COMPARISON OF IRRIGATION PUMPAGE AND CHANGE IN WATER STORAGE OF THE HIGH PLAINS AQUIFER IN CASTRO AND PARMER COUNTIES, TEXAS, 1975-83

By Gary W. Mackey

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METRIC CONVERSION FACTORS

The inch-pound units of measurement used in this report may be converted to metric (International system) units by using the following conversion factors:

Multiply inch-pound unit	By	To obtain metric unit
acre	4,047	square meter
acre-foot (acre-ft)	1,233	cubic meter
acre-foot per year (acre-ft/yr)	1,233	cubic meter per year
degree Fahrenheit (°F)	5/9 (°F-32)	degree Celsius
foot (ft)	0.3048	meter
foot per mile (ft/mi)	1.890	meter per kilometer
inch (in.)	25.40	millimeter
inch per day (in./d)	25.40	mllimeter per day
inch per hour (in./hr)	25.40	millimeter per hour
inch per year (in./yr)	25.40	millimeter per year
mile (mi)	1.609	kilometer
square mile (mi^2)	2.590	square kilometer

COMPARISON OF IRRIGATION PUMPAGE AND CHANGE IN WATER STORAGE OF THE HIGH PLAINS AQUIFER IN CASTRO AND PARMER COUNTIES, TEXAS, 1975-83

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ABSTRACT

An understanding of the relationship between irrigation pumpage and change in ground-water storage was needed to quantify the amount of water returning to the High Plains aquifer as a result of intensive irrigation in Castro and Parmer Counties, Texas. Irrigation pumpage for the 9-year period, 1975-83, was estimated by using the Blaney-Criddle consumptive-use formula adjusted by a factor to account for irrigation demand and field-measured crop applications. Total estimated pumpage for the 9-year period was 11,269,000 acre-feet and 8,914,000 acre-feet. The estimated pumpage was based upon reported crop acreage data and LANDSAT acreage data, respectively.

Aquifer storage for the same period was estimated as the product of specific yield, net water-level change, and area. Change in storage was 5,168,000 acre-feet. Many of the areas of the largest change in storage also were the areas of the largest saturated thickness. The only locations that did not experience substantial water-level declines were the northwest and northeast parts of the study area.

A comparison was made of water returning to the aquifer by calculating the difference between irrigation pumpage and the change in aquifer storage. Two estimates of this comparison, expressed as a percentage of irrigation pumpage, were obtained on the basis of two different sources of acreage data. This comparison was 54 percent of pumpage based on reported crop acreage data and 42 percent of pumpage based on LANDSAT interpreted acreage data.

INTRODUCTION

The U.S. Geological Survey conducted a 5-year study of the High Plains regional aquifer from 1978 to 1982, during phase 1 of the High Plains RASA (Regional Aquifer-System Analysis). The RASA program was initiated in 1978 in response to a congressional mandate to develop quantitative appraisals of the major ground-water systems of the United States. The RASA program represents a systematic effort to study a number of the Nation's most important aquifer systems which, in aggregate, underlie much of the country and represent many components of the Nation's total water supply.

The primary objective of the first phase of the High Plains RASA project was to provide the hydrologic information needed for the development of mathematical models to evaluate the aquifer's response to ground-water management alternatives (Weeks, 1978). The High Plains RASA has provided the regional description of the High Plains aquifer system and developed a regional ground-water-flow model (Luckey and others, 1986). The study showed that data on pumpage from the aquifer and water returning to the aquifer were critical for projecting future water levels. An indirect method for estimating pumpage was developed during the High Plains RASA, and water returning to the aquifer was adjusted during modeling to achieve calibration. The accuracy of the pumpage estimates and an independent estimate of return flow were needed to support the results of the regional investigation.

Castro and Parmer Counties were selected for a study of irrigation return flow in the High Plains of Texas because a previous study had shown large changes in saturated thickness (decreases of more than 50 ft) in those areas (Luckey and others, 1981). Those counties are representative of areas of the Texas High Plains where water withdrawals are large, owing to intensive irrigation. No data for historical pumpage were available for the Texas High Plains, and pumpage needed to be calculated from crop consumptive use and total irrigated acreage. Once pumpage could be estimated, it could be compared to change in storage to determine the amount of water returning to the aquifer as a result of water applied to crops. A similar study was conducted by the U.S. Geological Survey in three counties in Nebraska so the results of the two studies could be compared (Heimes and others, in press).

Purpose and Scope

Irrigation return flow is defined as a recharge segment of the water budget, which is irrigation water not consumed by evapotranspiration but returned to its source or to another body of ground or surface water. In the High Plains of Texas, there is a popular belief held by the general public that no water returns