figures 29 through 35) are as follows:

1. Sand accumulations in the Ogallala section of the Southern High Plains range from 20 to over 360 feet (6 to over 110 m), or 20 to 100 percent, regionally thinning to the southeast.

2. Clay thicknesses in the Ogallala section range from 0 to over 300 feet (0 to over 90 m), or 50 percent, regionally thickening to the north and northeast.

3. Local, thick clay accumulations scattered throughout the study area suggest the possibility of several Ogallala-age lake basins.

4. Gravel accumulations in the Ogallala section (excluding basal gravel) are thin and discontinuous—0 to 20 feet (0 to 6 m), or 0 to 10 percent. Gravel accumulations in suspected sinks or channels show higher values of 20 to 100 feet (6 to 30 m), or 15 to 30 percent.

5. Basal interformational gravels in the Ogallala section reveal two major stream systems flowing east-southeastward from the southern Rocky Mountains and entering the High Plains in New Mexico.

6. Gravel accumulations in Carson County, Texas, and in the southern region of the study area (Lea County in New Mexico and Andrews and Martin Counties in Texas) suggest the possibility of additional channels supplying sediment to the Southern High Plains.

7. The majority of sand and gravel to clay ratio values range from 1 to 4 for most of the study area, with higher values (up to 100) in the western (New Mexico counties) and northern regions (Deaf Smith, Randall, and Parmer Counties) of the Southern High Plains.

Post-Ogallala Rocks

Post-Ogallala sediments consist of windblown sand and silt, alluvium, and playa lake deposits. Windblown sands occupy the largest surface area of the High Plains of Texas and are of both Pleistocene and Recent (Holocene) age. They are primarily fine-grained to silty, sometimes calcareous, and are derived from lacustrine, fluvial, and eolian deposits. These sands and silts form sheet or cover sand, dunes, and dune ridges with thicknesses generally ranging from 0 to 10 feet (0 to 3 m).

Alluvium is present as fluvial floodplain and terrace sediments along the more active streams and rivers. The deposits consist of poorly sorted, often cross-bedded, gravel, sand, and silt.

Lacustrine deposits, consisting primarily of clay and silt, line the bottom of the many playa lakes on the High Plains. The sediments are virtually impermeable, thus restricting natural recharge to the underlying formation.

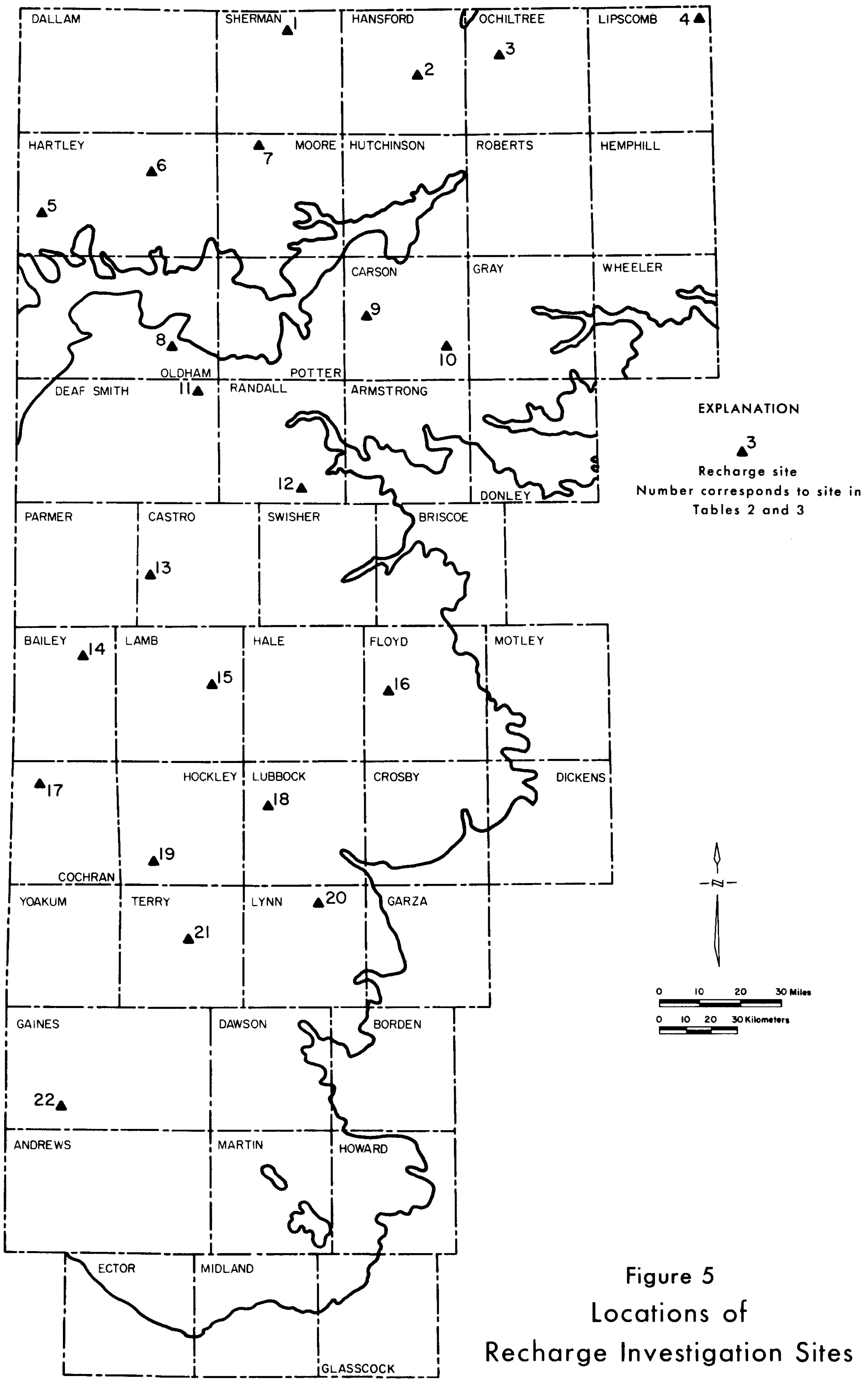


Figure 5
Locations of
Recharge Investigation Sites

Base adapted from U.S. Geological Survey, 1965

THE HIGH PLAINS AQUIFER

Recharge, Discharge, and Movement

Recharge to the High Plains aquifer occurs principally by infiltration of precipitation on the outcrop. 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 low infiltration rate.

A study conducted by the Department (Klemt, 1981), in which measurements were made of the rate of moisture infiltration at 22 locations (Figure 5), indicated that an average of less than 0.2 inch (0.5 cm) of water per year reaches the water table as natural recharge. This rate is variable and is influenced by climate, vegetative cover, soil type, and clay or caliche aquicludes. Tables 2 and 3 list the results of neutron moisture log analysis at irrigated and dryland sites. The infiltration study indicated that, due to the slow rate of deep percolation, irrigation water has probably not had sufficient time to reach the water table in most areas of the High Plains. Fields that had been irrigated 25 years or more showed evidence of deep percolation only to depths ranging from 20 to 30 feet (6 to 9 m), although sites in Carson, Gaines, and Terry Counties indicate wetting fronts that have advanced to depths greater than 30 feet (9 m).

Table 2

Results of Neutron Moisture Log Analysis at Irrigated Sites

Site	Depth of wetting (ft below land surface)	Wetting front infiltration rate (ft/yr)	Moisture gain or loss above wetting front (percent)	Estimated percolation (inches/yr)	Percolation as a percent of irrigation water applied (percent)
1	5.0	2.5	7.8	2.3	38.3
2	23.2	1.0	8.5	1.0	10.0
3	10.2	.6	7.7	.6	5.0
4	30.0	2.3	12.4	3.4	28.3
5	17.5	3.5	8.0	3.3	41.3
6	—	—	—	—	—
7	29.0	2.1	7.7	1.9	10.5
8	21.9	2.2	3.8	1.0	12.5
9	>30.0	2.0*	10.3**	2.5	41.7
10	14.8	.7	4.8	.4	20.0
11	28.5	1.2	9.0	1.3	8.1
12	4.8	1.6	1.8	.3	1.5
13	27.6	.8	5.3	.5	3.1
14	9.6	2.4	5.2	1.5	12.5
15	8.7	8.7	10.5	11.0	39.3

See footnotes at end of table.

Table 2

Results of Neutron Moisture Log Analysis at Irrigated Sites—Continued

Site	Depth of wetting (ft below land surface)	Wetting front infiltration rate (ft/yr)	Moisture gain or loss above wetting front (percent)	Estimated percolation (inches/yr)	Percolation as a percent of irrigation water applied (percent)
16	22.4	1.9	9.6	2.2	7.9
17	22.6	.9	3.8	.4	13.3
18	11.8	1.3	3.4	.5	6.3
19	29.3	1.2	2.4	.3	2.5
20	>30.0	2.0*	4.3**	1.0	25.0
21	>30.0	2.2*	3.4**	.9	7.5
22	27.9	1.7	2.6	.5	8.3

*Estimated wetting front infiltration rate
**Moisture loss determined from weekly logs for the 10- to 29-foot interval

Table 3

Results of Neutron Moisture Log Analysis at Dryland (Cultivated or Grassland) Sites

Site	Estimated infiltration rate (ft/yr)	Percent moisture change (10-29 ft)	Estimated total recharge (inches)	Recharge as percent of normal annual rainfall
1	0.50	3.7	0.2	1.0
2	.25	2.1	.1	.5
3	.25	4.9	.2	1.0
4	.50	.0	—	—
5	.50	2.6	.2	1.2
6	.25	.0	—	—
7	.50	.0	—	—
8	.50	5.9	.3	1.6
9	.25	3.6	.1	.5
10	.25	6.2	.2	1.0
11	.25	5.5	.2	1.0
12	.25	6.3	.2	1.0
13	.25	2.3	.1	.6
14	.50	2.9	.2	1.1

Table 3

Results of Neutron Moisture Log Analysis at Dryland (Cultivated or Grassland) Sites—Continued

Site	Estimated infiltration rate (ft/yr)	Percent moisture change (10-29 ft)	Estimated total recharge (inches)	Recharge as percent of normal annual rainfall
15	.50	3.7	.2	1.0
16	.25	.0	—	—
17	.50	2.1	.1	.6
18	.50	3.4	.2	1.0
19	.50	2.1	.1	.6
20	.50	3.3	.2	1.1
21	.50	1.8	.1	.6
22	.50	3.3	.2	1.4

For modeling purposes, the study area was delineated into six recharge zones (Figure 6) based on soil type and topography. Values assigned to these zones ranged from a maximum of 0.83 inch (2 cm) per year in the "sand hills" area of Bailey and Lamb Counties, to a minimum of 0.06 inch (0.15 cm) per year over areas of the central and north-central High Plains where Pullman clay is the predominate soil type. Based on these values, the total annual recharge to the High Plains aquifer is 371,910 acre-feet (459 hm^3).

Only a small portion of the 14 to 23 inches (36 to 58 cm) of average annual rainfall drains into the streams that traverse the plateau. Most of the precipitation drains into numerous shallow playa lakes that occur on the surface of the High Plains. The silt and clay bottom of the lakes and ponds is practically impermeable, restricting infiltration of the trapped water into the formation, although when the playa lakes are filled to capacity, more infiltration probably occurs around the edges where silt and clay may not have accumulated.

Recharge by infiltration is greatly hampered by the presence of caliche layers near the surface. Ries (1981) found that permeability and porosity of caliche, "calcrete," layers in the High Plains decreased with age due to increased induration. Average permeability of samples examined ranged from 0 to 3.26 inches (0-8.28 cm) per hour. Porosity was found to be almost entirely secondary.

Several studies have been conducted to determine the feasibility of artifically recharging the High Plains aquifer. Artificial recharge methods fall into two categories: (1) vertical recharge through surface spreading, and (2) lateral recharge through injection wells.

The primary constraint encountered when attempting recharge through surface spreading is the blockage of downward movement by impermeable layers of cemented calcium carbonate, or "caliche", located near the surface. This constraint can be overcome by excavating through these layers to form open pits or basins (Aronovici and others , 1970). Suspended matter in the water to be recharged will eventually form an impermeable layer on the bottom which can periodically be scraped off. Best locations for artificial recharge by surface spreading are in areas where

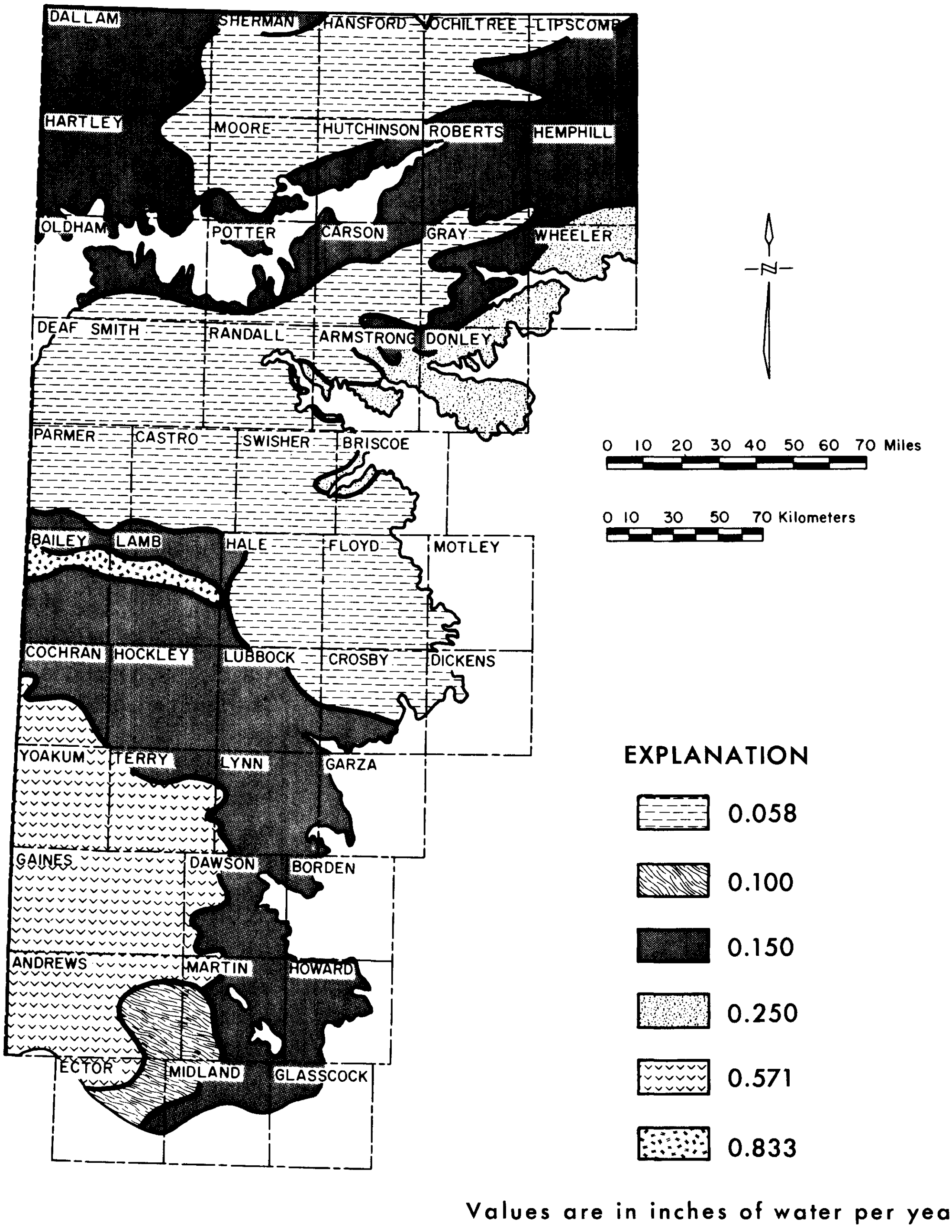


Figure 6
Values of Average Recharge for Model Application

permeable sands are near the surface and few caliche layers occur. In some areas water recharged by this method may form only perched water layers which may rapidly dissipate laterally.

Artificial recharge of water to the aquifer through injection wells has been attempted with varying success. This procedure usually requires the use of sediment free water in order to prevent clogging of the formation. Injection wells that have been rendered ineffective due to clogging can often be rejuvenated by pumping the well for a short period in order to free the formation of the clogging agent. Injection under pressure has also proven to be successful in overcoming clogging (Johnson, 1970).

The water used in the artificial recharge procedures is usually excess water, or tail water, from irrigation or meteoric water in playa lakes. In either case, these waters are usually sediment laden, rendering them undesirable for recharge use. A flocculant, such as aluminum sulfate or alum, added to the water causes the fine particles suspended in the water to aggregate and sink to the bottom of the reservoir. The relatively sediment free water, with greater recharge capability, can then be pumped into spreading basins or injection wells (Brown and others, 1978).

Although artificial recharge by surface spreading and injection has proven to be feasible, the affected area is generally small. Thus, the most beneficial use of artificial recharge may be as a procedure for temporary storage of water underground.

Discharge of ground water from the High Plains aquifer occurs naturally through seeps and springs and artificially through wells. The quantity of water naturally discharged is minimal and primarily occurs along both the eastern escarpment and the Canadian River.

Historically, springs have played an active role in the development of the High Plains. Prior to the 20th century, springs afforded essentially the only permanent supply of surface water in the region. Human activity thus centered around them and primary transportation routes were developed between them. Brune (1975) lists the major and historical springs in the study area. Before irrigation pumpage began removing ground water from storage, the aquifer was in dynamic equilibrium. Spring flow was approximately equivalent to average recharge. Large-scale irrigation practices have lowered the ground-water level to such an extent that few springs of appreciable size now exist. Spring flows into the Canadian River are so small that evaporation generally occurs before they can accumulate as base flow in the river.

Artificial discharge from the High Plains aquifer by well pumpage far exceeds recharge, resulting in the withdrawal of water held in storage. Pumpage on the Texas High Plains can be divided into three categories: (1) irrigation, (2) municipal and industrial, and (3) domestic and livestock. Historical pumpage and its effect on the High Plains aquifer are discussed in another section.

Ground water in the High Plains aquifer moves laterally down the hydraulic gradient with a direction of flow normally at right angles to the contours of the static water-level map (Figure 40) in the direction of decreasing altitude. North of the Canadian River, movement is toward the east while south of the river, movement is toward the east-southeast. In the vicinity of the Canadian River, movement is deflected toward the river, especially in Hemphill and Roberts Counties, and toward Wolf Creek in eastern Lipscomb County. The gradient of the water-level surface ranges from 5 to 50 feet per mile (1 to 9 m/km) with an average of approximately 15 feet per mile (3 m/km). The rate of movement is approximately 7 inches (18 cm) per day.

Ground-water movement is locally affected by pumpage. When a well is pumped, the water level is drawn down in the vicinity of the well, forming a cone of depression. The areal extent of this cone is dependent on rate and duration of pumpage, thickness of saturated strata above the pumping level, and the geohydiologic characteristics of the aquifer. The cone of depression formed by a pumping well or wells will change the hydraulic gradient within the influence of the cone, thus altering the rate and direction of movement.

Movement of ground water in the High Plains aquifer is also influenced by subsurface depositional environments. Buried drainage channels located throughout the study area provide passageways along which ground water more readily flows due to the higher permeability of the sediments filling the channels. These channels can be identified as basal troughs on the elevation of the base of aquifer map (Figure 20).

Hydraulic Characteristics

Results of Test Hole Core Analysis

The hydraulic characteristics of the High Plains aquifer were studied during an extensive test hole drilling project that was conducted by the Department (Ashworth, 1980). Cores retrieved from 41 test holes (Figure 7) were analyzed for porosity, specific yield, permeability, and grain-size distribution. Laboratory analyses were conducted on cores taken from the saturated zone, and therefore, the following results should not be considered indicative of the entire formational thickness.

The core analyses indicate that transmissivities range from 315 to 201,000 gallons per day per foot [3,910 to 2.496 million (l/d)/m], with an overall average of 30,400 (gal/d)/ft [377,500 (l/d)/m]; permeabilities range from 22 to 1,934 gallons per day per square foot [900 to 78,800 (l/d)/m^2], with an overall average of 232 (gal/d)/ft^2 [9,450 (l/d)/m^2]; and specific yield ranges from 7.23 to 19.54 percent, with an overall average of 16.06 percent. Figure 8 shows the relationship between porosity and specific yield as determined from the test cores.

A statistical analysis of data was undertaken to determine the weighted mean position or center of gravity (first moment), and the average dispersion or standard deviation (second moment) of transmissivity and specific yield throughout the saturated thickness of each test hole. The calculations indicate that the center of gravity occurs about midway in the saturated interval, and the standard deviation indicates a lack of concentration about the center of gravity. The results of these calculations for each test hole are shown in Table 4. Permeability and specific yield thus appear to be evenly distributed throughout the saturated zone.

Permeability versus depth for each test hole was plotted in an attempt to determine if permeability would increase with depth at a predictable rate as does median grain size over most of the study area. No predictable slope to the plots could be ascertained. An explanation for this lack of trend probably lies in the mode of deposition of the Ogallala. The initial deposits, composed of gravel and coarse sands and often intermixed with silts and clays, represent a high energy environment in which poor sorting, and thus retarded permeability, prevails. Sorting conditions generally improve upward in the formation along with decreasing grain size as a result of less energy involvement in deposition. No clear relationship enfolded between permeability and depth within the Ogallala Formation.

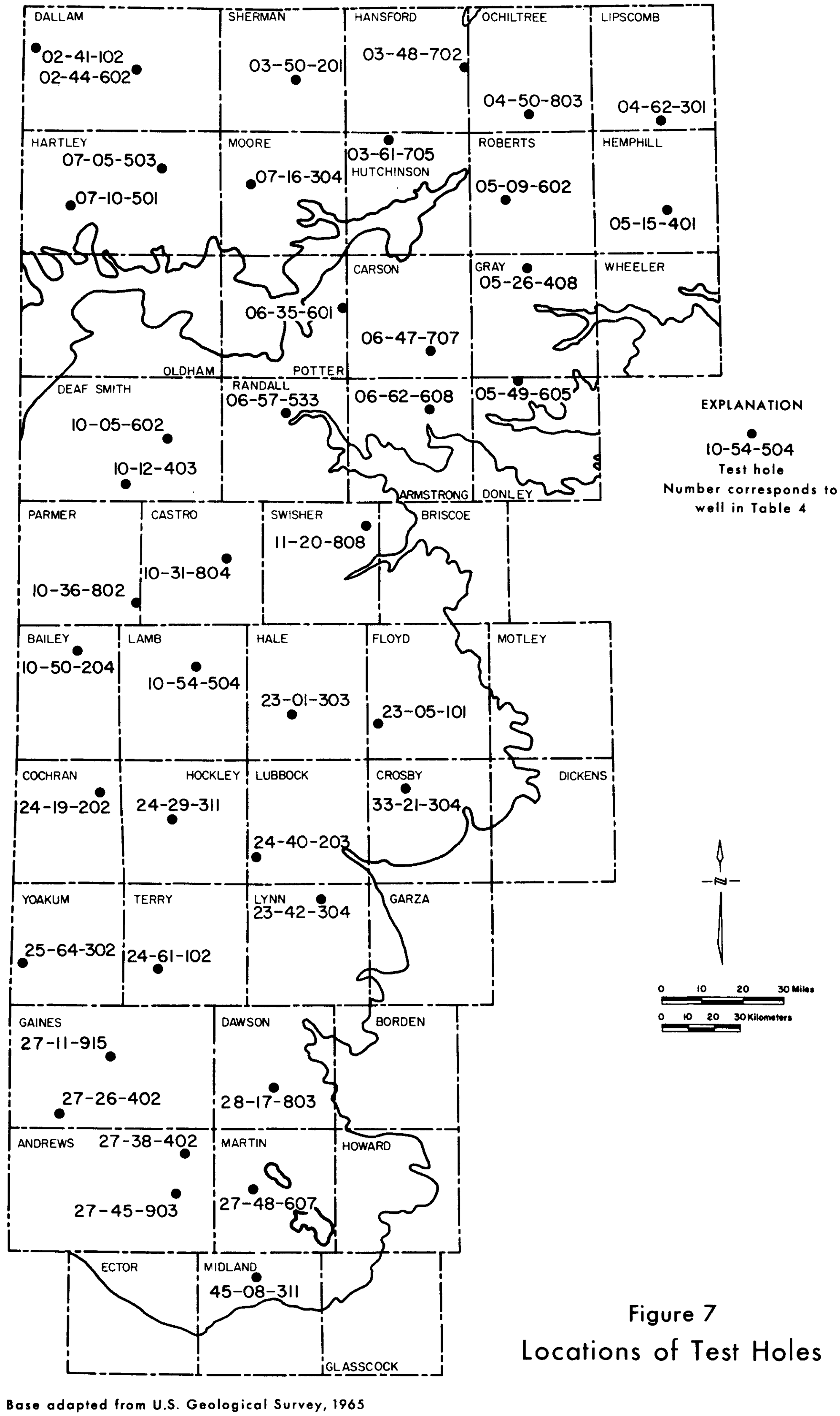


Figure 7
Locations of Test Holes

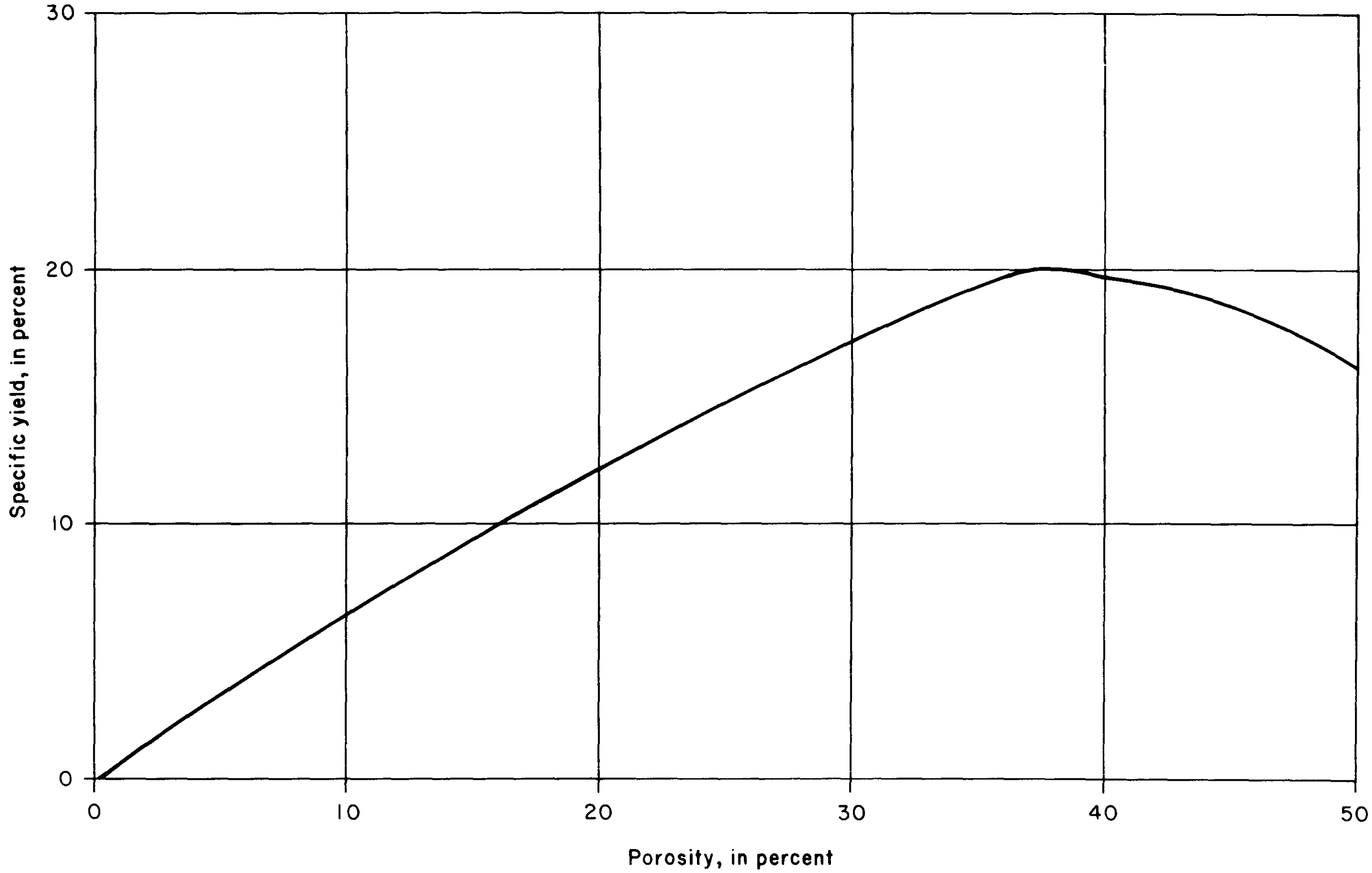


Figure 8

Specific Yield and Porosity From High Plains Aquifer Cores

The primary environment of deposition was determined for the saturated zone of each test hole based on lithologic description, characteristic geophysical log curves, and results of laboratory testing of samples. Four distinct lithofacies were identified, consisting of sediments from the following environments: (a) fluvial channel, (b) interdistributary, (c) frontal fan slope, and (d) distributary mouth. The fluvial channel and distributary mouth lithofacies characteristically have higher specific yields than the other lithofacies. Additionally, it has been noted that, due to a wide range of median grain size (D_{50}) and sorting values, the fluvial channel deposits have a much greater range of permeability than the other lithofacies. Figure 9 shows the range in permeability and specific yield in each of the four lithofacies.

Results of Surface Electrical Resistivity Surveys

As part of the High Plains aquifer study, the Department conducted surface electrical resistivity soundings (Muller, 1980) in selected areas of the Texas High Plains (Figure 10). A primary reason for utilizing vertical electrical soundings (VES) was to determine the geographical variation in the High Plains aquifer's hydrologic properties based on differences in geoelectrical parameters.

An interpretation of resistivity data collected in the field is summarized in Table 5. The apparent formation factor (F_a) and formation or aquifer resistivity (R_o) of the water-bearing sediments of the High Plains aquifer are a function of the relative proportions of clay, sand, and gravel particles and the quality of the interstitial water. An increase in the clay or silt content in the aquifer causes a decrease in the formation or aquifer resistivity providing the resistivity of the interstitial water remains constant. The apparent formation factor also decreases with an increase in clay content. As the clay or silt content in the stratigraphic sediments of the aquifer increases, intergranular permeability and effective porosity, or specific yield, decrease. Therefore, variations in the hydrologic properties or lithology of the stratigraphic sediments due to different clay or silt content can be qualitatively represented by the geophysical parameters of apparent formation factor and formation or aquifer resistivity.

Figures 11 and 12 were constructed to show the lateral variation in formation factors and formation or aquifer resistivities, respectively. These figures also indicate variations in lithofacies within the High Plains aquifer, as the properties mapped generally have an inverse relationship to clay or silt content. The areas of best permeabilities and specific yields (and lowest clay content) are indicated by the highest apparent formation factors and formation or aquifer resistivities.

Specific Yield and Permeability Distribution

Two primary physical characteristics of the High Plains aquifer that were studied are specific yield and permeability. Specific yield is the ratio of the volume of water a given mass of saturated rock will yield by gravity to the volume of that mass and is expressed as a percentage.

Permeability is the property or capacity of a rock for transmitting water without impairment to the structure of the medium and is expressed as the rate of flow in gallons per day through a cross section of one square foot under a unit hydraulic gradient, at the prevailing temperature.

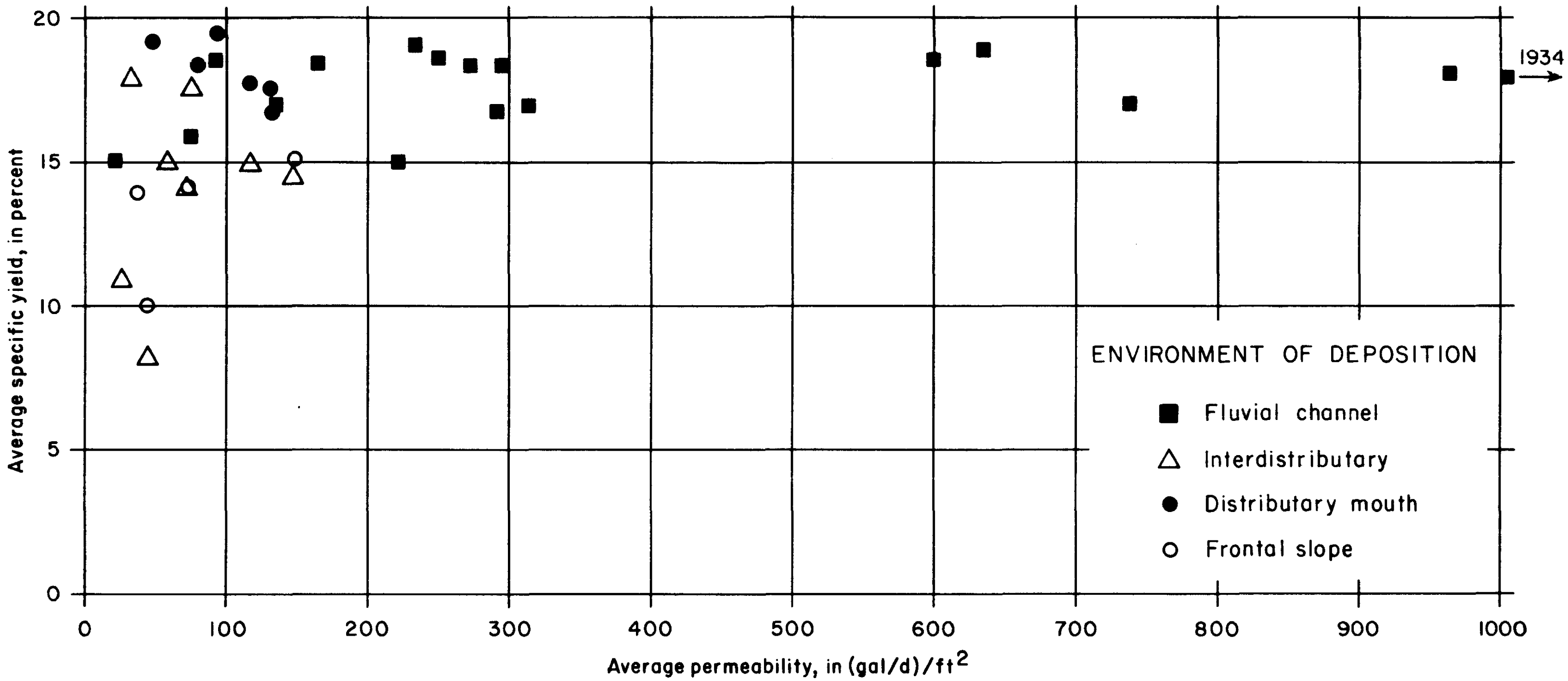
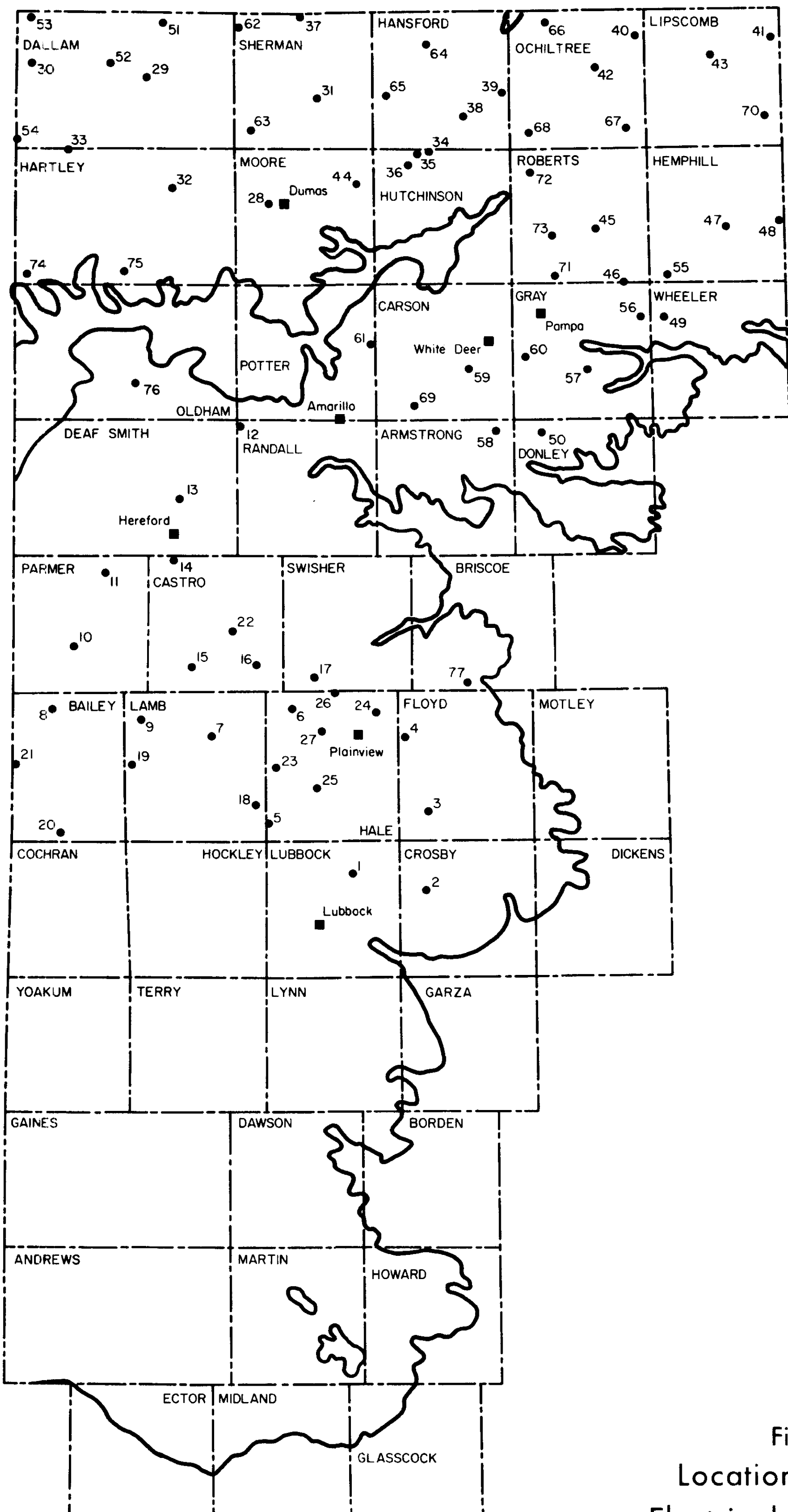


Figure 9
Distribution of Average Specific Yield and Permeability of the Four Lithofacies



EXPLANATION

•38
Sounding site
Number denotes the order in which soundings were conducted
Consult Table 5 for specific data

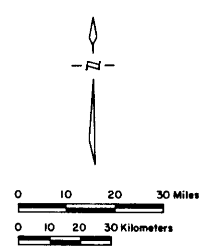


Figure 10
Locations of Vertical Electrical Sounding Sites

Base adapted from U.S. Geological Survey, 1965

Table 5.—Summary Data Derived From Vertical Electrical Sounding Surveys

VES site	County	Date	Elevation (ft)	Longitude (deg.	min.)	Latitude (deg.	min.)	Approximate altitude of base of Ogallala Formation (ft)	Aquifer thickness (ft)	Resistivity of ground water at 77 °F (R_w) (ohm-meters)	Resistivity of aquifer at 77 °F (R_o) (ohm-meters)	Apparent formation factor (F_a)
1	Lubbock	Oct. 19, 1978	3,259	101	44	33	44	2,954	100	16.67	29.47	1.77
2	Crosby	Oct. 21, 1978	3,140	101	28	33	40	2,775	230	15.72	29.47	1.87
3	Floyd	Nov. 2, 1978	3,203	101	21	33	55	2,770	188	14.20	40.19	2.83
4	Floyd	Nov. 3, 1978	3,300	101	32	34	11	2,920	178	11.79	58.94	5.00
5	Hale	Nov. 7, 1978	3,460	102	05	33	54	3,180	115	7.89	33.40	4.24
6	Hale	Nov. 8, 1978	3,580	101	59	34	16	3,291	100	12.55	71.44	5.69
7	Lamb	Nov. 18, 1978	3,651	102	18	34	11	3,350	178	14.97	29.07	1.94
8	Bailey	do	3,900	102	55	34	16	3,705	80	11.19	48.46	4.33
9	Lamb	Nov. 19, 1978	3,750	102	13	34	13	3,549	120	11.19	26.07	2.33
10	Parmer	Nov. 20, 1978	4,050	102	48	34	27	3,620	133	17.01	80.37	4.72
11	Parmer	Nov. 29, 1978	4,050	102	42	34	43	3,525	250	16.25	61.62	3.84
12	Randall	Nov. 30, 1978	3,864	102	10	35	10	3,498	108	16.95	75.01	4.43
13	Deaf Smith	Dec. 1, 1978	3,873	102	23	34	56	3,477	205	15.70	45.81	2.92
14	Castro	Dec. 2, 1978	3,880	102	25	34	44	3,515	147	16.95	58.05	3.42
15	Castro	Dec. 3, 1978	3,773	102	22	34	24	3,373	214	17.95	48.46	2.70
16	Castro	Dec. 4, 1978	3,680	102	06	34	25	3,300	156	15.75	53.58	3.40
17	Swisher	Dec. 5, 1978	3,565	101	52	34	21	3,223	110	15.23	36.61	2.40
18	Lamb	May 16, 1979	3,506	102	07	33	56	3,216	144	9.85	28.58	2.90
19	Lamb	May 23, 1979	3,850	102	35	34	04	3,640	108	11.04	26.79	2.43
20	Bailey	May 22, 1979	3,842	102	51	33	52	3,705	35	15.63	44.65	2.86
21	Bailey	do	3,840	103	02	34	04	3,700	45	4.63	10.72	2.31
22	Castro	May 23, 1979	3,783	102	12	34	30	3,388	135	14.73	62.51	4.24
23	Hale	May 24, 1979	3,495	102	02	34	03	3,150	193	12.30	40.19	3.27
24	Hale	May 29, 1979	3,360	101	39	34	15	3,014	175	14.06	35.72	2.54
25	Hale	May 30, 1979	3,410	101	54	34	01	3,060	160	14.79	49.12	3.32
26	Hale	do	3,500	101	48	34	18	3,150	150	15.65	40.19	2.57
27	Hale	June 27, 1979	3,465	101	52	34	12	3,130	147	15.08	26.79	1.78
28	Moore	June 29, 1979	3,625	102	07	36	03	2,937	375	15.43	22.33	1.45
29	Dallam	July 10, 1979	4,125	102	32	36	17	3,678	126	22.78	49.12	2.16
30[1]	Dallam	July 11, 1979	4,580	102	59	36	20	4,300	185	16.56	16.90	1.02
31	Sherman	July 16, 1979	3,505	101	49	36	13	3,005	287	20.20	24.11	1.19

See footnotes at end of table.

Table 5.—Summary Data Derived From Vertical Electrical Sounding Surveys—Continued

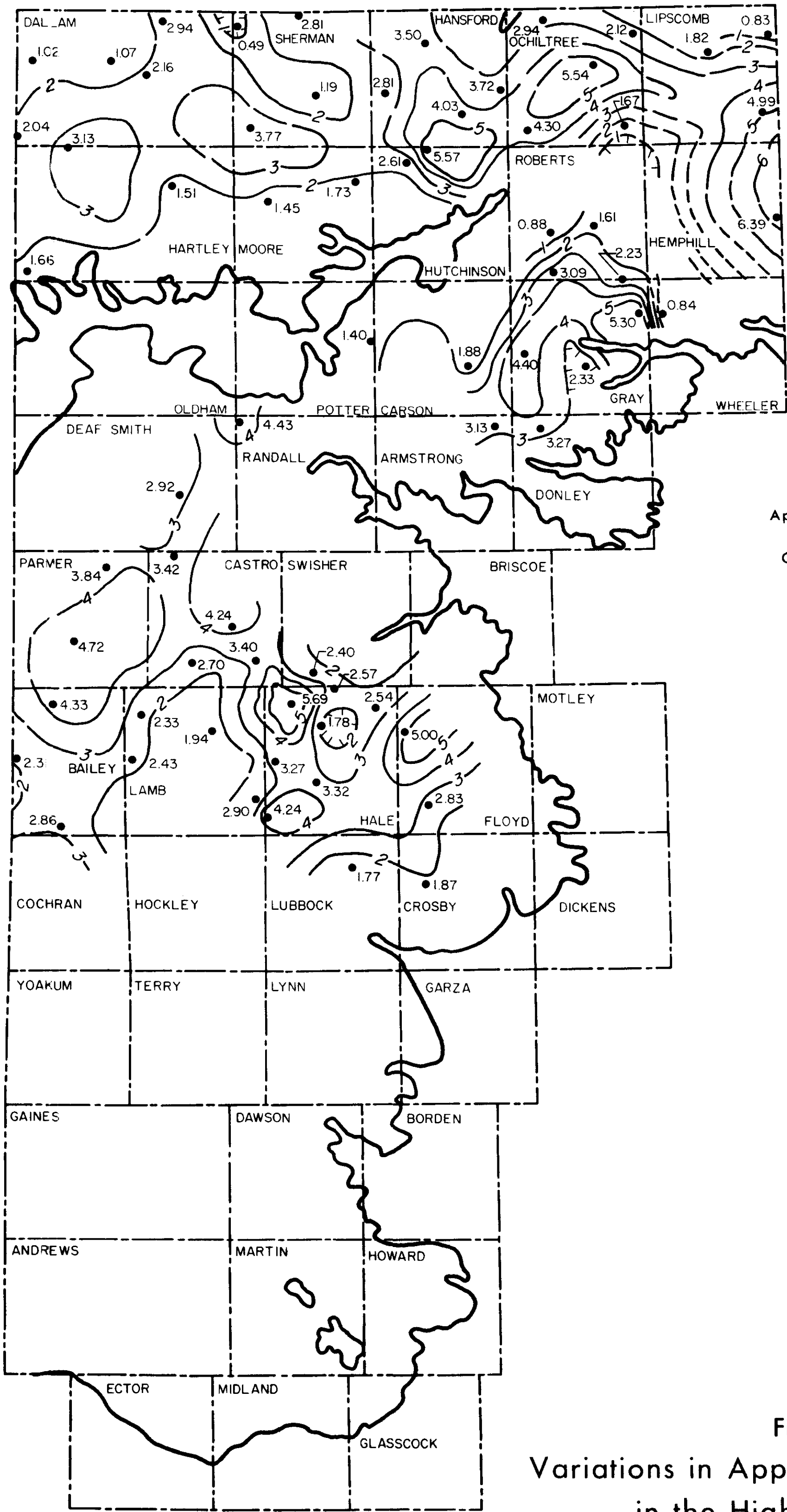
VES site	County	Date	Elevation (ft)	Longitude (deg.	min.)	Latitude (deg.	min.)	Approximate altitude of base of Ogallala Formation (ft)	Aquifer thickness (ft)	Resistivity of ground water at 77 °F (R_w) (ohm-meters)	Resistivity of aquifer at 77 °F (R_o) (ohm-meters)	Apparent formation factor (F_a)
32	Hartley	July 17, 1979	3,940	102	25	35	55	3,475	85	17.54	26.43	1.51
33	Hartley	July 18, 1979	4,330	102	50	36	03	3,851	280	20.00	62.51	3.13
34[2]	Hutchinson	July 24, 1979	3,220	101	25	36	03	2,840	180	21.65	120.56	5.57
35[2,3]	Hutchinson	July 25, 1979	3,195	101	27	36	02	2,870	225	22.22	24.11	1.09
36	Hutchinson	July 26, 1979	3,235	101	29	36	00	2,875	180	22.22	58.05	2.61
37	Sherman	July 31, 1979	3,485	101	54	36	30	3,150	145	17.01	47.80	2.81
38[2]	Hansford	Aug. 1, 1979	3,150	101	16	36	08	2,724	215	16.37	66.04	4.03
39	Hansford	Aug. 7, 1979	3,085	101	07	36	15	2,310	425	15.60	58.05	3.72
40	Ochiltree	Aug. 8, 1979	2,875	100	33	36	25	2,395	250	11.36	24.11	2.12
41	Lipscomb	Aug. 9, 1979	2,490	100	02	36	24	2,190	280	15.36	12.68	.83
42	Ochiltree	Aug. 10, 1979	2,910	100	45	36	20	2,335	275	9.09	50.40	5.54
43	Lipscomb	Aug. 11, 1979	2,720	100	17	36	22	2,310	246	15.67	28.58	1.82
44	Moore	Aug. 12, 1979	3,360	101	41	35	56	2,894	220	23.26	40.19	1.73
45	Roberts	Aug. 20, 1979	3,010	100	45	35	47	2,485	225	20.00	32.15	1.61
46	Roberts	Aug. 21, 1979	3,050	100	39	35	37	2,500	250	20.00	44.65	2.23
47[3]	Hemphill	Aug. 22, 1979	2,575	100	14	35	47	2,260	125	23.81	4.47	.19
48	Hemphill	Aug. 23, 1979	2,430	100	01	35	49	2,230	50	15.38	98.23	6.39
49	Wheeler	Aug. 24, 1979	2,700	100	29	35	31	2,600	50	25.51	21.43	.84
50	Donley	Aug. 25, 1979	3,205	100	58	35	10	2,700	200	24.57	80.37	3.27
51[1,2]	Dallam	Sept. 5, 1979	4,090	102	28	36	28	3,926	65	14.35	42.25	2.94
52[1,2]	Dallam	Sept. 6, 1979	4,225	102	40	36	20	4,071	20	16.61	17.75	1.07
53[1,2]	Dallam	Sept. 19, 1979	4,705	102	59	36	28	4,687	—	24.39	—	—
54[2]	Dallam	Sept. 20, 1979	4,505	103	02	36	03	4,095	—	23.64	48.22	2.04
55[2]	Hemphill	Sept. 24, 1979	2,905	100	29	35	38	2,183	—	—	—	—
56[2]	Gray	Sept. 25, 1979	2,800	100	34	35	30	2,500	200	18.55	98.23	5.30
57[2]	Gray	Sept. 26, 1979	3,005	100	48	35	19	2,687	30	27.62	64.30	2.33
58[2]	Armstrong	Sept. 27, 1979	3,100	101	10	35	09	2,850	100	20.00	62.51	3.13
59	Carson	Oct. 2, 1979	3,350	101	17	35	20	2,820	200	19.92	37.51	1.88
60	Gray	Oct. 3, 1979	3,300	101	03	35	23	2,775	175	18.87	83.05	4.40
61	Potter	Oct. 4, 1979	3,500	101	38	35	25	2,900	150	23.53	33.04	1.40
62	Sherman	Oct. 10, 1979	3,785	102	09	36	27	3,350	150	18.05	8.93	.49

See footnotes at end of table.

Table 5.—Summary Data Derived From Vertical Electrical Sounding Surveys—Continued

VES site	County	Date	Elevation (ft)	Longitude (deg.	min.)	Latitude (deg.	min.)	Approximate altitude of base of Ogallala Formation (ft)	Aquifer thickness (ft)	Resistivity of ground water at 77 °F (R_w) (ohm-meters)	Resistivity of aquifer at 77 °F (R_o) (ohm-meters)	Apparent formation factor (F_a)
63	Sherman	Oct. 11, 1979	3,700	102	06	36	09	3,190	250	18.94	71.44	3.77
64	Hansford	Oct. 12, 1979	3,200	101	25	36	24	3,200	200	18.87	66.08	3.50
65	Hansford	Oct. 16, 1979	3,355	101	33	36	13	2,865	285	18.73	52.69	2.81
66	Ochiltree	Oct. 17, 1979	2,950	100	58	36	28	2,550	225	15.20	44.65	2.94
67	Ochiltree	Oct. 18, 1979	2,850	101	38	36	06	2,255	375	18.66	31.26	1.67
68	Ochiltree	Oct. 19, 1979	3,095	101	01	36	06	2,505	200	11.43	49.12	4.30
69[3]	Carson	Oct. 20, 1979	3,460	101	19	35	14	3,015	125	20.20	205.39	10.17
70[2]	Lipscomb	Oct. 24, 1979	2,610	100	03	36	09	2,240	210	13.23	66.08	4.99
71	Roberts	Oct. 25, 1979	3,205	100	54	35	39	2,545	240	20.20	62.51	3.09
72[2]	Roberts	do	2,700	101	01	35	59	2,525	125	—	—	—
73[2]	Roberts	Oct. 27, 1979	3,050	100	56	35	48	2,525	375	20.20	17.86	.88
74[2]	Hartley	Oct. 28, 1979	4,100	102	59	35	40	3,985	100	21.65	35.91	1.66
75[2]	Hartley	do	3,790	102	36	35	41	—	—	—	—	—
76[2]	Oldham	Oct. 29, 1979	4,050	102	33	35	18	3,811	25	—	—	—
77[2]	Briscoe	Oct. 30, 1979	3,200	101	16	34	21	3,013	—	—	—	—

[1] Ogallala Formation dry, saturated zone is in underlying Cretaceous or Jurassic sediments.
[2] Primary purpose of sounding was to electrically sound the base of the Ogallala Formation.
[3] Electrical obstructions affect the results of the sounding.



EXPLANATION

•4.30

Apparent formation factor (Fa) derived from vertical electrical soundings
Consult Table 5 for additional data

— 3 —

Line (Isopleths) joining points of equal apparent formation factors
Interval 1 unit (dimensionless)

0 10 20 30 Miles

0 10 20 30 Kilometers

Figure 11
Variations in Apparent Formation Factor in the High Plains Aquifer

Base adapted from U.S. Geological Survey, 1965

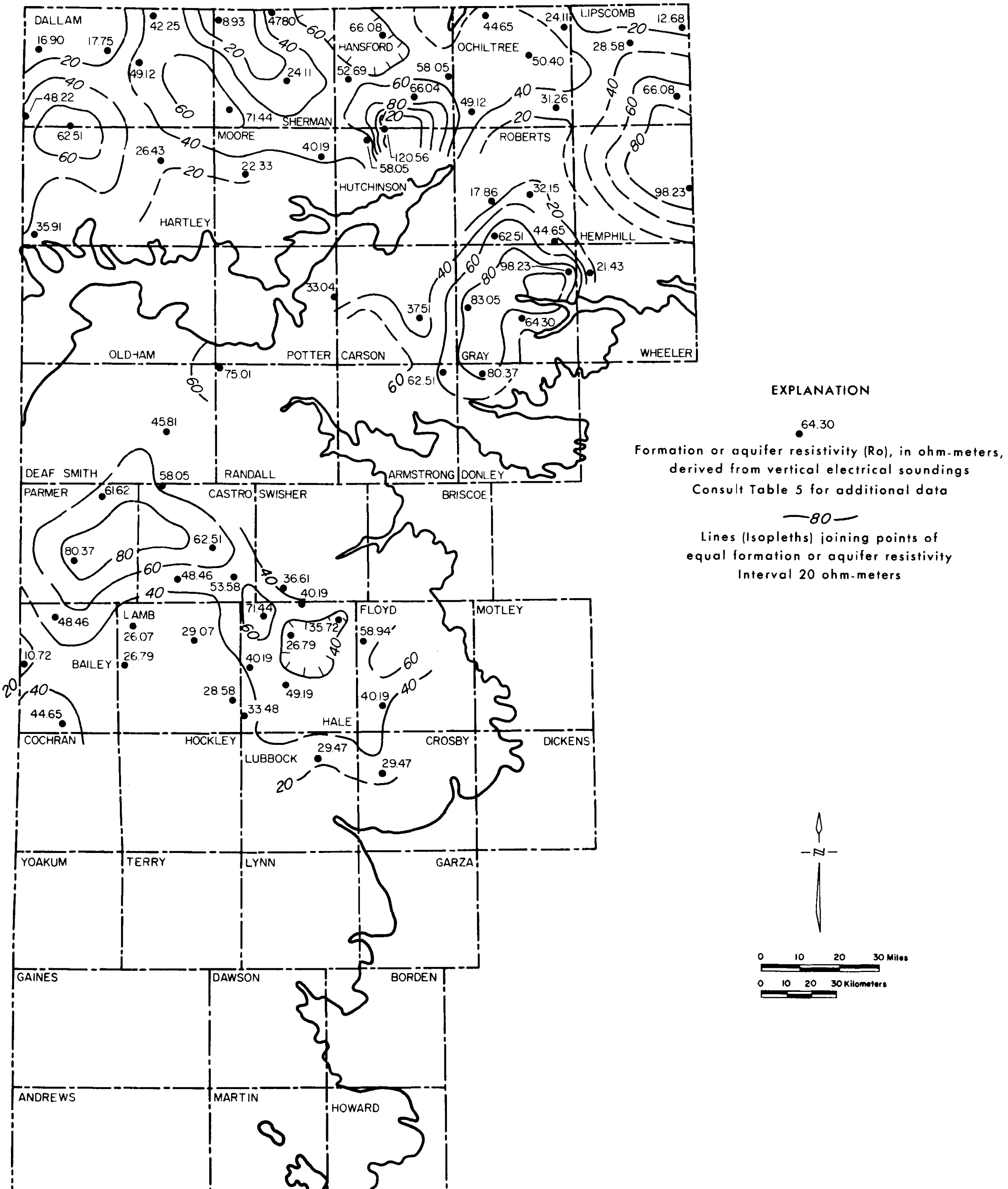


Figure 12

Variations in Formation or Aquifer Resistivity in the High Plains Aquifer

Base adapted from U.S. Geological Survey, 1965

Figure 36 shows the distribution of average specific yield values of the saturated zone of the High Plains aquifer, and Figure 37 shows the distribution of average permeability values. These maps represent the data used in the calibrated model. Specific yield and permeability can vary considerably over a short distance. Therefore, the values on the maps should be considered as only average values to identify trends. A specific well may encounter strata with higher or lower specific yield and permeability characteristics than those shown for the area.

Both specific yield and permeability are primarily dependent on sediment grain size and shape, degree of sorting, and amount of cementation. Layers of silt and clay have the most diminishing effect on the ground-water movement within the aquifer, especially in the vertical direction. All of these factors vary according to the environment of deposition and the energy involved during the depositional process. Sediments filling buried channels were deposited under high-energy conditions, and therefore are generally coarser grained and better sorted than those deposited in other environments. Channel deposits in the High Plains aquifer generally exhibit specific yield values of 18 percent or more and permeability values of 1,000 (gal/d)/ft^2 [40,700 (l/d)/m^2] or more. Sediments deposited in low-energy environments such as lakes and interchannel areas, which contain abundant silt and clay, have markedly lower average specific yield and permeability values.

Chemical Quality

The general quality of the ground water in the High Plains aquifer of Texas is illustrated in Figures 38 and 39. The maps show the dissolved solids and chloride content of water in the High Plains aquifer. Analyses of water from over 2,000 wells completed in the aquifer were used to construct the maps. Analyses from some wells show abnormally high constituent levels. Such data were not used because it was decided that the water sampled had been contaminated and was not representative of aquifer water in the region surrounding the well. Each interval on the map shows the range of dissolved solids or chloride that is common in the area. There may be isolated instances within the various intervals where concentrations of dissolved solids or chloride may be more or less than as indicated on the maps.

In general, both dissolved solids and chloride concentrations increase from north to south. Specifically, the area underlain by Cretaceous rocks has a markedly higher concentration of dissolved solids and chloride than the areas to the north. Also, much of the poorer water quality, especially in the areas underlain by Cretaceous rocks, seems to be associated with the several alkali lake basins in the area. These basins are located in Lamb, Hockley, Terry, Lynn, eastern Gaines, and Martin Counties. Other factors that may be contributing to higher concentrations of dissolved solids and chloride are declining water levels and saturated thickness of the aquifer, local contamination from industrial activities such as petroleum production and animal feed lots, and dissolution of Permian salt beds that underlie the aquifer.

Figure 38 depicts concentrations of dissolved solids in water from the High Plains aquifer. Concentrations range from between 200 and 400 milligrams per liter (mg/l) to over 3,000 mg/l, and actually exceed 6,000 mg/l in a few isolated instances. In the northern half of the region, dissolved solids are typically less than 400 mg/l. Notable exceptions include an extensive area in western Lipscomb and much of Ochiltree Counties where concentrations range from 400 to 800 mg/l. Another area of note is located in southern Roberts, northern Gray, and eastern Carson Counties where dissolved-solids concentrations range from 400 to over 1,000 mg/l. In the area northeast of White Deer in Carson County, concentrations of up to 1,900 mg/l occur.

In the southern half of the study area, where the Ogallala Formation is underlain by rocks of Cretaceous age, dissolved solids typically exceed 400 mg/l. Extensive areas where concentrations exceed 1,000 mg/l are common. Concentrations in the vicinity of alkali lakes almost without exception exceed 1,000 mg/l. The greatest concentrations of dissolved solids occur in an area around Cedar Lake in eastern Gaines County where concentrations greater than 2,000 mg/l are typical and some values of 6,000 to 9,000 mg/l have been recorded.

Figure 39 depicts the concentration of chloride in ground water from the High Plains aquifer. Chloride concentrations follow the same general patterns as the dissolved solids with concentrations generally increasing from north to south. Concentrations of chloride range from less than 50 mg/l to over 1 ,000 mg/l and actually exceed 2,000 mg/l in several instances. In the northern half of the region, concentrations of chloride in selected wells are typically less than 50 mg/l. Areas of higher concentrations generally coincide with the same area of high dissolved solids concentrations (Figure 38). In western Lipscomb and eastern Ochiltree Counties, concentrations range from 50 to over 250 mg/l. In southern Roberts, northern Gray, and northeastern Carson Counties, concentrations typically range between 50 and 250 mg/l. In isolated instances in Gray County, northeast of White Deer, chloride concentrations of 400 to 500 mg/l occur.

In the southern half of the region, chloride concentrations typically exceed 50 mg/l and commonly exceed 500 mg/l. As in the case with dissolved solids, the higher chloride concentrations coincide with areas underlain by Cretaceous rocks and with the areas around the alkali lakes where the concentrations commonly range from 150 to 500 mg/l. Again, the highest concentrations noted occur in the area around Cedar Lake and east and south of the lake in eastern Gaines County. Analyses of water from wells in this area show chloride concentrations ranging from 1,000 to 2,000 mg/l.

Water Levels

Water levels in an aquifer are primarily influenced by the rate of recharge to and discharge from the aquifer. As previously stated, recharge to the High Plains aquifer is minimal while discharge through wells is large, thus resulting in a decline of water levels over time. Since recharge to the aquifer is relatively constant, the rate of water-level change is thus the result of the rate of discharge through pumpage. When pumpage is heavy, water levels decline more rapidly. Conversely, when pumpage is reduced, such as in years of above-average rainfall, water levels decline more slowly, remain constant, or may even rise. A rise in the water level is usually the result of the aquifer reestablishing static equilibrium after prolonged pumpage(which created the cone of depression) ceases.

The water level or piezometric surface of the High Plains aquifer is generally declining due to the mining effect that results from abundant pumpage and lack of recharge. However, a large area occurs in the general vicinity of Borden, Cochran, Dawson, Gaines, Garza, Hockley, Lubbock, Lynn, Terry, and Yoakum Counties where the water level in wells has been generally rising over the past ten years. The reason for this rise is not fully understood, but may be the result of additional recharge by historical irrigation water that has infiltrated more rapidly through surface strata than previously estimated. Another factor contributing to the rise may be the case explained above where the water level in the area is readjusting to static equilibrium following a decrease in pumpage load. Another plausible explanation for the rise in water levels is enhanced recharge due to abnormally high precipitation. Also, farming practices could have increased the rate of deep percolation of water derived from precipitation or irrigation.

The basic data portion of this report (Volumes 2 through 4) contains county maps showing the elevation of the water level of the High Plains aquifer as measured in the winter of 1979-80. Also included are county maps showing saturated thickness, which is based on the distance between the 1979-80 water level and the base of aquifer. Figures 40 and41 are regional composites of the 1979-80 water level and saturated thickness county maps, respectively.

Aquifer Development and the Decline of Water Levels

The pumpage of ground water from the High Plains aquifer in Texas for the purpose of irrigation began near Plainview in 1911 and increased slowly until the mid-l940's (White and others, 1946). After World War II, economic and technologic conditions were right for a rapid expansion (Figure 13). In 1977, there were 71,417 wells irrigating 6.083 million acres (24,620 km^2) [New, 1977]. As of 1980, some parts of the High Plains are still experiencing irrigation growth but at a somewhat reduced rate.

Historical irrigation pumpage was calculated by multiplying acres irrigated by inches of water applied. The number of acres irrigated in each county was taken from the irrigation inventories for the years 1958, 1964, 1969, 1974, and 1979, which are compiled and published by the Department in cooperation with the U.S. Department of Agriculture Soil Conservation Service and the Texas State Soil and Water Conservation Board. The application rate for each county is an average of rates applied to the types of crops grown in the county and is dependent on the amount of precipitation that occurs during the growing season. Total pumpage for irrigation during the inventoried years is as follows (Texas Department of Water Resources, 198la): 1958-5.228 million acre-feet (6,450 hm^3); 1964-7.726 million acre-feet (9,530 hm^3); 1969-6.449 million acre-feet (7,950 hm^3); 1974-8.138 million acre-feet (10,000 hm^3); and 1979-5.584 million acre-feet (6,880 hm^3). Precipitation was higher than normal in 1979, resulting in less than normal amounts of water applied for irrigation.

Historical municipal and industrial pumpage was determined from annual reports made by each user to the Department. Municipal users include all sources providing water for public consumption. Primary industrial users include sources supplying water for manufacturing, processing, power generation, and water flooding for secondary recovery of hydrocarbons.

Although total pumpage for municipal and industrial use is much less than the total amount pumped for irrigation, its impact locally is often dramatic. In addition to heavy pumpage in a small area, municipal and industrial pumpage usually is continuous year-round which does not allow time for recovery of water levels. This results in a more rapid depletion of the aquifer locally. Due to dwindling ground-water supplies, several communities have switched either completely or partially to reliance on surface-water sources.

Historical domestic pumpage was determined by multiplying the estimated rural population by the estimated per capita water use. Both estimates were made by the Department's staff.

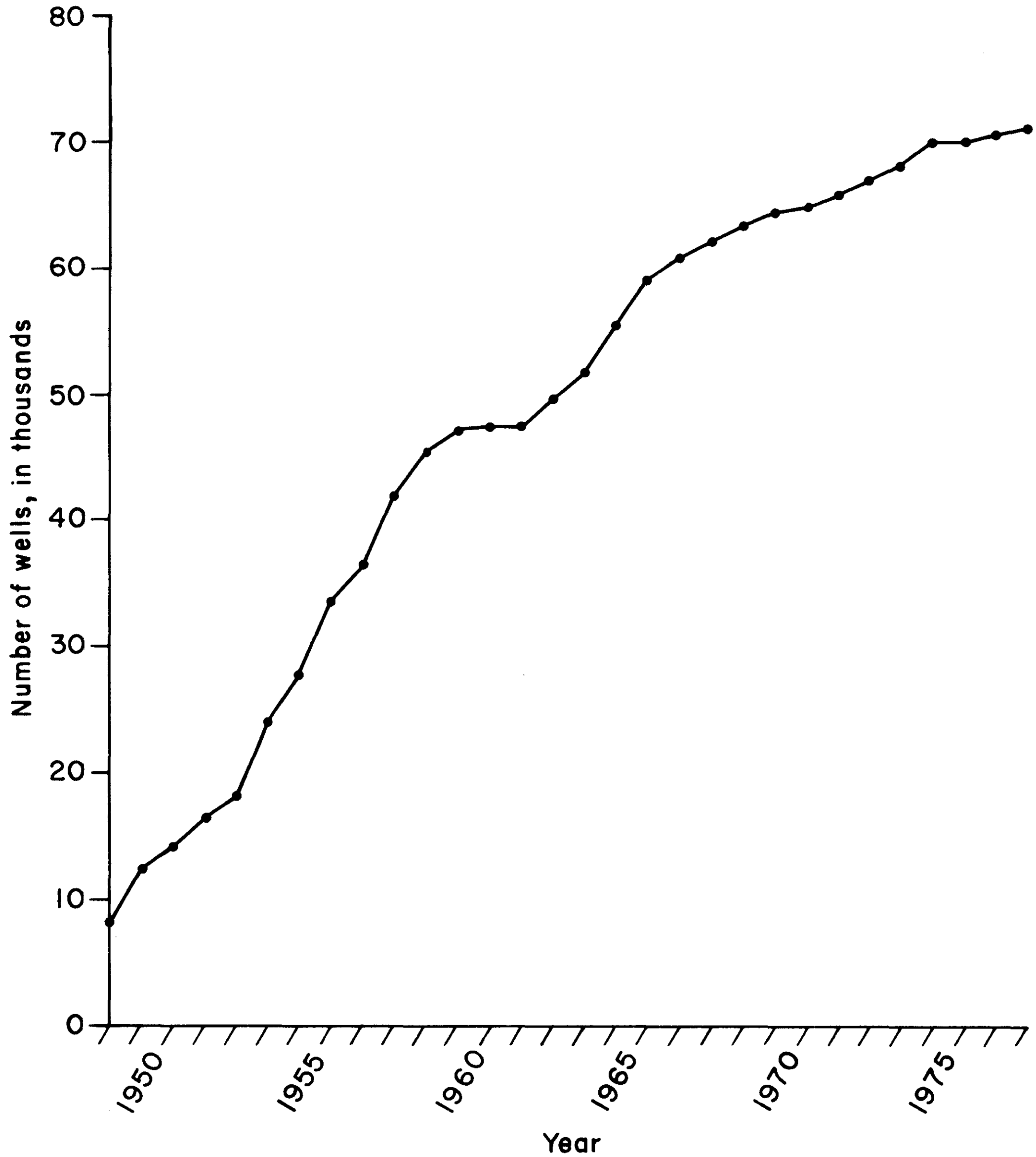


Figure 13
Number of Irrigation Wells in Use
From 1948 Through 1977 (After New, 1977)

Statistics on livestock compiled by the Texas Crop and Livestock Reporting Service (1981) were used to derive historical pumpage for livestock. Average annual municipal and industrial, domestic and livestock, and irrigation pumpage for the periods 1960-64, 1965-69, 1970-74, and 1975-79 are listed in Table 6.

Table 6

Average Annual Pumpage From the High Plains Aquifer

Period of years	Pumpage, in acre-feet			
	Municipal and industrial	Domestic and livestock	Irrigation[1]	Total
1960-64	183,164	20,344	7,726,487	7,929,995
1965-69	179,872	23,286	6,449,285	6,652,443
1970-74	143,420	28,700	8,137,534	8,309,654
1975-79	141,029	28,835	5,583,707	5,753,571

[1] A one-year value from irrigation inventory.

Changes in water levels, as a result of pumpage from the High Plains aquifer, are shown on Figures 42 through 45. These regional maps were constructed from computer-generated plots illustrating historical water levels for the winter measurements made in 1959-60, 1964-65, 1969-70, and 1974-75, respectively. The water-level measurements used in the construction of these maps were collected from a network of observation wells maintained by the Department and the three ground-water district cooperators. Approximately 1,900 measurements were made in 1960, increasing to over 3,800 in 1980. These measurements represent average data densities of about one per 18.5 square miles (48 km^2) in 1960, increasing to one in slightly over 9 square miles (23 km^2) in 1980. The coverage area was not uniform, however, due to sparsity of wells in various areas. Water-level measurements were taken during the winter, nongrowing season, in order to obtain measurements least affected by pumping.

All maps generally exhibit a piezometric gradient with an easterly slope in the area north of the Canadian River and an east-southeasterly slope south of the Canadian. The gradient averages approximately 15 feet per mile (3 m/km) with local anomalies which appear to be influenced by factors such as underlying structure and areas of high pumpage.

A comparison of the 1960 and 1980 water-level elevation maps indicates water-level rises in some areas in the Southern High Plains, but declines generally prevail over the entire region. Little or no change in water levels was indicated in some areas flanking the Canadian River, along the easternmost limits of the aquifer, and in some southwestern parts of the study area.

THE DIGITAL COMPUTER MODEL OF THE HIGH PLAINS AQUIFER

One purpose of this study was to develop a computer model of the aquifer. This model simulates water levels based on the physical constraints of the system and on the recharge and pumpage rates of the aquifer. A pumpage predicting routine is included in the model since the amount of water pumped is a function of the amount of water available for pumping.

The computer program written to perform the simulation is called *GWSIM-III, Ground-Water Simulation Program*, and the program documentation and user's manual was prepared by the Department of Water Resources (Knowles, 1981). The basic simulation procedure was developed by T. A. Prickett and C. G. Lonnquist, Illinois State Water Survey (Prickett and Lonnquist, 1971).

Governing Equation

The numerical simulation of the aquifer is based on a mathematical approximation of the basic ground-water flow equation. The equation for nonsteady flow in a nonhomogeneous aquifer was used by Prickett and Lonnquist (1971) and may be written as follows:

$$\frac{\partial}{\partial x}\left(T\frac{\partial h}{\partial x}\right) + \frac{\partial}{\partial y}\left(T\frac{\partial h}{\partial y}\right) = S\frac{\partial h}{\partial t} + Q,$$

where

T = aquifer transmissivity,
h = hydraulic head,
S = aquifer storage coefficient,
t = time,
Q = net ground-water flux per unit area, and
x, y = rectangular coordinates

Solution Technique

The numerical solution to this equation can be obtained by applying a finite difference approach. The basic assumption underlying the finite difference approach is that partial differentials can be approximated by a difference quotient.

The steps in applying the finite difference approach to ground-water movement are as follows:

(a) a finite difference grid is superimposed upon a map showing the extent of the aquifer, with the coordinate axes aligned with the principal directions of the transmissivity tensor, thus allowing the finite difference grid to replace the continuous aquifer with an equivalent set of discrete elements;

(b) the governing partial differential equation is written in finite difference form for each of the discrete elements; and

(c) the resulting set of linear finite difference equations is solved numerically for the head with the aid of a digital computer.

A portion of a finite difference grid which could be superimposed upon a map is illustrated in Figure 14. Each of the grid elements is referred to as a cell, and the center of each cell is called a node. Each of the cells has dimensions $m\Delta x \Delta y$, where m is the thickness of the cell, and Δx and Δy are the grid dimensions in the x and y directions, respectively. Each of the cells, or nodes, may be referenced by its row (i) and column (j) numbers which correspond to the y and x dimensions.

The finite difference approximation of the basic ground-water flow equation which was used to simulate the High Plains aquifer may be expressed as follows:

$$+ \frac{1}{\Delta x_j} \left[\left\{ T_{i,j+\frac{1}{2}} \left(\frac{h_{i,j+1} - h_{i,j}}{\Delta x_{j+\frac{1}{2}}} \right) \right\} - \left\{ T_{i,j-\frac{1}{2}} \left(\frac{h_{i,j} - h_{i,j-1}}{\Delta x_{j-\frac{1}{2}}} \right) \right\} \right]$$

$$+ \frac{1}{\Delta y_i} \left[\left\{ T_{i+\frac{1}{2},j} \left(\frac{h_{i+1,j} - h_{i,j}}{\Delta y_{i+\frac{1}{2}}} \right) \right\} - \left\{ T_{i-\frac{1}{2},j} \left(\frac{h_{i,j} - h_{i-1,j}}{\Delta y_{i-\frac{1}{2}}} \right) \right\} \right]$$

$$= \frac{S_{i,j}}{\Delta t} (h_{i,j} - H_{i,j}) + Q_{i,j},$$

where

Δx_j = grid spacing in the x-direction for column j,
Δy_i = grid spacing in the y-direction for row i,
$T_{i,\, j+\frac{1}{2}}$ = transmissivity between node i, j and i, j + 1,
$h_{i,\, j}$ = head at node i, j at end of time step,
$S_{i,\, j}$ = storage coefficient for cell i, j,
Δt = time step increment,
$H_{i,\, j}$ = head at node i, j at beginning of time step,
$Q_{i,\, j}$ = net withdrawal per unit surface area for cell i, j, and
$\Delta x_{j+\frac{1}{2}}$ = distance between node i, j and node i, j + 1.

A more detailed discussion of the derivation of the finite difference equation is presented in *GWSIM-III, Ground-Water Simulation Program* (Knowles, 1981).

The finite difference equation is written for each cell in the aquifer model. This results in a large system of simultaneous equations with the hydraulic head for each node, $h_{i,j}$, as the unknowns. This system of equations is solved by an iterative alternating direction implicit procedure which reduces the large system of equations into several small sets of systems of equations. One set of systems of equations is generated by assuming that each column in the finite difference grid is isolated so that only the hydraulic heads along the column are unknown. The second set of systems of equations is generated by assuming that each row is isolated and that only the head values along the row are unknown. Once the sets of systems of equations have been solved for the hydraulic head, one iteration of the solution procedure has been completed.

The process is repeated until it has converged to a solution. The terms $h_{i,j}$ are the simulated heads at the end of the time step, and they are used as the beginning heads for the following time step. For a more detailed discussion of the iterative alternating direction implicit procedure, see Peaceman and Rachford (1955) or Prickett and Lonnquist (l971).

For this model work, the solution procedure was considered converged when the total head change from one iteration to the next is less than a specified value. During the model calibration study, the convergence criterion was set equal to 1 foot. However, the program is designed to do at least four iterations to insure stability and the program rarely iterated more than four times.

Application to the High Plains Aquifer

The High Plains aquifer was discretized into a finite difference grid containing 6,302 cells. The grid is divided into two sections, in effect dividing the model into two parts. The division was necessary to reduce computer storage requirements. As illustrated in Figure 14, the division occurs east and southeast of Amarillo, an area of thin saturated thickness. The line separating the model portions is generally perpendicular to water-level contour lines. No boundary problems resulted from this division. The north model contains 42 rows and 61 columns for a total of 2,562 cells. The south model contains 85 rows and 44 columns for a total of 3,740 cells. As illustrated on Figure 14, only a portion of the finite difference grid actually overlies the aquifer. Only 1,763 of the 2,562 cells in the north model grid and 2,692 of the 3,740 cells in the south model grid are considered as part of the aquifer system and take part in the simulation process. The cells are square and of uniform size, 2.895 miles (4.658 km) on each side. Each cell contains approximately 8.4 square miles (21 .8 km^2 or 5,364 acres (2,171 hm^2).

The High Plains model contains three types of cells: water table, constant-head, and boundary. The program calculates heads only for water-table cells. The constant-head cells are used to satisfy boundary conditions The boundary cells are exterior to the ground-water system and do not enter into the simulation.

The program includes a procedure that calculates pumpage. The rate of pumpage is governed by the amount of water remaining in storage, and there had to be a connection in the model between the determination of the rate of pumping and calculation of the amount of water available for pumpirg. The pumpage calculation procedure uses externally controlled information, such as number of irrigated acres, irrigation application rate, and municipal and industrial pumpage. It also uses internally supplied information, such as saturated thickness and transmissivity.

Total pumpage is the sum of municipal and industrial, domestic and livestock, and irrigation pumpage. The municipal and industrial pumpage includes withdrawals where the locations of the producing well or wells are known. Examples are wells withdrawing water for cities, industries, and powerplants. This pumpage is assigned to individual cells. The domestic and livestock pumpage primarily includes water used by rural farmsteads. This pumpage is assigned by county, and the rate is applied uniformily to all cells in the county.

Irrigation pumpage is determined by using information not dependent upon the status of the aquifer model, such as acres under irrigation and irrigation application rate, and by using data that the model calculates, such as saturated thickness and transmissivity.

Irrigation inventories were conducted in 1958, 1964, 1969, 1974, and 1979. The distribution of irrigated acres and the average application rates were determined for each county. The model program was designed to use this type of information to calculate irrigation pumpage. These variables are independent of model variables. Each cell was assigned a percent irrigated value based on the irrigation inventory information. The product of this value, cell area, and application rate equals an irrigation pumpage rate for the cell, usually expressed in acre-feet per year.

The irrigation pumpage rate is adjusted by two constraints which attempt to reflect two physical processes that affect irrigation. The first is the reduction of well yield as the saturated thickness of the aquifer decreases. The decrease in saturated thickness reduces aquifer transmissivity, resulting in a decrease in the capacity of the aquifer to yield water to wells. For thick sections, the aquifer is capable of yielding more water to a well than the pump can lift to the surface. However, as the saturated thickness diminishes, a point is reached at which the capacity of the aquifer to yield water and the pumping capacity of the well are equal. At that point, the capacity of the aquifer to yield water becomes a limiting factor on pumpage. The program was constructed so that the irrigation pumpage rate was not adjusted so long as the transmissivity was larger than a given value, T-one. For transmissivities less than T-one, the irrigation pumpage rate was reduced linearly until the transmissivity equals the second constraint value, T-two. The pumping rate was reduced to one-tenth the original value for any transmissivities equal to or less than T-two.

The determination of the T-one and T-two constraint values was based on the assumption that a well's maximum discharge was that pumping rate that results in a water-level drawdown equal to two-thirds of the saturated thickness prior to pumping. The equation for steady radial flow to a well in an unconfined aquifer was used to calculate this discharge. The equation may be expressed as follows (adapted from Todd, 1959):

$$Q = \pi K \frac{H_o^2 - H_w^2}{\ln(R_o/R_w)},$$

where

Q = well discharge,
K = permeability coefficient,
H_o = saturated thickness in the aquifer prior to pumping,
H_w = saturated thickness at the well,
$\ln$ = natural logarithm,
R_o = distance from the well where the change in water level due to pumping is negligible, and
R_w = radius of the well.

For the High Plains area, an appropriate value for R_o is 750 feet (229 m), and for R_w, 8 inches (20 cm). The results from using the equation are not very sensitive to changes of these two parameters. Applying the equation to a well completed in an aquifer with initial saturated thickness of 85 feet (26 m) and permeability of 400 (gal/d)/ft^2 [16,300 (l/d)/m^2] results in a maximum discharge rate of approximately 800 gal/min (50 l/s). If the irrigation application rate was based on 800 gal/min wells, T-one and T-two would equal 34,000 and 10,800 (gal/d)/ft [422,000 and 134,000 (l/d)/m], respectively.

The second process that affects irrigation pumpage is the increase in pumping cost as pumping lifts increase. At some point, the cost of pumping the water equals the benefits derived from the water. Any increase in lift beyond that value should result in decreased pumping. The program was constructed so that the irrigation pumpage rate was not adjusted as long as the pumping lift was less than a prescribed value (PLT). For each foot of lift in excess of the prescribed value, the irrigation pumping rate was reduced a specified value (PLS). The maximum reduction was 90 percent.

All three categories of pumpage are subject to a third constraint, minimum saturated thickness. A very small saturated thickness can support only very small-capacity wells. The program was constructed so that for saturated thicknesses of less than 5 feet (1.5 m), the municipal and industrial and the irrigation pumpage categories are set equal to zero. The domestic and livestock pumpage is not affected until the saturated thickness reaches 2 feet (0.60 m), when it also is set equal to zero.

The program was constructed to assign a recharge rate to each cell. The rate represents the movement of water to the aquifer. This is different from the infiltration rate because that water does not instantaneously reach the saturated portion of the formation. Also, most of the water that infiltrates does not reach the water table but is returned to the land surface by evaporation or evapotranspiration by plants.

This modeling work did not attempt to model all of the ground-water system. Areas outside of Texas were not modeled. The aquifer extends into New Mexico and Oklahoma and conditions in those states affect the ground-water condition in adjacent areas of Texas. The model was extended only one cell into these adjoining states so that this boundary condition could be handled. Cells in the other states were constant-head types which means that ground water may flow between them and active cells, but the program does not calculate new water levels for those cells. It was assumed that the water levels for these cells are known or can be predicted with sufficient accuracy.

Some of the model input and output uses a county designation. The model is based on cells, and cell boundaries do not always coincide with county boundaries. Cells are assigned to counties based on the location of the center of the cell; thus a cell may include parts of more than one county. This characteristic of the model means that county-categorized data may not represent the actual condition for the county, but instead represents the data for that portion of the model which is referred to by the county name.

RESULTS OF MODEL OPERATION

Model Calibration

The calibration phase of model development involves the simulation of the aquifer for a time period when the response of the aquifer is known. Water levels are known at the start and end of the calibration period along with the pumpage and recharge values for the same time period. A comparison of the observed and simulated water levels for the calibration period is an indication of how well the model is simulating the aquifer’s response.

For this study, the calibration period extends from January 1960 through December 1979. Water-level data are available for the winter of 1959-60, 1964-65, 1969-70, 1974-75, and 1979-80. For simplicity, these periods will be referred to as 1960, 1965, 1970, 1975, and 1980, respectively. These water levels allow several opportunities to gage the accuracy of the simulation results. This period was chosen because of the availability of data. The density of wells in which water levels were measured increased during this period, with the 1980 measuring effort giving the best coverage.

The modeling period was divided into four 5-year periods. Each of these periods end and begin at the time for which water-level maps were constructed. Also, each period includes one of the years during which an irrigation inventory was conducted. The other categories of pumpage, for municipal, industrial, rural domestic, and livestock uses, are known for this period.

Assignment of pumpage values for each cell for each time period distributes the pumpage in space and time. The pumping centers for which the location and rate of withdrawal are known are included in the municipal and industrial category. For each year, the volume of water pumped from each pumping center was assigned to a cell. The cell pumpage values were averaged for each 5-year period to yield an average pumpage rate for each period. Rural domesticand livestock water uses are included in the domestic and livestock categories. For each year, county values are available and their values were averaged to yield an average use rate for each 5-year period.

The irrigation inventories were used to develop pumpage for irrigated agriculture. An inventory was conducted during the last year of each 5-year period. From the 1964 and 1979 inventories, the number of acres irrigated with ground water obtained from the High Plains aquifer was assigned to cells by using the irrigation inventory county maps which show acres irrigated. For 1969 and 1974, the number of acres irrigated in each cell was determined by interpolating between the 1964 and 1979 values and adjusting the values so that county totals of acres irrigated agree with the values of both inventories. These values were then converted to percent irrigated by dividing by the area of each cell. An average application rate is also presented for each county for each inventory. This rate was assigned to cells based on their county designation. The data obtained from each inventory, percent irrigated and application rate, are used to calculate pumpage for irrigation for the appropriate 5-year period. If a cell's saturated thickness was not greater than 10 feet (3 m) at the beginning of a period, its percent irrigated was set equal to zero. It was anticipated that percent irrigated and rate parameters would be adjusted during calibration since they represent pumpage for one year and the model expects data to represent average conditions over a 5-year period.

Recharge to the aquifer is small compared to withdrawals. In 1937, the effective recharge to the Southern High Plains was estimated at 0.175 inch (0.445 cm) per year (Theis, 1937). For this work, however, an annual recharge rate of 0.2 inch (0.5 cm) or 371,910 acre-feet (459 hm3) was applied to the entire aquifer. This rate was distributed to the six recharge zones by using the zone's infiltration rate to determine a weighted rate. All cells in a zone were assigned the appropriate recharge rate.

Measured water levels were coded from water-level maps. Regional maps, Figures 42 through 45, were used to code 1960, 1965, 1970, and 1975 water-level information, respectively. County maps showing 1980 water levels were used to code 1980 water levels.

County maps showing the elevation of the base of aquifer (see Figure 2 of Volumes 2,3, and 4) were used to code base of aquifer data. Elevation of the land surface was obtained from the U.S. Geological Survey computerized file of land-surface elevations and $1^0 \times 2^0$ topographic maps.

Regional maps showing specific yield and permeability were used for input to the model. It was readily apparent that large variations between neighboring cells existed. To reduce these large changes, weighted averages of the parameter values for each cell were calculated using values for five cells. Also it was apparent that some irrigated areas showed low permeabilities. This could have been caused by inappropriate selection of well logs when constructing the original maps. To remove this problem, the initial estimates of permeability were adjusted based on the percent-irrigated value for the first time step. If a cell's 1974 percent-irrigated value is 25 or less, the permeability of the cell must equal at least 150 $(gal/d)/ft^2$ [6,100 $(l/d)/m^2$]. For irrigated values greater than 25 percent and up to 50 percent, the minimum permeability equaled 200 $(gal/d)/ft^2$ [8,150 $(l/d)/m^2$]. If the values were greater than 50 percent and not more than 75 percent, the minimum permeability was 250 $(gal/d)/ft^2$ [10,200 $(l/d)/m^2$]. For values greater than 75 percent, the minimum permeability was 300 $(gal/d)/ft^2$ [12,200 $(l/d)/m^2$].

South Model

The initial runs of the south model showed simulated water levels being significantly lower than measured levels at the end of each 5-year period. As a first step in calibration, the south model was applied separately to each 5-year period using measured water levels as starting conditions. The irrigation application rates for each 5-year period were adjusted so that the average simulation error (simulated water level minus measured water level) for each county for each period was less than 10 feet (3 m). These adjusted application rates were used to simulate the 20-year period. In order to reduce simulation errors, adjustments were made on a cell-by-cell basis to the irrigation application rate, storage coefficient, and permeability. The application rates and storage coefficients were adjusted more often than was permeability. A decrease in application rate and an increase in storage coefficient both tend to reduce the magnitude of water-level decline.

It became evident that the amount of irrigation water use, determined during model calibration, is significantly less than the amount determined by the irrigation inventory. The procedures used to do the inventories and the modeling were investigated and no errors in procedures or data were identified which explain the difference. However, this difference may be caused by overestimation of irrigation pumpage by the inventory, by improper modeling of physical processes, or by both. One of the many parameters used in the inventories are operator estimates of pumpage. Wells are seldomly equipped with flow meters and the wells often do not produce as much water as estimated by their operator due to factors such as reduced saturated thickness, worn equipment, and overestimation by the well driller of initial pumping capacity. Also, the inventory represents one year, and the model values are averages for a five-year period. Two processes which may be occurring, and which may also help explain the difference, are returns of irrigation water to the aquifer and increased recharge of precipitation due to land-surface alteration and irrigation. These processes were not included in this model because our studies did not yield information showing that they were occurring in significant amounts. The rise of water levels on the South Plains may, however, be caused by these processes. The modeling procedure is based on a water balance in that inflow minus outflow equals change in storage. It was felt that the data describing volumes of water in storage were very good. Since the principal use of the model is to determine volume of water in storage, it was decided that the model is usable even though the withdrawals necessary to reproduce water-level changes do not agree with the pumpage rates available from other sources. To reduce confusion, net withdrawal instead of pumpage was used to describe water removed from the aquifer as determined by modeling.

During the calibration runs for the south model, it became apparent that the coded water levels showed some inconsistency, especially in the earlier years. This inconsistency was caused by the scarcity of data in some areas and was removed by changing some of the coded measured water levels. The changes were generally less than the contour interval of the maps from which the data were taken. The 1960,1965,1970, and 1975 regional maps have contour intervals of 50 feet (15 m).

The south model tended to show large positive simulation errors along the eastern side of the modeled area. The model treated this edge as a no-flow boundary. The hydraulic gradient was to the southeast and water was stacking up against this no-flow boundary. Most of the easternmost cells in a given row represent areas that are below the caprock and are not significantly irrigated. These cells were declared to be constant head, and water no longer “ponded” at the model boundary.

As discussed previously, water levels in several southern counties show rises after 1970. The region includes all or part of Borden, Cochran, Dawson, Gaines, Garza, Hockley, Lubbock, Lynn, Terry, and Yoakum Counties. The recharge rates for the third and fourth time steps were increased so the model would adequately reproduce this rise. Based on rises in water levels, the region was divided into two categories. The first category includes areas where water levels were rising at an approximate rate of 0.5 foot (0.15 m) per year. The rate for the other category is 1.0 foot (0.3 m) per year. The amount of increase in recharge equals the rate of water level rise in feet per year times the cell’s specific yield times the cell area. The total amount of added recharge equals 222,600 acre-feet (274 hm^3) per year. Total recharge for the south model equals 248,700 acre-feet (307 hm3) per year for the period 1960 through 1969, and 471,300 acre-feet (581 hm3) per year for the period 1970 through 1979.

The distribution of the simulation errors is an important indicator as to the validity of the model. The simulation error is the simulated water level minus the measured water level. The mean error for the south model is 0.72 foot (0.22 m) for 1965,0.36 foot (0.11 m) for 1970, -1.26 feet (-0.38 m) for 1975, and -1.29 feet(-0.39 m) for 1980. More than 93 percent of the 1980 errors are smaller than 25 feet (8 m), and more than 36 percent of the errors are smaller than 5 feet(l.5 m). The regression coefficient is 0.999. The initial inputs (prior to model calibration) of specific yield and permeability averaged 15.5 percent and 530 $(gal/d)/ft^2$ [21,600 $(l/d)/m^2$], respectively. After model calibration the average values are 15.6 and 510 $(gal/d)/ft^2$ [20,800 $(l/d)/m^2$], respectively. Figures 36 and 37 show the distributions of specific yield and permeability in the calibrated model.

During the 20-year calibration period, net withdrawals for the south model equal 59.58 million acre-feet (73,500 hm^3). Municipal and industrial categories account for 3 percent of the total, domestic and livestock account for 0.6 percent, and irrigation accounts for 96.4 percent. Recharge totals 7.20 million acre-feet (8,880 hm^3) during the period. The net flow of water from New Mexico into Texas was 84,800 acre-feet (105 hm^3) per year using January 1970 water levels, and 67,600 acre-feet (83.4 hm^3) per year using January 1980 water levels. The largest rates of flow into Texas are near the Parmer-Bailey County line, near the Bailey-Cochran County line, and near south-central Gaines County. Flow into constant-head cells which form the eastern boundary was 80,900 acre-feet (100 hm^3) per year using January 1970 water levels, and 48,350 acre-feet (59.6 hm^3) per year using January 1980 water levels. The south model shows that 5.69 million acre-feet (7,020 hm^3) of water was taken into storage and 57.79 million acre-feet (71,300 hm^3) was released from storage. The net decrease in storage is 52.10 million acre-feet (64,200 hm^3). Seventeen percent of the cells show a water-level decline greater than 55 feet (17 m); 41.5 percent show a decline greater than 25 feet (8 m). Nineteen and one-half percent of the cells show a water level change of less than 5 feet (1.5 m), and 13.9 percent of the cells show a rise of more than 5 feet (1.5 m). Tables 7 and 8 show the net withdrawals and volume of water in storage for counties in the south model. The distribution of saturated thickness is shown in Table 9.

Table 7

Average Annual Net Withdrawals During Calibration Period, South Model

	Withdrawal, in acre-feet per year			
County[1]	1960-64	1965-69	1970-74	1975-79
Andrews	19,400	8,840	10,740	12,260
Armstrong[2]	7,450	4,850	2,680	4,900
Bailey	104,590	136,190	194,460	153,500
Borden	0	0	0	190
Briscoe	30,380	31,460	28,080	26,780
Castro	221,170	298,510	259,770	304,890
Cochran	46,790	31,960	40,890	87,900
Crosby	175,480	109,210	157,010	16,640
Dawson	84,100	25,420	18,120	20,270
Deaf Smith	243,180	254,900	252,940	259,770
Dickens	2,420	1,770	1,840	1,880
Ector	12,370	8,090	7,340	7,190
Floyd	267,280	312,520	282,760	258,570
Gaines	224,940	123,480	200,090	254,540
Garza	7,720	3,000	4,190	4,320
Glasscock	4,630	2,870	6,650	6,230
Hale	339,690	305,770	331,980	214,420
Hockley	65,070	77,320	80,740	42,060
Howard	2,430	1,800	1,750	810
Lamb	172,130	204,620	229,680	202,020
Lubbock	150,390	94,730	83,730	27,660
Lynn	38,850	28,170	28,740	30,200
Martin	45,170	33,380	32,620	23,230
Midland	17,380	33,610	28,090	27,240

See footnotes at end of table.

Table 7

Average Annual Net Withdrawals During Calibration Period, South Model—Continued

County[1]	Withdrawal, in acre-feet per year 1960-64	1965-69	1970-74	1975-79
Motley	0	0	0	100
Oldham[2]	17,010	16,040	16,510	6,750
Parmer	364,080	269,830	334,260	363,790
Potter[2]	6,510	5,670	5,430	1,550
Randall[2]	111,680	68,370	62,230	64,850
Swisher	280,840	235,900	214,200	102,830
Terry	150,520	45,650	111,380	106,210
Yoakum	42,550	49,740	89,580	84,730
Total	3,256,200	2,823,670	3,118,480	2,718,280

[1] Approximate representation of counties.
[2] Part of county in north model.

Table 8

Simulated Volume of Water in Storage During Calibration Period, South Model

County[1]	Volume, in millions of acre-feet 1960[3]	1965	1970	1975	1980
Andrews	4.74	4.79	4.88	4.96	5.02
Armstrong[2]	.21	.18	.16	.15	.14
Bailey	8.38	8.04	7.54	6.78	6.19
Borden	.03	.02	.02	.03	.03
Briscoe	1.93	1.74	1.54	1.38	1.22
Castro	19.43	18.10	16.41	14.92	13.24
Cochran	3.96	3.80	3.70	3.67	3.40
Crosby	7.88	7.10	6.66	5.99	5.99
Dawson	5.17	4.71	4.58	4.71	4.83
Deaf Smith	16.90	15.66	14.35	13.07	11.77
Dickens	.70	.67	.64	.62	.59
Ector	2.32	2.28	2.25	2.23	2.21
Floyd	15.13	13.84	12.34	11.02	9.85
Gaines	15.06	14.25	13.93	13.36	12.51
Garza	.36	.33	.33	.33	.34
Glasscock	1.02	1.01	1.00	.98	.96

See footnotes at end of table.

Table 8

Simulated Volume of Water in Storage During Calibration Period, South Model—Continued

County[1]	Volume, in millions of acre-feet				
	1960[3]	1965	1970	1975	1980
Hale	20.20	18.57	17.14	15.61	14.66
Hockley	4.86	4.62	4.31	4.01	3.89
Howard	.82	.83	.85	.87	.90
Lamb	15.01	14.22	13.23	12.10	11.09
Lubbock	6.52	5.82	5.38	4.96	4.81
Lynn	2.87	2.70	2.58	2.64	2.70
Martin	4.73	4.57	4.46	4.35	4.29
Midland	1.90	1.83	1.70	1.59	1.48
Motley	.57	.58	.57	.55	.53
Oldham[2]	1.40	1.31	1.24	1.15	1.12
Parmer	17.42	15.58	14.25	12.59	10.84
Potter[2]	.55	.53	.51	.49	.49
Randall[2]	5.31	4.79	4.49	4.21	3.92
Swisher	8.86	7.50	6.38	5.36	4.88
Terry	4.57	3.93	3.82	3.67	3.55
Yoakum	5.16	5.05	4.89	4.68	4.49
Total	203.97	188.95	176.13	163.03	151.93

[1] Approximate representation of counties.
[2] Part of county in north model.
[3] From measured data.

Table 9

Distribution of Saturated Thickness During Calibration Period, South Model

Range of saturated thickness, in feet		Area, in millions of acres				
Greater than	Equal to or less than	1960	1965	1970	1975	1980
0	20	1.518	1.674	1.824	1.920	1.990
20	40	1.963	2.108	2.162	2.349	2.639
40	60	2.033	2.130	2.392	2.644	2.612
60	80	1.851	1.990	1.920	1.775	1.824
80	100	1.271	1.239	1.255	1.244	1.169
100	120	.939	.944	.890	.864	.966
120	140	.730	.654	.628	.719	.751

Table 9

Distribution of Saturated Thickness During Calibration Period, South Model—Continued

Range of saturated thickness, in feet		Area, in millions of acres				
Greater than	Equal to or less than	1960	1965	1970	1975	1980
140	160	.617	.654	.617	.751	.654
160	180	.622	.574	.698	.499	.429
180	200	.520	.579	.451	.349	.247
200	240	.901	.654	.510	.338	.252
240	300	.536	.333	.209	.107	.027
300	—	.059	.027	.005	0	0

Figures 15 and 16 show saturated thickness for 1960 and 1980, respectively. The area with 20 feet (6 m) or less of saturated thickness increased 31 percent during the calibration period. It is difficult to obtain sufficient water for irrigation by wells where the saturated thickness is not greater than 20 feet (6 m). For 1980, 14.7 percent of the area has 20 feet (6 m) or less of saturated thickness. Generally, well yields are not a limiting factor for irrigation if saturated thickness is 100 feet (30 m) or greater. For 1980, 24.5 percent of the area had 100 feet (30 m) or more of saturated thickness. This is a 32.5 percent decrease from the 1960 value.

North Model

The initial run of the north model contained inconsistencies between the simulated and the measured water levels at the end of each 5-year period. Correlation between adjacent cells appeared vague, particularly in areas with little pumping activity. In addition, these areas have sparse historical water-level data, especially for the early years. For example, water levels for 68 percent of the north model area are poorly defined, meaning low measurement density, for 1960. Consequently, in some areas for modeling purposes, 1960 water-level elevations were necessarily estimated from data for later years and from probable decline rates. By 1980, the density of data significantly increased, thereby reducing that part of the area with poorly defined water levels to 16 percent.

Adjustments of the permeability, storage coefficient, and irrigation application rates on a cell by cell basis resulted in further reduction of simulation errors. For certain cells, adjustments of the application rate were not pertinent to all of the time steps.

Cells in New Mexico and Oklahoma that adjoin Texas represent constant-head boundary conditions. Using the 1960-80 water-level decline data, 1965, 1970, and 1975 water-level data were generated for these cells. The data are in agreement with data from regional water-level maps when using adjacent areas with sufficient water-level measurements for comparison.

The distribution of simulation error is an important indicator of the validity of a model. The mean error for the north model is 0.47 foot (0.14 m) for 1965, 2.35 feet (0.72 m) for 1970, 1.83 feet (0.56 m) for 1975, and 2.23 feet (0.68 m) for 1980. More than 91 percent of the 1980 errors were smaller than 25 feet (8 m), and more than 32 percent of the errors smaller than 5 feet (1.5 m). The regression coefficient is 0.999. The initial inputs (prior to model calibration) of specific yield and permeability averaged 16.1 percent and 450 (gal/d)/ft^2 [18,330 (l/d)/m^2], respectively. After calibration, the average values are 16.6 percent and 227 (gal/d)/ft^2 [9,250 (l/d)/m^2], respectively. Figures 36 and 37 show the distributions of specific yield and permeability in the calibrated model.

During the 20-year calibration period, withdrawals for the north model equal 33.61 million acre-feet (41,400 hm^3). Municipal and industrial withdrawals account for 4.2 percent of the total, domestic and livestock account for 0.4 percent, and irrigation accounts for the remaining 95.4 percent. Total recharge for the calibration period is 2.47 million acre-feet (3,050 hm^3). The net flow of water from New Mexico on the west into Texas equals 24,900 acre-feet (30.7 hm^3) per year using January 1970 water levels and 24,500 acre-feet (30.2 hm^3) per year using January 1980 water levels. Net flow into constant head cells, which form the eastern boundary, equals 18,100 acre-feet (22.3 hm^3) per year using January 1970 water levels and 17,400 acre-feet (21.5 hm^3) using January 1980 water levels. The largest rate of flow into Texas from the west occurs across the Dallam-Union County, New Mexico line. The largest flow from Texas to the east is across the Lipscomb-Ellis County, Oklahoma line. Net southward flow from Oklahoma into Texas equals 3,700 acre-feet (4.6 hm^3) per year using January 1970 water levels and 15,400 acre-feet (19 hm^3) using January 1980 water levels. The largest rates of flow into Texas are across the Dallam-Cimarron County, Oklahoma line. The largest rates of flow from Texas are across the Hansford-Texas County, Oklahoma line. Significant flow also occurs into Beaver County, Oklahoma.

The north model shows that 6.87 million acre-feet (8,470 hm^3) of water was taken into storage and 37.74 million acre-feet (46,500 hm^3) of water was released from storage. The net decrease in storage is 30.87 million acre-feet (38,100 hm^3). Fifteen percent of the cells show a water-level decline greater than 55 feet (17 m); 40 percent show a decline greater than 25 feet (8 m). Tables 10 and 11 show net withdrawals and volume of water in storage for counties in the north model. The distribution of saturated thickness is shown in Table 12.

Table 10

Average Annual Net Withdrawals During Calibration Period, North Model

County[1]	Withdrawal, in acre-feet per year			
	1960-64	1965-69	1970-74	1975-79
Armstrong[2]	20,990	21,500	18,770	10,430
Carson	153,720	179,810	187,190	152,770
Dallam	128,200	164,600	245,320	334,990
Donley	22,940	19,710	38,510	16,230
Gray	33,090	46,620	51,930	35,020
Hansford	211,410	317,800	363,280	361,690
Hartley	71,530	110,160	142,050	175,610
Hemphill	2,000	2,400	4,930	8,120
Hutchinson	68,460	83,940	85,940	76,310

See footnotes at end of table.

Table 10

Average Annual Net Withdrawals During Calibration Period, North Model—Continued

County[1]	Withdrawal, in acre-feet per year			
	1960-64	1965-69	1970-74	1975-79
Lipscomb	2,910	5,630	30,690	55,980
Moore	170,720	179,900	252,630	230,120
Ochiltree	52,440	139,410	237,980	164,600
Oldham[2]	30	50	70	100
Potter[2]	2,510	3,890	4,240	4,520
Randall[2]	3,400	3,880	5,380	6,080
Roberts	7,850	9,000	13,770	13,160
Sherman	185,360	305,520	349,390	290,630
Wheeler	4,370	3,270	7,310	7,880
Total	1,141,930	1,597,090	2,039,380	1,944,240

[1]Approximate representation of counties.
[2]Part of county in south model.

Table 11

Simulated Volume of Water in Storage During Calibration Period, North Model

County[1]	Volume, in millions of acre-feet				
	1960[3]	1965	1970	1975	1980
Armstrong[2]	4.15	3.98	3.83	3.70	3.61
Carson	17.51	16.82	16.02	15.20	14.56
Dallam	35.32	34.70	33.88	32.67	31.04
Donley	8.32	8.31	8.31	8.22	8.24
Gray	14.66	14.46	14.19	13.89	13.68
Hansford	30.28	29.37	27.93	26.23	24.53
Hartley	31.54	31.23	30.72	30.05	29.20
Hemphill	16.30	16.42	16.53	16.63	16.71
Hutchinson	12.48	12.24	11.91	11.56	11.25
Lipscomb	21.46	21.47	21.43	21.26	20.95
Moore	17.81	17.07	16.30	15.19	14.21
Ochiltree	22.51	22.26	21.57	20.42	19.65
Oldham[2]	.03	.03	.04	.04	.04
Potter[2]	2.89	2.79	2.68	2.56	2.46
Randall[2]	.62	.61	.59	.56	.53

See footnotes at end of table.

Table 11

Simulated Volume of Water in Storage During Calibration Period, North Model—Continued

County[1]	Volume, in millions of acre-feet 1960[3]	1965	1970	1975	1980
Roberts	27.82	27.97	28.09	28.18	28.26
Sherman	29.64	28.55	26.89	25.03	23.47
Wheeler	8.12	8.15	8.19	8.21	8.23
Total	301.46	296.43	289.10	279.60	270.62

[1] Approximate representation of counties.
[2] Part of county in south model.
[3] From measured data.

Table 12

Distribution of Saturated Thickness During Calibration Period, North Model

Range of saturated thickness, in feet		Area, in millions of acres				
Greater than	Equal to or less than	1960	1965	1970	1975	1980
0	20	.263	.290	.279	.263	.263
20	40	.338	.300	.311	.338	.349
40	60	.311	.311	.327	.343	.354
60	80	.392	.418	.434	.451	.477
80	100	.510	.526	.477	.510	.520
100	120	.504	.472	.542	.520	.536
120	140	.500	.569	.558	.617	.633
140	160	.483	.467	.493	.520	.590
160	180	.488	.482	.526	.552	.654
180	200	.504	.601	.676	.751	.691
200	240	1.202	1.202	1.255	1.293	1.352
240	300	1.657	1.674	1.625	1.566	1.486
300	340	.907	.848	.778	.654	.536
340	400	.601	.531	.445	.408	.359
400	440	.123	.145	.113	.064	.059
440	—	.097	.043	.038	.027	.016

Figures 15 and 16 show saturated thickness for 1960 and 1980, respectively. The area with 20 feet (6 m) or less of saturated thickness changed little during the calibration period. For 1980, 3 percent of the area has 20 feet (6 m) or less of saturated thickness. For 1980, 78 percent of the area has 100 feet (30 m) or more of saturated thickness, representing a 2 percent decrease from 1960.

Taking the two models as a whole, the initial inputs (prior to model calibration) of specific yield and permeability averaged 15.7 percent and 500 $(gal/d)/ft^2$ [20,370 $(l/d)/m^2$], respectively. After calibration the values are 16.0 percent and 400 $(gal/d)/ft^2$ [16,300 $(l/d)/m^2$], respectively.

Simulation of Future Conditions

The model was applied to simulate the aquifer response to projected pumpage and recharge rates. The aquifer response is indicated by simulated water levels which are directly convertable into saturated thickness. The simulation period began January 1980 and extended through December 2029. Five-year time steps were used.

For the model application, the basic recharge rates developed during the model calibration phase were used for the future simulations. For the south model, the rates for the last two calibration periods, 1970-80, were used. However, it became apparent that using these rates resulted in significant water-level rises in those areas where the recharge rates were increased. These areas are immediately south and southwest of Lubbock County. An analysis of water-level records indicated that if the added recharges were reduced by 70 percent, the water levels could be near original level by 2030. Very recent water-level measurements indicate that the rate of rise of water levels may be slowing, perhaps to the point of remaining constant. Stabilization of water levels would give credence to the idea that the rise in water levels resulted from an isolated event (such as abnormally high precipitation) and justify the decision to reduce the additional recharge. The recharge rates were adjusted and are shown in Tables 13 and 14.

Table 13
Recharge, South Model

	Recharge, in acre-feet per year		
	Calibration Periods		Future Periods
County[1]	1960-69	1970-79	1980-2029
Andrews	25,730	25,720	25,720
Armstrong[2]	100	100	100
Bailey	14,110	14,110	14,110
Borden	130	670	300
Briscoe	770	780	780
Castro	3,280	3,310	3,310
Cochran	16,110	39,880	23,240
Crosby	2,850	2,860	2,860
Dawson	11,290	55,630	24,600

See footnotes at end of table.

Table 13

Recharge, South Model—Continued

County[1]	Recharge, in acre-feet per year: Calibration Periods 1960-69	1970-79	Future Periods 1980-2029
Deaf Smith	4,500	4,550	4,550
Dickens	180	180	180
Ector	4,850	4,850	4,850
Floyd	2,700	2,730	2,730
Gaines	42,830	69,280	50,750
Garza	740	4,040	1,730
Glasscock	940	940	940
Hale	5,910	5,930	5,930
Hockley	7,080	8,860	7,620
Howard	2,610	2,610	2,610
Lamb	14,600	14,600	14,600
Lubbock	6,820	6,830	6,830
Lynn	8,230	42,720	18,590
Martin	7,750	7,760	7,760
Midland	3,270	3,270	3,270
Motley	210	210	210
Oldham[2]	1,690	1,700	1,700
Parmer	3,230	3,260	3,260
Potter[2]	380	380	380
Randall[2]	2,420	2,440	2,440
Swisher	2,570	2,600	2,600
Terry	26,080	85,910	44,040
Yoakum	24,700	52,620	33,070
Total	248,660	471,330	315,660

[1] Approximate representation of counties.
[2] Part of county in north model.

The pumpage projections were determined for municipal and industrial, domestic and livestock, and irrigation needs for the period 1980 through 2029. Projected ground-water demand for municipal and domestic use is based on an October 1981 series D population projection made by the Department in which the estimated surface-water usage was subtracted from the total projected water need. These projections represent estimated maximum needs under drought conditions. Refinement of predictions was made for the most populated cities of Amarillo, Lubbock, Midland, and Odessa from a statistical study (Texas Department of Water Resources, 1981b). Industrial and livestock projected ground-water demand is based on a November 1976 estimate made by the Department.

Table 14
Recharge, North Model

County[1]	Recharge, in acre-feet per year
Armstrong[2]	4,420
Carson	6,120
Dallam	16,190
Donley	10,350
Gray	8,040
Hansford	4,270
Hartley	13,610
Hemphill	9,460
Hutchinson	4,820
Lipscomb	8,910
Moore	3,730
Ochiltree	4,930
Oldham[2]	450
Potter[2]	2,640
Randall[2]	980
Roberts	9,580
Sherman	5,530
Wheeler	9,220
Total	123,250

[1] Approximate representation of counties.
[2] Part of county in south model.

Projection of net withdrawals for irrigation pumpage was based on recent pumping patterns and projected changes in irrigation efficiency. The irrigation pattern for the last 5-year calibration period is from the 1979 irrigation inventory and was the basis for determining withdrawals. The amounts of water withdrawn were adjusted during the calibration phase. Since the amount of water withdrawn is the product of irrigated area times application rate, the adjustment could be applied to either of the terms, or both could be adjusted so that the product equaled the adjusted value. The latter procedure was used. The adjustment was applied equally to each term subject to two constraints. First, the amount of area irrigated cannot indicate that more than 100 percent of the cell is irrigated. Second, the application rate cannot be reduced by more than one-third. The reason for this is the assumption that a certain minimum amount of irrigation was necessary to affect production. If a farmer's water supply was so limited that this minimum amount of water could not be applied to all the farm, then the size of the area irrigated would be reduced so that this minimum amount could be applied.

Irrigation net withdrawals are reduced when saturated thickness becomes thin. The model handles this in two ways-saturated thickness constraint and transmissivity constraint. For further details on these constraints, see the previous "Application to the High Plains Aquifer" section. The T-one constraint values are equal to the smaller of the transmissivity in 1980 or the transmissivity necessary for a 400-gal/min (25-l/s) well as determined by applying the steady radial flow equation. The T-two values were calculated based on the flow equation with the well flow equal to one-tenth of the calculated well flow with transmissivity equal to T-one. A set of T-one and T-two values was calculated for each cell.

The program allows for the effect of pumping lift on irrigation pumpage. The reduction in water used is based on economics (cost of energy, value of crop produced, etc.). Since this study did not include economic projections, the pumping lift constraint was not applied.

The Department has made projections of changes in irrigation practices that result in small application rates. This work was primarily in support of a High Plains Ogallala aquifer study funded in part by the U.S. Department of Commerce (Camp Dresser & McKee, Inc., and others, 1982). As visualized in these projections, the changes in water use would be the result of (1) using soil moisture meters to better determine amount and timing of irrigation, (2) using furrow diking to conserve precipitation and control applied irrigation water, and (3) using better irrigation procedures to increase application efficiency. The base year for this work is 1977, and the efficiency improvements would be fully utilized by 1990. The use of soil moisture meters would reduce per acre water requirements by 20 percent on 85 percent of the areas irrigated. Furrow diking would reduce water use by 25 percent and would be utilized on 85 percent of the areas. Average application efficiency would increase to 85 percent. The average efficiency in 1977 was 61.5 percent with a range of 54 to 70 percent.

For the 1977 base year study,, application rates were determined for five regions of the High Plains. The counties comprising the regions are shown below.

Region	Counties
I	Dallam, Hansford, Hartley, Hemphill, Hutchinson, Lipscomb, Moore, Ochiltree, Roberts, and Sherman.
II	Armstrong, Briscoe, Carson, Castro, Crosby, Deaf Smith, Dickens, Donley, Floyd, Gray, Hale, Motley, Oldham, Parmer, Potter, Randall, Swisher, and Wheeler.

Region	Counties
III	Bailey, Borden, Cochran, Dawson, Garza, Hockley, Lamb, Lubbock, and Lynn.
IV	Gaines, Terry, and Yoakum.
V	Andrews, Ector, Glasscock, Howard, Martin, and Midland.

Irrigation application rates were determined for 1977 and projected for 1985, 1990, 2000, and 2020. Since 1977 is in the last calibration period, the application rates for that period are comparable to the 1977 application rates determined for the study. The application rates projected for future years were divided by the 1977 application rate to obtain an adjustment factor that was applied to the application rate determined for the fourth 5-year calibration period. This procedure implies a one-to-one correspondence between reductions in irrigation applications and reductions in net withdrawals of water from storage due to improved efficiency. This implication would not be true if the increases in efficiency reduced only the amount of over-irrigation and this over-irrigation returned rapidly to the aquifer. If there is return flow of excess irrigation water, the flow would be slow. Since this study did not document return flows and to avoid the problem of timing the impacts of efficiency changes on return flows, the changes were applied directly and fully to net withdrawals. Table 15 lists the factors used.

Table 15

Projected Application Rate Adjustment Factors

Period	Base or projection year	High Plains Region				
		I	II	III	IV	V
1980-1984	1977	1.00	1.00	1.00	1.00	1.00
1985-1990	1985	.89	.59	.63	.68	.64
1990-1999	1990	.70	.40	.43	.49	.50
2000-2009	2000	.62	.37	.41	.48	.50
2010-2019	2000	.62	.37	.41	.48	.50
2020-2029	2020	.62	.36	.39	.48	.68

Conditions along the boundaries affect the results of that portion of the model that is near the boundary. To develop boundary conditions for the periods in the future, it was assumed that the historical water-level change pattern would continue. For the south model, the water-level conditions for New Mexico cells were based on changes in saturated thickness for cells in column 2 of the grid (first Texas cell in each row). The percent of 1975 saturated thickness remaining in 1980 was calculated, and this factor was applied to each 5-year period. For example, if the saturated thickness is 110 feet (34 m) in 1975 and 100 feet (30 m) in 1980, 90.9 percent of the saturated thickness remains. Applying this factor for future time periods results in 90.9 feet (27.7 m) remaining in 1985, 82.6 feet (25.2 m) remaining in 1990, and so on. For each row, the percent of saturated thickness remaining was applied to the column 1 cells (constant water-level wells in New Mexico) to create a set of water-level changes for each 5-year future period. No water-level rises were allowed. The same type of procedure was used for the north model constant-head cells that are in New Mexico and Oklahoma. For those constant water-level cells that form the eastern boundary of the south model, water levels do not change.

The models were applied for the future period assuming that the adjustments in irrigation efficiency would occur fully as projected. Between 1980 and 2030, the area with less than 20 feet (6 m) of saturated thickness in the south model increases 1.438 million acres (5,820 km²), an increase of 83 percent. In 1980, 12.7 percent of the area has 20 feet (6 m) or less of saturated thickness, by 2000 the percentage is 17.7, and by 2030, 23.3 percent. Between 1980 and 2030, the area with more than 100 feet (30 m) of saturated thickness decreases 1.894 million acres (7,670 km²), a decrease of 60.6 percent. In 1980, 23.4 percent of the area has more than 100 feet (30 m) of saturated thickness, by 2000 the percentage is 15.6, and by 2030, 9.2 percent. Table 16 shows the distribution of saturated thickness.

Table 16

Distribution of Saturated Thickness for Future Period, South Model

Range of saturated thickness, in feet		Area, in millions of acres					
Greater than	Equal to or less than	1980	1990	2000	2010	2020	2030
0	20	1.727	2.156	2.403	2.671	2.870	3.165
20	40	2.408	2.913	3.079	3.116	3.315	3.358
40	60	2.703	2.719	2.628	2.559	2.494	2.403
60	80	2.076	1.861	1.743	1.883	1.851	1.990
80	100	1.320	1.218	1.421	1.362	1.352	1.212
100	120	.906	1.024	.949	.885	.799	.703
120	140	.837	.735	.638	.552	.451	.429
140	160	.638	.434	.354	.285	.268	.182
160	180	.440	.252	.193	.150	.102	.064
180	200	.225	.193	.123	.075	.048	.043
200	240	.241	.054	.027	.021	.011	.011
240	300	.038	0.	0.	0.	0.	0.

Between 1980 and 2030, the area with less than 20 feet (6 m) of saturated thickness in the north model area increases 252,100 acres (1,020 km²), an increase of 80 percent. In 1980, 4 percent of the area has 20 feet (6 m) or less of saturated thickness, for 2000 the percentage remains at 4, and by 2030 it increases to 6 percent. Between 1980 and 2030, the area with more than 100 feet (30 m) of saturated thickness decreases 1.287 million acres (5,210 km²), a decrease of 19 percent. In 1980, 77 percent of the area has more than 100 feet (30 m) of saturated thickness, by 2000 the percentage is 72, and by 2030, 63 percent. Table 17 shows the distribution of saturated thickness for the north model. Figures 17 and 18 show projected saturated thickness of the High Plains aquifer for the years 2000 and 2030, respectively.

Table 17

Distribution of Saturated Thickness for Future Period, North Model

Range of saturated thickness, in feet		Area, in millions of acres					
Greater than	Equal to or less than	1980	1990	2000	2010	2020	2030
0	20	.316	.322	.349	.386	.456	.569
20	40	.365	.381	.434	.493	.552	.595
40	60	.359	.413	.483	.515	.579	.729
60	80	.440	.558	.574	.681	.756	.729
80	100	.558	.622	.644	.676	.697	.703
100	120	.628	.622	.719	.719	.719	.740
120	140	.590	.772	.708	.767	.799	.772
140	160	.644	.622	.756	.735	.681	.767
160	180	.622	.697	.713	.708	.762	.676
180	200	.611	.703	.676	.724	.660	.601
200	240	1.261	1.234	1.153	1.024	.939	.869
240	300	1.550	1.164	1.019	.906	.810	.687
300	—	.933	.767	.649	.542	.467	.440

Tables 18 and 19 list the volumes of water remaining in storage. During the 50-year period, the total volume of water in storage in the south model decreases 47.82 million acre-feet (59,000 hm^3), a decline of 31 percent. Some counties show small changes, and three counties show a net increase in storage. Probably, the recharge rates used for these areas are slightly large. The counties showing the largest decreases in volume of storage are those which are most heavily irrigated. Bailey, Castro, Deaf Smith, Floyd, Gaines, Hale, Lamb, and Parmer Counties show a total decline in volume of water in storage of 39.25 million acre-feet (48,400 hm^3) or 82 percent of the total for the south model.

During the 50-year period, the total volume of water in storage in the north model decreases 62.10 million acre-feet (76,600 hm^3), a decline of 23 percent. Hemphill and Roberts Counties show a net increase in volume of storage. Hansford, Sherman, and Moore Counties show the largest decrease in volume of storage and are among the most heavily irrigated. The total decline for these counties is 29.06 million acre-feet (35,800 hm^3) or 47 percent of the total decline for the north model.

Table 18

Simulated Volume of Water in Storage for Future Period, South Model

	Volume, in millions of acre-feet					
County[1]	1980[3]	1990	2000	2010	2020	2030
Andrews	4.66	4.80	4.95	5.10	5.24	5.35
Armstrong[2]	.10	.09	.09	.09	.09	.08
Bailey	6.80	5.77	5.25	4.73	4.25	3.84
Borden	.04	.03	.03	.03	.03	.03
Briscoe	1.34	1.07	.95	.86	.79	.73
Castro	13.35	10.67	9.20	8.14	7.02	5.99
Cochran	3.61	3.07	2.90	2.77	2.65	2.55
Crosby	5.71	5.66	5.61	5.53	5.43	5.31
Dawson	4.85	4.79	4.82	4.85	4.90	4.94
Deaf Smith	11.51	9.52	8.68	7.94	7.23	6.56
Dickens	.67	.61	.57	.55	.53	.52
Ector	2.26	2.23	2.22	2.23	2.24	2.24
Floyd	9.83	8.18	7.49	6.88	6.29	5.75
Gaines	13.41	11.90	11.31	10.79	10.34	9.97
Garza	.33	.32	.32	.33	.34	.34
Glasscock	.98	.95	.94	.93	.93	.91
Hale	13.83	12.26	11.54	10.86	10.14	9.39
Hockley	4.24	3.95	3.83	3.74	3.67	3.59
Howard	.97	1.00	1.04	1.08	1.12	1.15
Lamb	11.15	9.46	8.50	7.60	6.78	6.04
Lubbock	4.68	4.43	4.28	4.14	3.99	3.84
Lynn	2.70	2.63	2.69	2.76	2.82	2.88
Martin	4.37	4.27	4.25	4.26	4.28	4.28
Midland	1.68	1.53	1.48	1.44	1.40	1.34
Motley	.53	.49	.45	.42	.39	.37
Oldham[2]	1.18	1.11	1.07	1.03	1.00	.96
Parmer	11.35	8.66	7.41	6.33	5.32	4.44
Potter[2]	.48	.45	.43	.42	.41	.40
Randall[2]	3.74	3.22	2.86	2.56	2.38	2.24
Swisher	4.80	4.00	3.59	3.22	2.86	2.53
Terry	3.94	3.52	3.52	3.53	3.54	3.56
Yoakum	5.04	4.51	4.33	4.23	4.19	4.19
Total	154.13	135.15	126.60	119.37	112.59	106.31

[1] Approximate representation of counties.
[2] Part of county in north model.
[3] From measured data.

Table 19

Simulated Volume of Water in Storage for Future Period, North Model

County[1]	Volume, in millions of acre-feet					
	1980[3]	1990	2000	2010	2020	2030
Armstrong[2]	3.41	3.22	3.05	2.90	2.76	2.64
Carson	14.52	13.30	12.16	11.08	10.05	9.06
Dallam	30.14	27.16	25.08	23.36	21.74	20.26
Donley	7.98	8.02	8.04	8.05	8.06	8.06
Gray	13.50	13.08	12.67	12.25	11.82	11.46
Hansford	24.68	21.48	19.23	17.31	15.45	13.70
Hartley	28.57	26.91	25.71	24.66	23.65	22.69
Hemphill	16.30	16.46	16.61	16.76	16.88	16.98
Hutchinson	10.86	10.27	9.77	9.35	8.96	8.56
Lipscomb	20.55	20.06	19.68	19.33	18.97	18.62
Moore	14.41	12.57	11.22	9.98	8.70	7.38
Ochiltree	19.04	17.61	16.57	15.67	14.79	13.92
Oldham[2]	.03	.04	.04	.05	.06	.07
Potter[2]	2.65	2.41	2.19	1.99	1.82	1.66
Randall[2]	.58	.51	.46	.41	.37	.33
Roberts	27.62	27.75	27.88	27.99	28.08	28.15
Sherman	23.49	20.53	18.33	16.34	14.39	12.50
Wheeler	8.12	8.13	8.17	8.21	8.26	8.31
Total	266.45	249.51	236.86	225.69	214.81	204.35

[1] Approximate representation of counties.
[2] Part of county in south model.
[3] From measured data.

Ground-water flow from New Mexico in the south model is 44,400 acre-feet (54.7 hm^3) per year and 28,800 acre-feet (35.5 hm^3) per year using January 1, 2000, and January 1, 2030, water levels, respectively. Flows out of the model into the constant-head cells along the eastern boundary equal 44,800 acre-feet (55.2 hm^3) per year and 32,900 acre-feet (40.6 hm^3) per year using January 1, 2000, and January 1, 2030, water levels, respectively.

Ground-water flow from New Mexico for the west side of the north model is 21,100 acre-feet (26.0 hm^3) per year and 16,700 acre-feet (20.6 hm^3) per year using January 1, 2000, and January 1, 2030, water levels, respectively. Net southward flow into Texas from Oklahoma is 23,500 acre-feet (29 hm^3) per year and 27,900 acre-feet (34.4 hm^3) per year for 2000 and 2030 water levels, respectively. Net flow of water on the east side of the north model from Texas into Oklahoma is 13,700 acre-feet (16.9 hm^3) and 16,100 acre-feet (19.9 hm^3) per year for 2000 and 2030, respectively.

Tables 20 and 21 list the net withdrawals for the future period for the two models. For the 50-year period, the south model net withdrawals are reduced 1.869 million acre-feet(2,300 hm^3) per year, a reduction of 67 percent. Withdrawals for the north model area during the same period are reduced 769,740 acre-feet (949 hm^3) per year, a reduction of 40 percent. These reductions result from a decrease in application rates due to projected increases in application efficiency and from the depletion of the aquifer. The increase in efficiency changes the annual water requirement for irrigation for the south model by 1.601 million acre-feet (1,970 hm^3) per year, a reduction of 61 percent; and by 632,000 acre-feet (779 hm^3) per year for the north model, a reduction of 34 percent. Tables 22 and 23 list water requirement data as well as other information related to the model runs. As the aquifer is depleted, the ability of wells to yield water decreases. The transmissivity and saturated thickness constraints attempt to represent this process. If the transmissivity constraint is applied to a cell, the reduction is applied equally to the area irrigated and to the application rate. If the saturated thickness constraint applies to a cell, no irrigation takes place. Tables 22 and 23 show the impact of these two constraints on the area under irrigation. During the 50-year period, the reduction equals 618,000 acres (2,500 km^2), a 20 percent reduction for the south area, and 167,000 acres (676 km^2), an 11 percent reduction for the north area.

Table 20
Annual Net Withdrawals for Future Period, North Model

County[1]	Withdrawal, in acre-feet per year					
	1980	1990	2000	2010	2020	2030
Armstrong[2]	11,140	10,300	9,570	9,030	8,570	7,860
Carson	147,140	137,590	131,500	124,580	119,350	115,020
Dallam	334,990	23 1,360	199,430	189,540	177,210	165,240
Donley	16,530	16,380	16,320	16,330	16,420	16,520
Gray	36,400	34,960	34,900	36,510	39,310	30,770
Hansford	361,630	247,160	214,690	208,980	197,870	185,010
Hartley	178,360	124,950	109,610	107,830	104,280	97,590
Hemphill	9,160	7,890	8,060	9,120	10,520	6,490
Hutchinson	75,200	55,600	53,460	57,840	40,530	70,400
Lipscomb	56,140	39,730	35,510	35,700	35,850	36,030
Moore	230,880	165,030	150,180	152,910	154,090	152,660
Ochiltree	165,700	116,540	101,410	100,000	98,680	97,320
Oldham	100	110	160	190	230	260
Potter[2]	4,690	4,860	5,610	4,810	5,760	2,920
Randall[2]	6,430	5,740	5,220	4,840	4,430	4,120
Roberts	13,420	9,590	8,550	8,580	8,660	8,750
Sherman	290,900	205,350	183,010	182,900	181,500	170,590
Wheeler	7.500	7,500	7,670	7,920	8,350	9,020
Total	1,946,310	1,420,640	1,274,860	1,257,610	1,211,610	1,176,570

1 Approximate representation of counties.
2 Part of county in south model.

Table 21
Annual Net Withdrawals for Future Period, South Model

County[1]	Withdrawal, in acre-feet per year					
	1980	1990	2000	2010	2020	2030
Andrews	12,960	8,600	8,740	9,180	11,100	12,000
Armstrong[2]	4,930	1,520	1,410	1,380	1,300	1,250
Bailey	155,940	68,880	67,540	67,340	56,360	62,150
Borden	190	70	60	60	50	50
Briscoe	26,940	8,810	7,660	7,100	6,440	5,930
Castro	305,990	120,910	109,340	106,010	99,550	92,640
Cochran	88,950	33,620	30,540	29,120	26,900	26,430
Crosby	17,930	8,250	8,370	8,390	8,840	9,670
Dawson	20,730	9,740	9,500	9,690	9,640	10,230
Deaf Smith	269,290	88,400	78,020	74,160	70,400	68,630
Dickens	2,210	1,130	1,070	1,090	1,120	1,170
Ector	8,680	5,640	3,530	3,310	4,270	4,820
Floyd	257,040	98,790	88,050	85,410	80,540	77,870
Gaines	261,640	120,540	114,110	103,500	94,040	86,410
Garza	4,310	1,660	1,560	1,570	1,530	1,570
Glasscock	6,290	2,740	2,630	2,570	3,410	3,360
Hale	220,900	92,840	88,040	91,280	92,350	98,590
Hockley	50,600	26,470	25,660	20,920	19,280	19,980
Howard	1,140	1,260	1,280	1,320	1,540	1,220
Lamb	214,150	102,990	92,610	86,620	74,150	80,110
Lubbock	27,240	14,660	14,980	15,920	16,210	17,600
Lynn	31,730	11,870	11,210	11,320	11,150	11,340
Martin	25,870	16,510	13,790	10,660	13,340	13,610
Midland	26,950	11,410	10,110	9,520	12,080	10,900
Motley	100	40	40	30	30	20
Oldham[2]	6,810	2,690	2,540	2,590	2,680	2,830
Parmer	359,350	139,080	123,230	115,890	104,780	91,160
Potter[2]	1,600	510	400	350	330	300
Randall[2]	68,740	40,470	40,820	27,100	33,510	15,940
Swisher	104,470	38,960	35,470	34,660	30,260	28,360
Terry	106,670	40,140	39,550	39,630	39,720	39,850
Yoakum	98,850	43,640	41,000	30,980	25,210	24,240
Total	2,789,190	1,162,840	1,072,860	1,008,670	952,110	920,230

[1]Approximate representation of counties.
[2]Part of county in north model.

Table 22

Selected Results for Future Period, South Model

Item	1980	1990	2000	2010	2020	2030
Irrigation						
Water requirement[1]	2,641	1,119	1,055	1,055	1,040	1,040
Amount supplied[1]	2,625	990	897	856	795	740
Amount unsupplied[1]	16	129	158	199	245	300
Percent unsupplied	1	12	15	19	24	29
Acres supplied[2]	3,085	2,868	2,785	2,693	2,582	2,467
Municipal and industrial						
Water requirement[1]	121	130	138	135	155	188
Amount supplied[1]	120	126	124	95	91	105
Amount unsupplied[1]	0	4	14	40	64	83
Percent unsupplied	0	3	10	30	41	44
Domestic and livestock						
Water requirement[1]	44	48	53	61	69	80
Amount supplied[1]	44	47	52	58	66	75
Amount unsupplied[1]	0	1	1	3	3	5
Percent unsupplied	0	2	2	5	4	6

[1]Thousands of acre-feet per year.
[2]Thousands of acres.

Table 23

Selected Results for Future Period, North Model

Item	1980	1990	2000	2010	2020	2030
Irrigation						
Water requirement[1]	1,873	1,374	1,241	1,241	1,241	1,241
Amount supplied[1]	1,873	1,345	1,185	1,151	1,106	1,040
Amount unsupplied[1]	0	29	56	90	135	201
Percent unsupplied	0	2	5	7	11	16
Acres supplied[2]	1,503	1,484	1,464	1,436	1,397	1,336
Municipal and industrial						
Water requirement[1]	53	53	64	81	103	135
Amount supplied[1]	53	53	64	78	74	101
Amount unsupplied[1]	0	0	0	3	29	34
Percent unsupplied	0	0	0	4	28	25

See footnotes at end of table.

Table 23

Selected Results for Future Period, North Model—Continued

Item	1980	1990	2000	2010	2020	2030
Domestic and livestock						
Water requirement[1]	21	23	26	29	32	36
Amount supplied[1]	21	23	26	29	32	31
Amount unsupplied[1]	0	0	0	0	0	1
Percent unsupplied	0	0	0	0	0	3

[1]Thousands of acre-feet per year.
[2]Thousands of acres.

The projected amounts of water withdrawn to supply water for uses other than irrigation also are affected by the depletion of the aquifer. The saturated thickness constraint allows water to be withdrawn for domestic and livestock uses only if the saturated thickness is greater than 2 feet (0.6 m). As shown in Tables 22 and 23, the aquifer was able to supply almost all of this water requirement.

However, based on the projections, the aquifer was unable to supply water to many municipal and industrial water users. Water can be withdrawn for these uses only if saturated thickness exceeds 5 feet (1.5 m). By 2010, 20 percent of the requirement is not supplied, and the shortage approaches 36 percent by 2030. The following is a list of the significant municipal and industrial users whose water requirements are not supplied.

Year	User
1990	Abernathy, New Deal, and Canyon's near city well field
2000	Abernathy; Lockney; New Deal; Bovina; Littlefield; Canyon's near city well field; and Panhandle Eastern Pipe Line Company, Sneed Station and Phillips Petroleum Company, Sneed Plant east of Dumas
2010	Abernathy; Lubbock's sand hills well field (Bailey and Lamb Counties); Lockney; New Deal; Midland's Davis well field; Bovina, Kress; Littlefield; Canyon's near city well field; Amarillo's northwest Randall County well field; Panhandle Eastern Pipe Line Company, Sneed Station and Phillips Petroleum Company, Sneed Plant east of Dumas; Phillips Petroleum Company, Herring-Pantex and Kay-Pantex Water Stations northwest of Stinnett; and miscellaneous industrial users in north Amarillo
2020	Abernathy; Lubbock's sand hills well field (Bailey and Lamb Counties); Sudan; Lockney; New Deal; Midland's Davis well field; Bovina; Tulia; Kress; Denver City; Littlefield; Canyon's near city well field; Amarillo's northwest Randall County well field; Panhandle Eastern Pipe Line Company, Sneed Station and Phillips Petroleum

Year	User
	Company, Sneed Plant east of Dumas; Phillips Petroleum Company, Herring-Pantex and Kay-Pantex Water Stations northwest of Stinnett; miscellaneous industrial users in north Amarillo; and El Paso Natural Gas Company and Phillips Petroleum Company, Dumas Plants south of Dumas
2030	Abernathy; Lubbock's sand hills well field (Bailey and Lamb Counties); Sudan; Lockney; New Deal; New Home; Midland's Davis well field; Bovina; Friona; Tulia; Kress; Denver City; Littlefield; Canyon's near city well field; Canyon's northwest Randall County well field; Amarillo's northwest Randall County well field; Panhandle Eastern Pipe Line Company, Sneed Station; Phillips Petroleum Company, Sneed Plant east of Dumas; Phillips Petroleum Company, Herring-Pantex and Kay-Pantex Water Stations northwest of Stinnett; miscellaneous industrial users in north and northeast Amarillo; El Paso Natural Gas Company and Phillips Petroleum Company, Dumas Plants south of Dumas; (Colorado Interstate Gas Company, Bivins Station south of Dumas; Cabot Corporation, Pampa Plant and Celanese Chemical Company Plant southwest of Pampa; Wheeler Beef Cattle Company near Wheeler; Canadian; and Cities Service Gas Company, Higgins Station near Canadian

Also, Hereford almost was unable to meet its water requirements for 2030. Many of these users probably have plans to obtain water supplies from other areas or sources. The above listed information does not mean that the users will be without water.

Results of the models were used to estimate the amounts of water available for future development. Previous estimates of availability for the Ogallala aquifer were based on projected rates of pumpage with the associated change in volume of water in storage. Also, it was assumed in the previous estimates that the lower 20 feet (6 m) of the aquifer was not capable of sustaining large-yield wells, therefore the volume of water contained in the lower 20 feet (6 m) was not available for production. The volume of water available for production equaled total volume minus the volume of water stored in the lower 20 feet (6 m) of the aquifer. For this study, a similar technique was used. Tables 20 and 21 list net withdrawals for the future period. These values could be used to represent the annual ground-water availability for the aquifer since the projected volume of water in storage did not go below that volume deemed to be recoverable. For this study, the unrecoverable volume is the volume of water in storage in the lower 10 feet (3 m) of the aquifer. The change from 20 to 10 feet (6 to 3 m) was made because of the greatly improved, detailed information known about the aquifer which allows rnore precise measurements to be made and because of the projected increase in irrigation efficiency. The large decrease in application rates means that low yielding portions of the aquifer can support irrigation easier. It is realized that 10 feet (3 m) is insufficient for large-capacity wells, but it is believed that the use of 10 feet (3 m) will result in more realistic estimates of the unrecoverable volume of water. Tables 24 and 25 list the unrecoverable volume as well as the volume of recoverable water for 1980, 2000, and 2030. The values for 2000 and 2030 are only one set of the many values which could occur.

The initial runs of the north and south models used the full application rate adjustments anticipated due to changes in irrigation practices. In order to adequately represent the impact such adjustments would have on the volume of water in storage, on the annual net withdrawal, and on the total irrigated acres, subsequent runs were made with one-half of the total adjustments and without application rate adjustments applied. Tables 26 and 27 show the results of the north and south future model runs under the three conditions.

Table 24

Recoverable Volume of Water in Storage, North Model

	Volume, in millions of acre-feet			
	Unrecoverable	Recoverable		
County[1]		1980	2000	2030
Armstrong[2]	0.47	2.94	2.58	2.17
Carson	.92	13.60	11.24	8.14
Dallam	1.71	28.43	23.37	18.55
Donley	.64	7.34	7.40	7.42
Gray	1.02	12.48	11.65	10.44
Hansford	1.06	23.62	18.17	12.64
Hartley	1.61	26.96	24.10	21.08
Hemphill	.93	15.37	15.68	16.05
Hutchinson	.69	10.17	9.08	7.87
Lipscomb	.96	19.59	18.72	17.66
Moore	.76	13.65	10.46	6.62
Ochiltree	.90	18.14	15.67	13.02
Oldham[2]	.03	.0	.01	.04
Potter[2]	.27	2.38	1.92	1.39
Randall[2]	.12	.46	.34	.21
Roberts	1.01	26.61	26.87	27.14
Sherman	1.05	22.44	17.28	11.45
Wheeler	.58	7.54	7.59	7.73
Total	14.73	251.72	222.13	189.62

[1]Approximate representation of counties.
[2]Part of counties in south model.

Table 25

Recoverable Volume of Water in Storage, South Model

	Volume, in millions of acre-feet			
	Unrecoverable	Recoverable		
County[1]		1980	2000	2030
Andrews	1.23	3.43	3.72	4.12
Armstrong[2]	.03	.07	.06	.05

See footnotes at end of table.

Table 25

Recoverable Volume of Water in Storage, South Model—Continued

	Volume, in millions of acre-feet			
	Unrecoverable	Recoverable		
County[1]		1980	2000	2030
Bailey	.81	5.99	4.44	3.03
Borden	.01	.03	.02	.02
Briscoe	.24	1.10	.71	.49
Castro	1.05	12.30	8.15	4.94
Cochran	.83	2.78	2.07	1.72
Crosby	.53	5.18	5.08	4.78
Dawson	.70	4.15	4.12	4.24
Deaf Smith	1.54	9.97	7.14	5.02
Dickens	.04	.63	.53	.48
Ector	.45	1.81	1.77	1.79
Floyd	.99	8.84	6.50	4.76
Gaines	1.37	12.04	9.94	8.60
Garza	.07	.26	.25	.27
Glasscock	.14	.84	.80	.77
Hale	1.12	12.71	10.42	8.27
Hockley	.88	3.36	2.95	2.71
Howard	.39	.58	.65	.76
Lamb	1.05	10.10	7.45	4.99
Lubbock	.80	3.88	3.48	3.04
Lynn	.80	1.90	1.89	2.08
Martin	.86	3.51	3.39	3.42
Midland	.41	1.27	1.07	.93
Motley	.08	.45	.37	.29
Oldham[2]	.30	.88	.77	.66
Parmer	.98	10.37	6.43	3.46
Potter[2]	.09	.38	.34	.31
Randall[2]	.79	2.95	2.07	1.45
Swisher	.80	4.00	2.79	1.73
Terry	.96	2.98	2.56	2.60
Yoakum	.83	4.21	3.50	3.36
Total	21.17	132.95	105.43	85.14

[1] Approximate representation of counties.
[2] Part of county in north model.

Table 26

Effect of Application Rate Adjustment on Volume of Water in Storage, Annual Net Withdrawal, and Irrigated Acres for Future Period, North Model

Year	Total volume in storage (millions of acre-feet)	Average annual withdrawal (acre-feet per year)	Total irrigated area (acres)
	I. No application rate adjustment		
1980	266.43	1,946,310	1,502,700
1990	248.61	1,909,540	1,482,520
2000	231.22	1,853,370	1,448,400
2010	214.63	1,727,730	1,379,210
2020	199.46	1,577,820	1,270,400
2030	186.18	1,342,820	1,131,730
	II. One-half application rate adjustment		
1980	266.43	1,946,310	1,502,700
1990	249.02	1,665,240	1,483,120
2000	233.99	1,567,450	1,456,150
2010	220.05	1,501,250	1,413,230
2020	206.80	1,433,540	1,338,090
2030	194.64	1,268,440	1,246,500
	III. Full application rate adjustment		
1980	266.43	1,946,310	1,502,700
1990	249.51	1,420,640	1,483,810
2000	236.86	1,274,860	1,463,660
2010	225.69	1,257,610	1,435,710
2020	214.81	1,211,610	1,396,530
2030	204.35	1,176,570	1,336,400

By 2030, the north model area shows an 18.17 million acre-feet (22,400 hm^3) difference in the volume of water in storage between the run with the full adjustment applied and the run without adjustments. For the south model, the difference is 32.6 million acre-feet (40,200 hm^3). The average annual net withdrawal in the south model decreases 63 percent between 1980 and 2030 using no application rate adjustments, 61 percent using the one-half rate adjustments, and 67 percent using the full rate adjustments. Similarly, in the north model, the decreases in the average annual net withdrawal are 31 percent, 35 percent, and 40 percent, respectively. Between 1980 and 2030, irrigated acres in the north model decrease by 370,970 acres (1,500 km^2) without adjustment, 256,200 acres (1,040 km^2) with one-half of the adjustment rate, and 166,300 acres (673 km^2) with full application of the rate adjustment. The south model shows decreases of 1.590 million acres (6,430 km^2), 1.142 million acres (4,620 km^2), and 618,680 acres (2,500 km^2), respectively. Graphical representations of these data are shown in Figure 19.

Table 27

Effect of Application Rate Adjustment on Volume of Water in Storage, Annual Net Withdrawal, and Irrigated Acres for Future Period, South Model

Year	Total volume in storage (millions of acre-feet)	Average annual withdrawal (acre-feet per year)	Total irrigated area (acres)
	I. No application rate adjustment		
1980	154.13	2,789,180	3,085,480
1990	130.53	2,437,170	2,805,940
2000	110.44	2,060,120	2,491,660
2010	94.43	1,611,930	2,109,450
2020	82.60	1,291,060	1,784,940
2030	73.71	1,042,410	1,495,800
	II. One-half application rate adjustment		
1980	154.13	2,789,180	3,085,480
1990	132.81	1,816,880	2,838,540
2000	118.27	1,641,830	2,649,160
2010	105.68	1,431,410	2,429,690
2020	95.17	1,210,530	2,178,300
2030	86.69	1,085,990	1,943,710
	III. Full application rate adjustment		
1980	154.13	2,789,180	3,085,480
1990	135.15	1,162,840	2,867,700
2000	126.60	1,072,860	2,785,440
2010	119.37	1,008,670	2,692,790
2020	112.59	952,110	2,582,330
2030	106.31	920,230	2,466,800

When considering the quantity of water available for future development, it is important to know in what areas and at what depths water exists. Tables 28 and 29 list values which describe the location of recoverable water. Of particular interest may be the data which indicate the volume of water stored in various depth intervals. For example, 5.49 million acre-feet (6,770 hm^3) of water is stored in Castro County in that portion of the aquifer that is between 200 and 300 feet (60 and 90 m) below land surface. The northern area contains 65 percent of the water in storage but at greater depth. On the average, water in the north is 70 feet (20 m) deeper than water in the south. For the south model, almost 50 percent of the water is within 200 feet (60 m) of the land surface, 81 percent within 300 feet (90 m), and 98 percent within 400 feet (120 m). For the north area, 30 percent is within 200 feet (60 m) of the surface, 56 percent within 300 feet (90 m), 81 percent within 400 feet (120 m), and 98 percent within 600 feet (180 m). However, the north and south area each contain about the same amount of water within 300 feet (90 m) of the land

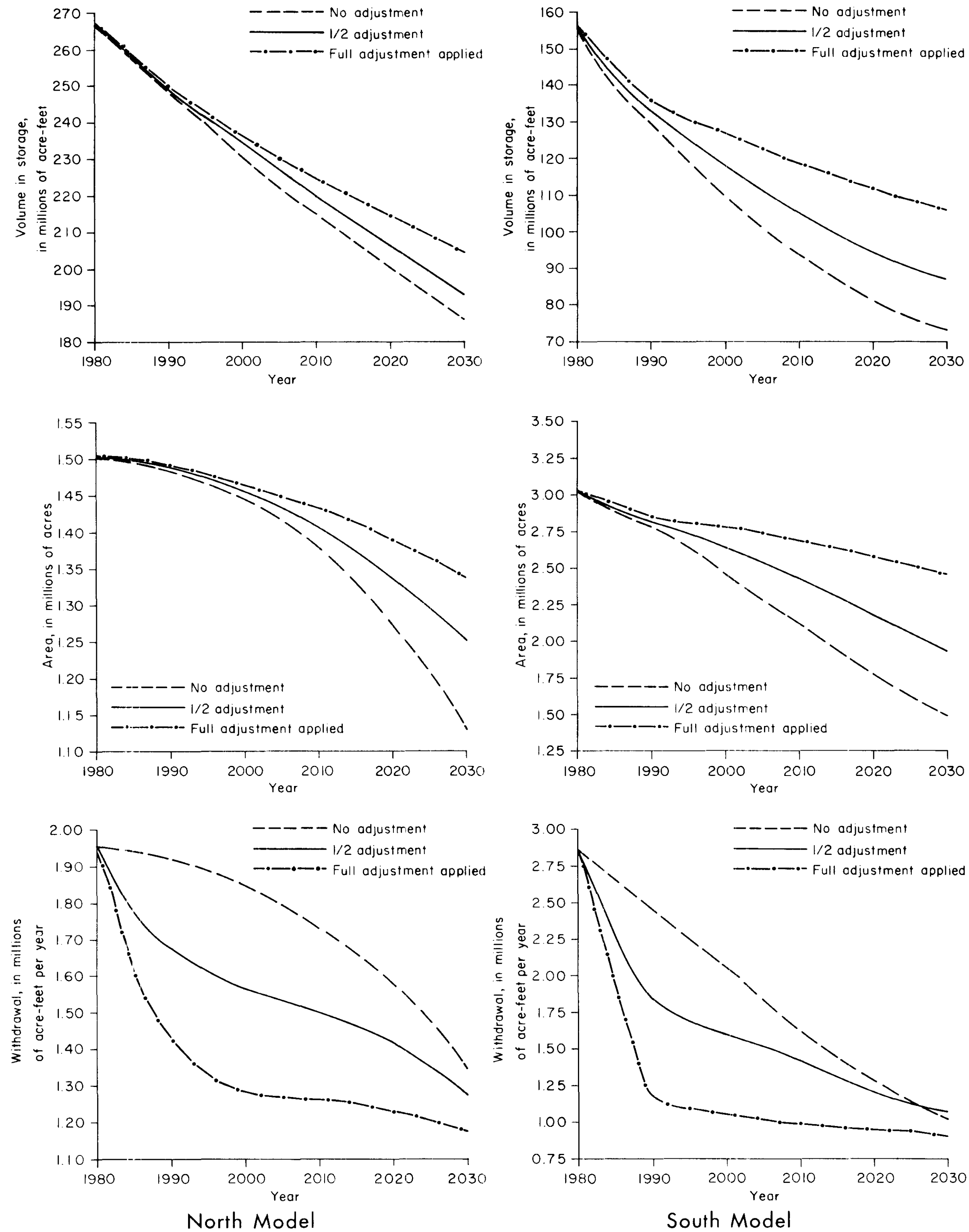


Figure 19
Selected Results for Future Period

Table 28

Condition of Aquifer in 1980, South Model

County[1]	Area (thousands of acres)	Average depth to base (feet)	Average Depth to water level (feet)	Average saturated thickness (feet)	Volume of recoverable water by ranges of depth below land surface (millions of acre-feet)				
					0-100 feet	100-200 feet	200-300 feet	300-400 feet	400-500 feet
Andrews	910	112	75	37	1.93	1.50	—	—	—
Armstrong[2]	20	168	135	33	—	.07	—	—	—
Bailey	550	172	94	78	1.40	2.96	1.21	0.42	—
Borden	10	61	28	33	.03	—	—	—	—
Briscoe	160	202	145	57	.06	.74	.30	—	—
Castro	590	326	200	125	.06	.95	5.49	5.24	0.56
Cochran	480	194	153	41	.06	2.11	.61	—	—
Crosby	350	333	222	111	.03	.64	2.53	1.92	.06
Dawson	490	137	68	68	1.71	2.39	.05	—	—
Deaf Smith	940	274	200	73	.23	1.74	4.73	3.09	.18
Dickens	40	400	250	150	—	.06	.16	.36	.05
Ector	280	116	65	51	1.20	.61	—	—	—
Floyd	560	307	206	100	.11	.81	4.89	2.88	.15
Gaines	900	185	86	99	2.51	8.57	.96	—	—
Garza	60	101	49	51	.21	.05	—	—	—
Glasscock	80	150	80	69	.26	.43	.15	—	—
Hale	690	278	157	120	.04	2.77	8.02	1.82	.06
Hockley	550	165	117	47	.49	2.43	.44	—	—
Howard	210	76	51	25	.55	.03	—	—	—
Lamb	660	229	130	98	.42	4.28	4.12	1.28	—
Lubbock	560	187	129	58	.60	1.73	1.32	.23	—
Lynn	570	83	50	32	1.26	.42	.19	.03	—

See footnotes at end of table.

Table 28

Condition of Aquifer in 1980, South Model—Continued

County[1]	Area (thousands of acres)	Average depth to base (feet)	Average Depth to water level (feet)	Average saturated thickness (feet)	Volume of recoverable water by ranges of depth below land surface (millions of acre-feet)				
					0-100 feet	100-200 feet	200-300 feet	300-400 feet	400-500 feet
Martin	430	122	71	50	1.82	1.66	0.03	—	—
Midland	280	99	57	42	.95	.32	—	—	—
Motley	40	229	159	70	.06	.16	.16	.07	—
Oldham[2]	210	170	131	38	.11	.38	.36	.03	—
Parmer	540	371	254	117	—	.26	3.54	5.21	1.36
Potter[2]	50	151	102	49	.11	.21	.06	—	—
Randall[2]	500	185	140	45	.30	1.49	1.09	.07	—
Swisher	540	199	140	58	.41	2.09	1.32	.18	—
Terry	650	139	98	41	1.19	1.78	.01	—	—
Yoakum	530	172	112	60	.41	3.63	.17	—	—
Total	13,540	199	128	70	18.52	47.27	41.91	22.83	2.42

[1]Approximate representation of counties.
[2]Part of county in north model.

Table 29
Condition of Aquifer in 1980, North Model

County[1]	Area (thousands of acres)	Average depth to base (feet)	Average depth to water level (feet)	Average saturated thickness (feet)	Volume of recoverable water by ranges of depth below land surface (millions of acre-feet)							
					0-100 feet	100-200 feet	200-300 feet	300-400 feet	400-500 feet	500-600 feet	600-700 feet	700+ feet
Armstrong[2]	320	251	179	71	0.15	1.23	1.30	0.24	0.02	—	—	—
Carson	530	454	292	162	.05	.42	1.54	3.63	3.63	2.34	1.61	0.38
Dallam	1,000	402	225	176	1.04	4.42	7.27	10.13	5.14	.43	—	—
Donley	380	222	100	122	1.71	2.66	.99	.98	.64	.29	.07	—
Gray	570	352	218	134	.86	2.00	2.15	3.79	2.85	.83	—	—
Hansford	630	458	230	228	.29	2.04	5.88	7.42	5.17	1.85	.76	.21
Hartley	900	390	217	173	.42	3.45	6.95	7.42	6.24	2.34	.14	—
Hemphill	540	276	99	176	2.14	5.65	4.31	2.27	.69	.23	.08	—
Hutchinson	410	319	165	154	.72	2.18	2.56	2.99	1.60	.12	—	—
Lipscomb	650	369	158	211	.47	3.65	7.22	5.72	2.22	.31	—	—
Moore	510	411	230	181	.16	.52	2.41	4.90	3.29	1.40	.68	.29
Ochiltree	590	493	288	205	0.	.30	2.22	5.46	5.19	2.90	1.58	.49
Oldham[2]	30	120	108	11	.00	—	—	—	—	—	—	—
Potter[2]	200	252	157	95	.19	.55	.75	.42	.27	.17	.03	—
Randall[2]	100	240	194	46	0.	.06	.40	—	—	—	—	—
Roberts	590	462	187	275	1.65	3.96	5.43	6.24	5.60	3.15	.53	.05
Sherman	610	443	219	224	.04	.99	7.37	9.10	4.31	.60	.01	—
Wheeler	340	212	73	139	1.66	2.67	1.79	.99	.32	.11	—	
Total	8,900	378	199	178	11.55	36.75	60.54	71.70	47.18	17.07	5.49	1.42

[1]Approximate representation of counties.
[2]Part of county in south model.

surface. For the entire aquifer in Texas, 30 percent of the water is within 200 feet (60 m) of the land surface, 56 percent within 300 feet (90 m), 81 percent within 400 feet (120 m), and 94 percent within 500 feet (150 m). And, for the entire aquifer in Texas, the average depth to base of aquifer is 270 feet (82 m), average depth to water in 1980 is 156 feet (48 m), and average saturated thickness in 1980 is 112 feet (34 m).

The land surface was categorized as either “caprock” or breaks, the caprock being the relatively flat, easily cultivated portion of the area. The breaks is the area that is rolling and unsuited for cultivation. Canyons, ravines, and gullies fall into the breaks category. For the south model, 147.05 million acre-feet (181,000 hm^3) of water was stored in the caprock areas, and 7.08 million acre-feet (8,730 hm^3) was stored in the breaks in 1980. For the north model, 143.73 million acre-feet (177,000 hm^3) of water was stored in the caprock areas and 122.72 million acre-feet 151,000 hm3) was stored in the breaks in 1980. For the total aquifer in Texas, 290.78 million acre-feet (359,000 hm^3) was stored in the caprock areas and 129.80 million acre-feet (160,000 hm^3) was stored in the breaks in 1980. For the future simulations, almost all the decline in volume in storage for the south model and 85 percent of the decline in the north model was in caprock areas. For the total aquifer in Texas, over 90 percent of the decline in volume in storage was in caprock areas. For the south model, approximately 55 percent of the water stored in caprock areas remains in storage in 2030, and approximately 90 percent of the water in the breaks remains. For the north model, approximately 60 percent of the caprock area water remains in 2030 and 95 percent of the breaks water remains. For the total aquifer in Texas approximately 55 percent of the water stored in caprock areas remains in 2030 and 90 percent of the water in the breaks remains.

RESULTS AND CONCLUSIONS

The High Plains aquifer of Texas consists of the saturated sediments of the Ogallala Formation and those underlying units of Cretaceous, Jurassic, and Triassic age that are in hydraulic continuity and which contain potable water. Hydraulically connected Cretaceous water-bearing strata occur in the southern half of the study area and in northwest Dallam County. Jurassic water-bearing strata occur in north-central Dallam County, and Triassic water-bearing strata occur in Hansford, Hutchinson, Moore, and Randall Counties to the north and in all or parts of Crosby, Dickens, Garza, and Motley Counties to the southeast.

The principal water-bearing unit, the Ogallala, consists primarily of fluvial elastics which fine upward from coarse-grained basal sediments, and is often capped by a hard, indurated, semi-impermeable layer of caliche. A knowledge of the distribution and zonation of the various sediment types comprising the Ogallala is essential in understanding the hydraulic properties of the aquifer.

Recharge to the High Plains aquifer occurs principally by infiltration of precipitation on the outcrop. An average of less than 0.2 inch (0.5 cm) of water per year reaches the water table as natural recharge due to a combination of small annual precipitation, high evaporation rate, and low infiltration rate. Artificial recharge through surface spreading and injection wells has proven feasible although the area influenced is generally small.

Discharge of ground water from the aquifer occurs naturally through seeps and springs and artificially through wells. Few springs now exist on the Texas High Plains due to the lowering of the water table by pumpage. Discharge through pumping wells is greater than recharge, resulting in the mining of the aquifer.

Ground water in the High Plains aquifer generally moves toward the east to east-southeast at an average rate of approximately 7 inches (18 cm) per day.

Results from the analysis of cores retrieved from 41 test holes indicated that: transmissibilities range from 315 to 200,987 (gal/d)/ft [3,910 to 2.496 million (l/d)/m], permeabilities range from 22 to 1,934 (gal/d)/ft^2 [900 to 78,800 (l/d)/m^2], and specific yields range from 7.23 to 19.54 percent. Statistical calculations concerning the weighted mean position and average dispersion of the transmissibility and specific yield of each test hole indicated that permeability and specific yield are fairly evenly distributed throughout the saturated zone.

Surface electrical resistivity soundings identified geographical variations in the aquifer's hydraulic properties based on differences in geoelectrical parameters. Areas of low permeability and specific yield, due to high silt and clay content, were identified as having a low formation resistivity (R_o) and low apparent formation factor (F_a).

The distribution of specific yield and permeability of the High Plains aquifer was mapped based on lithologic descriptions. Areas of the aquifer identified as channel deposits generally exhibit specific yield values of 18 percent or more and permeability values of 1,000 (gal/d)/ft^2 [40,700 (l/d)/m^2] or more. Sediments deposited in lower energy environments have markedly lower average specific yield and permeability values.

The concentration of chloride and dissolved solids in the aquifer generally increases from north to south. In the northern part of the study area, except for local deviations, the chloride content typically is less than 50 mg/l and the dissolved solids less than 400 mg/l. To the south, specifically the area underlain by Cretaceous rocks and associated with alkali lake basins, the chloride content typically exceeds 50 mg/l and commonly exceeds 500 mg/l. Dissolved solids in this area typically exceed 400 mg/l, and extensive areas where concentrations exceed 1,000 mg/l are common.

Historical development of the High Plains aquifer in Texas basically commenced with the introduction of ground-water pumpage for irrigation in 1911 and has steadily increased, especially since the mid-1940's. The current major users of ground water include the agriculture industry, petroleum extraction and refining industry, and municipalities. Today's annual demand for ground water for all purposes exceeds 6 million acre-feet (7,400 hm^3). The effect of this pumpage is evident in the decline of water levels over most of the study area.

A two-part digital model of the aquifer was successfully constructed. The model was calibrated for the period 1960 through 1980. In 1960, the aquifer contained 505.43 million acre-feet (623,000 hm^3) of water, 92.9 percent deemed recoverable. During the 20-year calibration period, 93.19 million acre-feet (115,000 hm^3) of water was withdrawn, 9.67 million acre-feet (11,900 hm^3) was recharged, and 82.97 million acre-feet (102,000 hm^3) was removed from storage. In 1980, the aquifer contained 420.58 million acre-feet (519,000 hm^3), 91.5 percent recoverable. As determined by calibration, the aquifer's average specific yield is 16 percent, and average permeability is 400 (gal/d)/ft^2 [16,300 (l/d)/m^2].

The model was applied to predict the future condition of the aquifer if certain-practices occur. The Department has projected that improved management will significantly reduce irrigation application rates. The basic application of the model to simulate future conditions assumed that these improvements in water use would occur. Two other applications were made, one assuming that the improvement would only reduce rates by one-half and another that assumed that no reduction in application rates would apply.

For the basic application, the aquifer would contain 363.46 million acre-feet (448,000 hm^3) in 2000 and 310.66 million acre-feet (383,000 hm^3) in 2030, 90 and 88.4 percent recoverable, respectively. Net withdrawals are 2.348 million acre-feet (2,900 hm^3) per year in 2000 and 2.097 million acre-feet (2,590 hm^3) per year in 2030, reductions of 50.4 and 55.7 percent, respectively, from the 1980 level. Area irrigated is 4.249 million acres (17,200 km^2) in 2000 and 3.803 million acres (15,400 km^2) in 2030, reductions of 7.4 and 17.1 percent, respectively, from the 1980 level.

For the application assuming that one-half the projected improvement in management practices is effective, the aquifer would contain 352.25 million acre-feet (434,000 hm^3) in 2000 and 281.33 million acre-feet (347,000 hm^3) in 2030,89.8 and 87.2 percent recoverable, respectively. Net withdrawals are 3.209 million acre-feet (3,960 hm^3) per year in 2000 and 2.354 million acre-feet (2,900 hm^3) in 2030, reductions of 32.2 and 50.3 percent, respectively from the 1980 level. Area irrigated is 4.105 million acres (16,600 km^2) in 2000 and 3.190 million acres (12,900 km^2) in 2030, reductions of 10.5 and 30.5 percent, respectively, from the 1980 level.

The application with no change in application rates shows that the aquifer would contain 341.66 million acre-feet (421,000 hm^3) in 2000 and 259.89 million acre-feet (320,000 hm^3) in 2030; 89.5 and 86.2 percent recoverable, respectively. Net withdrawals were 3.913 million acre-feet (4,820 hm^3) per year in 2000 and 2.385 million acre-feet (2,940 hm^3) per year in 2030, reductions of 17.4 and 49.6 percent, respectively, from the 1980 level. Area irrigated is 3.940 million acres (15,900 km^2) in 2000 and 2.628 million acres (10,600 km^2) in 2030, reductions of 14.1 and 42.7 percent, respectively, from the 1980 level.

The aquifer supplies water for several uses, the largest of which is for irrigation. Withdrawals of water exceed recharge and the volume of water in storage is declining, resulting in the mining of the aquifer. Because of the large volume of water in storage overall, the aquifer can continue to support irrigation for many years. However, there will be areas where the water in storage is depleted. Most of the water in storage in the High Plains aquifer in Texas is in the northern High Plains where land-surface conditions are not generally conducive to irrigated agriculture. Therefore, the ground-water resources could be further developed in this area to provide additional water for municipal, industrial, and irrigation use in areas where the aquifer is being depleted.

LIMITATIONS AND RECOMMENDATIONS

In any study of this proportion, certain limitations exist that should be explained in order to properly qualify the results. The following limitations and recommendations should be considered for this study.

The data points used for control on the base of aquifer maps were located on topographic maps from directions supplied, in most cases, by the driller. Those wells tabulated in Volumes 2 through 4 in the Records of Wells, and designated on the well location maps by a numeric-alpha well number (such as 7A), were plotted on maps using such information. These wells used as data points were not field located by Department personnel, and hence the accuracy of the well locations can only be as accurate as information supplied by the drillers. Only those well drillers' reports that contained sufficient well location information, cross-referenced in many instances with ownership or operator maps, U.S. Soil Conservation Service maps, and well symbols on topographic maps, were used for this study in an effort to eliminate as many location errors as possible.

The lack of data for control in certain portions of the study area resulted in contour lines of inferred value, especially on maps depicting water-level elevations, saturated thicknesses, aquifer base, permeability, and specific yield. On some maps, these areas are represented by dashed contour lines.

The neutron moisture logging technique for determining soil moisture has the following limitations: (a) the logging instrument is probably not accurate enough to reflect small moisture changes of less than 1 percent; (b) sharp differences (boundaries) in moisture content cannot be adequately indicated due to the large sphere of influence of the neutron technique; (c) some soils contain appreciable quantities of nonwater hydrogen; however, nonwater hydrogen is generally absent in coarse-textured soils but may be present in appreciable quantities in organic soils and clays; (d) the moisture log can be affected by variations in the wall thickness of the access tube or eccentric positioning of the probe while logging; and (e) based on the calibration studies, the possibility of error appears to be greater as the moisture content increases.

Core analysis results obtained during the test hole investigation were affected by the condition of the "undisturbed" core samples. Except for a few "undisturbed" sandstone cores, the large majority of cores were either unconsolidated or poorly consolidated, which resulted in their reaching the laboratory in a "disturbed" condition. Some disturbance of the samples also occurred during transportation of the specimens from the High Plains to the Department's laboratory in Austin. This distortion and possible contamination of the samples may have affected the core analysis results.

Important to the moment calculations is the knowledge of the change of the medium grain size (D_{50}) and sorting with depth. Because only a limited number of core samples were obtained, drilling or cutting samples were taken at regular depth intervals and later subjected to mechanical analysis in order to predict the grain size and sorting changes with depth. The information gained from cuttings or drilling samples resulted in a somewhat dampened depth trend due to contamination of the sample from other horizons, drilling mud, and crushed gravels.

By its very nature, the surface electrical method of investigation is restricted to supplying data that support other forms of geohydrological information such as test-hole data, water-level measurements, and laboratory analyses. The results of this study are qualitative in nature since laboratory tests were not conducted to determine the effect of clays within the heterogenous Ogallala Formation and the degree to which current flows through the formation matrix. Quantitative results could be obtained only if the Ogallala Formation consisted of a clean sand or if the effect of its clays was known.

The ground-water model developed during this study is based on the assumption that the continuous aquifer may be divided into many discrete elements, called cells. The model simulates a water level in the center of each cell based on the value of the hydraulic parameters of the cell and of all other cells in the aquifer. Since each cell represents a large land area, the value for each hydraulic parameter must represent the average or composite value of the hydraulic coefficients for the entire area. The pumpage and recharge are assumed to be spread uniformly across the cell. There are no point sources (recharge wells) or point sinks (pumping wells) in the model. Each square foot of the cell is assumed to have its portion of pumpage and recharge. These facts require that the water level simulated by the model be considered as the representative value for the entire cell. Therefore, one limitation to this model is that the simulated water levels represent regional values and do not represent the water level in a producing well. This limitation in no way restricts the use of the model in evaluating the long-term effects of pumpage and recharge on the aquifer.

Also, the size of the cells used in the study is large, and it is possible that features of the aquifer that have small areal extent may not be present in the model. This is a common limitation of regional models.

Five-year time steps were used in the model applications. This length of time was used because data for irrigation pumpage were available only every five years. This means that only end of 5-year period values for water levels are available from the simulations and, therefore, is a limitation of the model in that annual and seasonal variations of withdrawals, recharge, and water levels do not appear.

It became evident early in the study that poor coverage and limited availability of historical water-level measurements reduced the accuracy of maps showing altitude of water level. The intensive water-level measurement effort expended in 1980 resulted in more accurate maps. Therefore, it is recommended that, at least periodically, intensive water-level measuring efforts be made so that the most accurate water-level maps possible can be prepared.

An accurate value of pumpage from the aquifer is extremely difficult to determine and is a very important value related to determining the life of the aquifer. During the calibration phase of model development, the amount of water pumped, as determined by the irrigation inventories, and the amount of withdrawals, as calculated from water-level changes, do not agree well. The possible reasons for the discrepancy are many and should be investigated. Therefore, it is recommended that the volume of water pumped be monitored by physical means and the mechanism of recharge and recirculation of irrigation water be investigated further.

The results of model applications are expressed by several terms, including irrigated area. The model is based on irrigation volume and not irrigated area or irrigation application rate. The irrigated area term should be used to compare results of the model and should not be compared against more sophisticated estimates of irrigated area. A limitation of the model, then, is that the irrigated area values should only be used to compare various model results.

The model was calibrated by adjusting permeability, specific yield, and net pumpage on a node-by-node or county-by-county basis. This introduces a large number of degrees of freedom into the calibration and allows the model to be calibrated to a high degree of precision. However, since the model was not verified by simulating the aquifer for another time period, it is not possible to accurately evaluate the accuracy of the model. A limitation of the model, then, is that its accuracy has not been verified. The model potentially could contain errors due to the calibration procedure.

SELECTED REFERENCES

Alexander, W. H., Jr., 1946a, Records of wells, Deaf Smith County, Texas: Texas Board of Water Engineers duplicated rept., 83 p.

______ 1946b, Ground water in the vicinity of Lamesa: Texas Board Water Engineers memo., 20 p.

______ 1961, Geology and ground-water resources of the Northern High Plains of Texas, Progress Rept. No. 1: Texas Board Water Engineers Bull. 6109, 39 p.

Alger, R. P., (undated), Interpretation of electric logs in fresh water wells in unconsolidated formations: Schlumberger Well Surveying Corp., Houston, Texas, 25 p. (Presented at Society of Professional Well Log Analysts Symposium, 1966).

American Public Health Association, and others, 1971, Standard methods for the examination of water and wastewater, 13th ed.: Washington, D.C., Am. Public Health Assoc., 874 p.

Aronovici, V. S., 1971, Percolation of water through Pullman soils, Texas High Plains: Texas A&M Univ., Agricultural Experiment Station B-1110, 8 p.

Aronovici, V. S., and Schneider, A. D., 1972, Deep percolation through Pullman soil in the Southern High Plains: Reprinted from the Jour. of Soil and Water Conservation, v. 27, no. 2, p. 70-73.

Aronovici, V. S., Schneider, A. D., and Jones, O. R., 1970, Basin recharging the Ogallala aquifer through Pleistocene sediments, Texas High Plains, *in* Ogallala Aquifer Symposium: Texas Tech Univ. Special Rept. 39, p. 182-192.

Ashworth, J. B., 1980, Evaluating the ground-water resources of the High Plains of Texas, Results of test hole drilling: Texas Dept. Water Resources LP-129, 41 p.

Baker, C. L., 1921, The Cretaceous of West Texas and its oil possibilities: Bull. Am. Assoc. Petroleum Geologists, v. 5, no. 1, p. 5-28.

Baker, E. T., Jr., 1963, Reconnaissance investigation of the ground-water resources of the Red River, Sulphur River, and Cypress Creek basins, Texas: Texas Water Comm. Bull. 6306, 127 p.

Baldwin, Brewster, and Muehlberger, W. R., 1959, Geologic studies of Union County, New Mexico: New Mexico Bur. Mines and Mineral Resources Bull. 63, 171 p.

Barnes, H. E., 1954, Electrical subsurface exploration simplified: Roads and Streets, v. 97, p. 81-84.

Barnes, J. R., Ellis, W. C., Leggat, E. R., Scalapino, R. A., George, W. O., and Irelan, Burdge, 1949, Geology and ground water in the irrigated region of the Southern High Plains in Texas, Progress Rept. No. 7: Texas Board Water Engineers duplicated rept., 51 p.

Beard, D. C., and Weyl, P. K., 1973, Influence of texture on porosity and permeability of unconsolidated sand: Bull. Am. Assoc. Petroleum Geologists, v. 57, no. 2, p. 349-369.

Brand, J. P., 1953, Cretaceous of Llano Estacado of Texas: Univ. Texas at Austin, Bur. Econ. Geol. Rept. of Inv. No. 20, 59 p.

Brown, R. F., Signor, D. C., and Wood, W. W., 1978, Artificial ground water recharge as a water-management technique on the Southern High Plains of Texas and New Mexico: Texas Dept. Water Resources Rept. 220, 32 p.

Brune, Gunnar, 1975, Major and historical springs of Texas: Texas Water Devel. Board Rept. 189, 95 p.

Buika, P. H., 1979, Preliminary investigation of the sedimentary zonation of the Ogallala aquifer, Southern High Plains: Texas Tech Univ., unpublished master's thesis, 85 p.

Bureau of Economic Geology, 1967, Lubbock geologic atlas sheet: Univ. Texas at Austin, Bur. Econ. Geology map.

______ 1968, Plainview geologic atlas sheet: Univ. Texas at Austin, Bur. Econ. Geology map.

______ 1969, Amarillo geologic atlas sheet: Univ. Texas at Austin, Bur. Econ. Geology map.

______ 1970, Perryton geologic atlas sheet: Univ. Texas at Austin, Bur. Econ. Geology map.

______ 1974a, Brownfield geologic atlas sheet: Univ. Texas at Austin, Bur. Econ. Geology map.

______ 1974b, Big Spring geologic atlas sheet: Univ. Texas at Austin, Bur. Econ. Geology map.

______ 1975, San Angelo geologic atlas sheet: Univ. Texas at Austin, Bur. Econ. Geology map.

______ 1976a, Pecos geologic atlas sheet: Univ. Texas at Austin, Bur. Econ. Geology map.

______ 1976b, Hobbs geologic atlas sheet: Univ. Texas at Austin, Bur. Econ. Geology map.

______ 1978, Clovis geologic atlas sheet: Univ. Texas at Austin, Bur. Econ. Geology map.

Byrd, C. L., 1971, The origin and history of the Uvalde gravel of central Texas, *in* Baylor Geol. Studies: Baylor Univ. Bull. 20, 42 p.

Camp Dresser & McKee, Inc., Black & Veatch, and Arthur D. Little, Inc., 1982, Six-state High Plains-Ogallala aquifer regional resources study: High Plains Associates rept., 492 p.

Couch, H. E., and Muller, D. A., 1972, Water well and ground-water chemical analysis data, Glasscock County, Texas: Texas Water Devel. Board Rept. 143, 68 p.

Cromack, G. H., 1944, Records of wells, Terry County, Texas: Texas Board Water Engineers duplicated rept. 28 p.

Cromack, G. H., 1945, Records of wells, Yoakum County, Texas: Texas Board Water Engineers duplicated rept., 28 p.

Cronin, J. G., 1961, A summary of the occurrence and development of ground water in the Southern High Plains of Texas: Texas Board of Water Engineers Bull. 6107, 104 p.

______ 1964, A summary of the occurrence and development of ground water in the Southern High Plains of Texas: U.S. Geol. Survey Water-Supply Paper 1693, 88 p.

______ 1969, Ground water in the Ogallala Formation in the Southern High Plains of Texas and New Mexico: U.S. Geol. Survey Hydrol. Inv. Atlas HA-330, 9 p., 4 pls.

______ 1972, Ground water in Dickens and Kent Counties, Texas: Texas Water Devel. Board Rept. 158, 79 p.

Cronin, J. G., Follett, C. R., Shafer, G. H., and Rettman, P. L., 1963, Reconnaissance investigation of the ground-water resources of the Brazos River basin, Texas: Texas Water Comm. Bull. 6310, 152 p.

Cronin, J. G., and Wells, L. C., 1960, Geology and ground-water resources of Hale County, Texas: Texas Board Water Engineers Bull. 6010, 146 p.

Cumley, J. C., 1938, Records of wells, Dawson County, Texas: Texas Board Water Engineers duplicated rept., 40 p.

Dante, J. H., 1946, Records of wells, Briscoe County, Texas: Texas Board Water Engineers duplicated rept., 25 p.

______ 1946, Records of wells, Swisher County, Texas: Texas Board Water Engineers duplicated rept., 91 p.

Darton, N. H., 1898, Preliminary report on the geology and water resources of Nebraska, west of the one hundred and third meridian: U.S. Geol. Survey 19th Annual Rept., pt. 4, Hydrography, p. 719-785.

Davis, G. H., Green, J. H., Olmsted, F. H., and Brown, D. W., 1959, Ground-water conditions and storage capacity in the San Joaquin Valley, California: U.S. Geol. Survey Water-Supply Paper 1469, p. 199-214.

Domenico, P., and Stephenson, D., 1964, Application of quantitative mapping techniques to aid in hydrologic systems analysis of alluvial aquifers: Jour. of Hydrology, 1964, v. 2, p. 164-181.

Draper, D. C., 1961, Water levels in observation wells, Southern High Plains, Texas, 1960 and 1961: Texas Board Water Engineers Bull. 6101, 53 p.

Ellis, W. C., 1949, Ground-water resources of Borden County, Texas: Texas Board Water Engineers duplicated rept., 26 p.

Evans, G. L., and Meade, G. E., 1948, Geology of the Blanco beds of West Texas in Pleistocene of the Great Plains (Symposium): Geol. Soc. America Bull., v. 59, no. 6, p. 617-619

Fink, B. E., 1963, Ground-water geology of Triassic deposits, northern part of the Southern High Plains of Texas: High Plains Underground Water Conservation Dist. No. 1 Rept. 163, 76 p.

Frye, J. C., and Leonard, A. B., 1957, Studies of Cenozoic geology along eastern margin of Texas High Plains, Armstrong to Howard Counties: Univ. Texas at Austin Bur. Econ. Geol. Rept. of Inv. 32, 62 p.

______ 1959, Correlation of the Ogallala Formation (Neogene) in western Texas with type localities in Nebraska: Univ. Texas at Austin Bur. Econ. Geol. Rept. of Inv. 39, 46 p.

______ 1964, Relation of Ogallala Formation to the Southern High Plains in Texas: Univ. Texas at Austin Bur. Econ. Geol. Rept. of Inv. 51, 25 p.

Gammon, S. W., and Muse, W. R., 1966, Water-level data from observation wells in the Southern High Plains of Texas: Texas Water Devel. Board Rept. 21, 537 p.

Gard, Chris, 1958, Ground-water conditions in Carson County, Texas: Texas Board Water Engineers Bull. 5802, 115 p.

Godfrey, C. L., McKee, G. S., and Oakes, H., 1973, General soil map of Texas: Texas Agricultural Experiment Station and Soil Conservation Service map.

Goemaat, R. L., 1977a, Ground-water levels in observation wells in Oklahoma, 1975: U.S. Geol. Survey open-file rept. 77-238, prepared in cooperation with The Oklahoma Water Resources Board, 35 p.

______ 1977b, Selected water-level records for western Oklahoma, 1975-1976: U.S. Geol. Survey open-file rept. 77-239, prepared in cooperation with The Oklahoma Water Resources Board, 50 p.

Goldberg, Irving, and others, 1955, Measurement of moisture content and density of soil masses using radioactivity methods: National Conference on Clays and Clay Minerals, 3rd Proceedings, National Academy of Sciences, National Research Council Pub. 395, p. 516-548.

Gould, C. N., 1907, The geology and ground-water resources of the western portion of the Panhandle of Texas: U.S. Geol. Survey Water Supply and Irrigation Paper No. 191, p. 12-35.

Gutentag, E. D., and Weeks, J. B., 1981, Evaluating vertical variability of transmissivity and specific yield for the High Plains regional aquifer system: Geol. Soc. of Amer., Programs with abstracts, Rocky Mountain Section, v. 13, n. 4, p. 199.

Hart, D. L., Jr., 1963, Ground-water levels in observation wells in Oklahoma, 1956-60: U.S. Geol. Survey open-file rept., prepared in cooperation with The Oklahoma Water Resources Board, 197 p.

______ 1967, Ground-water levels in observation wells in Oklahoma, 1965-66: U.S. Geol. Survey open-file rept., prepared in cooperation with The Oklahoma Water Resources Board, 61 p.

Hart, D. L., Jr., and others, 1971, Records of water-level measurements in wells in the Oklahoma Panhandle, 1966-70: U.S. Geol. Survey open-file rept., prepared in cooperation with The Oklahoma Water Resources Board, 66 p.

Hart, D. L., Jr., Hoffman, G. L., and Geomaat, R. L., 1976, Geohydrology of the Oklahoma Panhandle, Beaver, Cimarron, and Texas Counties: U.S. Geol. Survey Water Resources Inv. 25-75, 62 p.

Hoffman, G. L., and Hart, D. L., Jr., 1973, Records of selected water wells and test holes in the Oklahoma Panhandle: U.S. Geol. Survey open-file rept., prepared in cooperation with The Oklahoma Water Resources Board, 59 p.

Jacob, C. E., 1961, Memorandum on the prospective and hypothetical future of the mining of the groundwater deposited under the Southern High Plains of Texas and New Mexico: High Plains Underground Water Conservation Dist. No. 1, 13 p.

Johnson, A. I., 1967, Specific yield-compilation of specific yields for various materials: U.S. Geol. Survey Water-Supply Paper 1662-D, 74 p.

Johnson, Philip, 1970, Application of surface pressure to assist water recharge into the Ogallala aquifer, in Ogallala Aquifer Symposium: Texas Tech Univ., Special Rept. 39, p. 193-204.

Jorgensen, D. G., Determining specific yield: U.S. Geol. Survey open-file rept., 7 p.

Klemt, W. B., 1981, Evaluating the ground-water resources of the High Plains of Texas, Neutron-probe measurements of deep soil moisture as an indication of aquifer recharge rates: Texas Dept. Water Resources LP-142, 31 p.

Knowles, D. B., 1952, Ground-water resources of Ector County, Texas: Texas Board Water Engineers Bull. 5210, 112 p.

Knowles, Tommy, 1981, Evaluating the ground-water resources of the High Plains of Texas, Ground-water simulation program GWSIM-III: Texas Dept. of Water Resources UM-36,84 p.

Krumbein, W. C., and Libby, W. G., 1956, Application of moments to vertical variability maps of stratigraphic units: Bull. Am. Assoc. Petroleum Geologists, v. 41, no. 2, Feb. 1957, p. 197-211.

Leggat, E. R., 1952, Geology and ground-water resources of Lynn County, Texas: Texas Board Water Engineers Bull. 5207, 71 p.

1957, Geology and ground-water resources of Lamb County, Texas: Texas Board Water Engineers Bull. 5704, 181 p.

Leonard, A. B., and Frye, J. C., 1974, Pliocene and Pleistocene deposits and molluscan faunas, east central New Mexico: New Mexico Bur. of Mines and Mineral Resources Mem. 30, 14 p.

Livingston, Penn, and Bennett, R. R., 1944, Geology and ground-water resources of the Big Spring Area, Texas: U.S. Geol. Survey Water-Supply Paper 913, 113 p.

Long, A. T., Jr., 1961, Geology and ground-water resources of Carson County and part of Gray County, Texas, Prog. Rept. No. 1: Texas Board Water Engineers Bull. 6102, 45 p.

Lucas, R. C., 1961, Annual water-level measurements in observation wells, Northern High Plains, Texas, 1960 and 1961: Texas Board Water Engineers Bull. 6103, 19 p.

Maderak, M. L., 1973, Ground-water resources of Wheeler and eastern Gray Counties, Texas: Texas Water Devel. Board Rept. 170, 66 p.

Masch, F. D., and Denny, K. J., 1966, Grain size distribution and its effect on the permeability of unconsolidated sands: Water Resources Research, v. 2, no. 4, p. 665-677.

Matthews, W. H., III, 1969, The geologic story of Palo Duro Canyon: Univ. Texas at Austin, Bur. of Econ. Geol. Guidebook No. 8, p. 22-23.

McAdoo, G. D., Leggat, E. R., and Long, A. T., 1964, Geology and ground-water resources of Carson County and part of Gray County, Texas, Prog. Rept. No. 2: Texas Water Comm. Bull. 6402, 27 p.

McDaniels, L. L., 1960, Consumptive use of water by major crops in Texas: Texas Board Water Engineers Bull. 6019, 21 p.

McGowen, J. H., Granata, G. E., and Seni, S. J., 1979, Depositional framework of the lower Dockum Group (Triassic), Texas Panhandle: Univ. Texas at Austin, Bur. Econ. Geol. Rept. of Inv. No. 97, 60 p.

McHenry, J. R , 1963, Theory and application of neutron scattering in the measurement of soil moisture: Soil Science, v. 95, p. 294-307.

McKee, E. D., and others, 1959, Paleotectonic maps, Triassic System: U.S. Geol. Survey Misc. Geologic Inv. Map I-300, p. 13-14 and pl. 4.

Menzer, F. J., and Slaughter, B. H., 1971, Upland gravels in Dallas County, Texas, and their bearing on the former extent of the High Plains physiographic province: Texas Jour. of Science, v. 22, no. 2 and 3, p. 217-222.

Merritt, R. B., and Follett, C. R., 1946, Records of wells, Hale County, Texas: Texas Board Water Engineers duplicated rept., 177 p.

Moore, R. L., 1972, Ground-water levels in observation wells in Oklahoma, 1969-70: U.S. Geol. Survey open file rept., prepared in cooperation with The Oklahoma Water Resources Board, 86 p.

Morris, D. A., and Johnson, A. I., 1967, Summary of hydrologic and physical properties of rock and soil materials, as analyzed by the hydrologic laboratory of the U.S. Geol. Survey, 1948-60: U.S. Geol. Survey Water-Supply Paper 1839-D, 42 p.

Morton, R. B., 1973, Preliminary investigations of the hydrogeology of the Permian to Tertiary rocks of the Oklahoma Panhandle: U.S. Geol. Survey Misc. Geologic Inv. Map I-738.

Mount, J. R., Rayner, F. A., Shamburger, V. M., Jr., Peckham, R. C., and Osborne, F. L., Jr., 1967, Reconnaissance investigation of the ground-water resources of the Colorado River basin, Texas: Texas Water Devel. Board Rept. 51, 107 p.

Mueller, C. B., Lang, J. W., and Broadhurst, W. L., 1940, Records of wells, Hockley County, Texas: Texas Board Water Engineers duplicated rept., 72 p.

Muller, D. A., 1980, Evaluating the ground-water resources of the High Plains of Texas, Results of surface electrical resistivity surveys: Texas Dept. Water Resources LP-130, 27 p.

Muller, D. A., and Price, R. D., 1979, Ground-water availability in Texas—Estimates and projections through 2030: Texas Dept. Water Resources Rept. 238, 77 p.

Myers, B. N., 1969, Compilation of results of aquifer tests in Texas: Texas Water Devel. Board Rept. 98, 532 p.

New, Leon, 1964-1977, High Plains irrigation survey (1964-1977): Texas A&M Univ., Texas Agricultural Extension Service.

Nicholson, J. H., 1960, Geology of the Texas Panhandle, *in* Aspects of the geology of Texas, a symposium: Univ. Texas at Austin, Bur. Econ. Geol. Pub. 6017, p. 51-63.

Nixon, P. R., and Lawless, G. P., 1960, Detection of deeply penetrating rain water with neutron-scattering moisture meter: Reprinted from Transactions of the Am. Soc. Agr. Engineers, v. 3, no. 1, p. 5-8.

Opfel, W. J., and Elder, G. R., 1978, Results of an infiltration study on the Carrizo Sand outcrop in Atascosa County, Texas: Texas Dept. Water Resources LP-61, 35 p.

Peaceman, D. W., and Rachford, H. H., Jr., 1955, The numerical solution of parabolic and elliptic differential equations: Soc. Indus. and Applied Math. Jour., v. 3, p. 28-41.

Popkin, B. P., 1973a, Ground-water resources of Donley County, Texas: Texas Water Devel. Board Rept. 164, 75 p.

______ 1973b, Ground-water resources of Hall and eastern Briscoe Counties, Texas: Texas Water Devel. Board Rept. 167, 84 p.

Prickett, T. A., and Lonnquist, C. G., 1971, Selected digital computer techniques for ground-water resource evaluation: Illinois State Water Survey Bull. 55, 62 p.

Prill, R. C., and Meyer, W. R., 1968, Neutron moisture measurements by continuous- and point-logging procedures: U.S. Geol. Survey Prof. Paper 600-B, p. B226-B230.

Rayner, F. A., and others, 1973, Mathematical management model of parts of the Ogallala aquifer, Texas: High Plains Underground Conservation Dist. No. 1 and Texas Tech Univ. Water Resources Center, 111 p.

Reeves, C. C., Jr., 1970, Origin, classification, and geologic history of caliche on the Southern High Plains, Texas, and eastern New Mexico: Jour. Geol., v. 78, p. 352-362.

Rettman, P. L., and Leggat, E. R., 1966, Ground-water resources of Gaines County, Texas: Texas Water Devel. Board Rept. 15, 185 p.

Ries, G. V., 1981, Preliminary work on calcrete horizon maps with infiltration rates: Texas Tech Univ. unpublished master's thesis.

Schlumberger Limited, 1973, Log interpretation charts: Houston, Texas, Schlumberger Ltd., 92 p.

Sellards, E. H., Adkins, W. S., and Plummer, F. B., 1932, The geology of Texas, v. 1, Stratigraphy: Univ. Texas at Austin Bull. 3232, 1007 p.

Seni, S. J., 1980, Sand-body geometry and depositional systems, Ogallala Formation, Texas: Univ. Texas at Austin, Bur. Economic Geol. Rept. of Inv. No. 105, 36 p.

Smelley, R. K., 1980, Sedimentary zonation of the Ogallala aquifer: Texas Tech Univ. unpublished master's thesis, 53 p.

Smith, J. T., 1973, Ground-water resources of Motley and northeastern Floyd Counties: Texas Water Devel. Board Rept. 165, 66 p.

Smith, W. O., 1961, Mechanisms of gravity drainage and its relation to specific yield of uniform sands: U.S. Geol. Survey Prof. Paper 402-A, 12 p.

Stanton, T. W., 1905, The Morrison Formation and its relations with the Comanche Series and the Dakota Formation: Jour. Geol., Nov.-Dec. 1905, p. 657-669.

______ 1921, Some problems connected with the Dakota Sandstone: Geol. Soc. of America Bull., Mar. 1922, v. 33, p. 255-272.

Stearman, Jack, 1960a, Water levels in observation wells, Southern High Plains, Texas, 1959 and 1960: Texas Board Water Engineers Bull. 6011, 47 p.

______ 1960b, Water levels in observation wells, Northern High Plains, Texas, 1958-1960: Texas Board Water Engineers Bull. 6012, 17 p.

Taylor, H. D., 1979, Water-level data from observation wells in the Southern High Plains of Texas, 1971-77: Texas Dept. Water Resources Rept. 228, 484 p.

______ 1980, Water-level data from observation wells in the northern Panhandle of Texas, 1972-78: Texas Dept. Water Resources Rept. 248, 191 p.

Teasdale, W. E., and Johnson, A. I., 1970, Evaluation of installation methods for neutron-meter access tubes: U.S. Geol. Survey Prof. Paper 700-C, p. C237-C241.

Texas Board Water Engineers, 1936, Records of wells, Martin County, Texas: Texas Board Water Engineers duplicated rept., 49 p.

Texas Board Water Engineers, 1937a, Records of wells, Dallam County, Texas: Texas Board Water Engineers duplicated rept., 49 p.

——— 1937b, Records of wells, Bailey County, Texas: Texas Board Water Engineers duplicated rept., 52 p.

——— 1937c, Records of wells, Howard County, Texas: Texas Board Water Engineersduplicated rept., 96 p.

——— 19374, Records of wells, Glasscock County, Texas: Texas Board Water Engineers duplicated rept., 49 p.

1937e, Records of wells, Ector County, Texas: Texas Board Water Engineers duplicated rept., 33 p.

——— 1938a, Records of wells, Lamb County, Texas: Texas Board Water Engineers duplicated rept., 33 p.

1938b, Records of wells, Midland County, Texas: Texas Board Water Engineers duplicated rept., 57 p.

1938c, Records of wells, Randall County, Texas: Texas Board Water Engineers duplicated rept., 31 p.

1938d, Records of wells, Potter County, Texas: Texas Board Water Engineers duplicated rept., 50 p.

1939a, Records of wells, Carson County, Texas: Texas Board Water Engineers duplicated rept., 54 p.

1939b, Records of wells, Crosby County, Texas: Texas Board Water Engineers duplicated rept., 54 p.

1940a, Records of wells, Andrews County, Texas: Texas Board Water Engineers duplicated rept., 33 p.

1940b, Records of wells, Armstrong County, Texas: Texas Board Water Engineers duplicated rept., 46 p.

1940c, Records of wells, Roberts County, Texas: Texas Board Water Engineers duplicated rept., 63 p.

1942, Records of wells, Donley County, Texas: Texas Board Water Engineers duplicated rept., 43 p.

1960, Reconnaissance investigation of the ground-water resources of the Canadian River basin, Texas: Texas Board Water Engineers Bull. 6016, 27 p.

Texas Crop and Livestock Reporting Service, Texas Department of Agriculture, [Compilers], 1981, 1980 Texas county statistics: U.S. Dept. Agri. Bull. 196, 277 p.

Texas Department of Water Resources, 1981a, Inventories of irrigation in Texas 1958, 1964, 1969, 1974, and 1979: Texas Dept. Water Resources Rept. 263, 295 p.

______ 1981b, Water use, projected water requirements, and related data and information for the standard metropolitan statistical areas in Texas: Texas Dept. Water Resources LP-141, 224 p.

Texas Tech University and High Plains Underground Water Conservation Dist. No. 1, 1970, Mathematical management model, unconfined aquifer: Texas Tech Univ. Water Resources Center rept., 148 p.

Theis, C. V., 1937, Amount of ground-water recharge in the Southern High Plains: Am. Geophys. Union Trans., v. 18, p. 564-568.

Todd, D. K., 1959, Ground-water hydrology: New York, John Wiley and Sons, Inc., 336 p.

Trask, P. D., 1932, Origin and environment of source sediments of petroleum: Houston, Gulf Publ. Co.

Trescott, P. C., Pinder, G. F., and Larson, S. P., 1976, Finite-difference model for aquifer simulation in two-dimensions with results of numerical experiments: U.S. Geol. Survey Techniques of Water Resources Inv., book 7, chapter C1, 20 p.

Turner, S. F., 1937, Records of wells, Andrews County, Texas: Texas Board Water Engineers duplicated rept., 33 p.

U.S. Geological Survey, 1979, Ground-water resources of the Palo Duro Creek Basin, Texas and Oklahoma: U.S. Geol. Survey open-file rept. 79-209, Fig. 6 and 15.

Walker, J. R., 1978, Geomorphic evolution of the Southern High Plains, *in* Baylor Geol. Studies: Baylor Univ. Bull. 35, 32 p.

Walker, L. E., 1979, Occurrence, availability, and chemical quality of ground water in the Edwards Plateau region of Texas: Texas Dept. Water Resources Rept. 235, 331 p.

Weeks, J. B., and Gutentag, E. D., 1981, Bedrock geology, altitude of base, and 1980 saturated thickness of the High Plains aquifer in parts of Colorado, Kansas, Nebraska, New Mexico, Oklahoma, South Dakota, Texas, and Wyoming: U.S. Geol. Survey Hydrol. Inv. Atlas HA-648.

Wenner, F., 1916, A method of measuring earth resistivity: U.S. Bureau of Standards Bull., v. 12, p. 469-478.

White, W. N., Broadhurst, W. L., and Lang, J. W., 1946, Ground water in the High Plains of Texas: U.S. Geol. Survey Water-Supply Paper 889-F, p. 381-420.

Worthington, P. F., and Barker, R. D., 1972, Methods for the calculation of true formation factors in the Bunter sandstone of northwest England: Eng. Geol., Vol. 6, p. 213-228.

Wyatt, A. W., 1970, Water-level data from observation wells in the Southern High Plains of Texas, 1965-I 970: Texas Water Devel. Board Rept. 121, 361 p.

1971, Water-level data from observation wells in the northern Panhandle of Texas: Texas Water Devel. Board Rept. 137, 263 p.

Zohdy, A. A. R., and Bisdorf, R. J., 1975, Computer programs for the forward calculation and automatic inversion of Wenner sounding curves: U.S. Geol. Survey, Denver, Colorado, duplicated rept., 9 p.

Zohdy. A. A. R., Eaton, G. P., and Mabey, D. R., 1974, Application of surface geophysics to ground-water investigations: U.S. Geol. Survey Techniques of Water-Resources Inv., book 2, chapter D1, 116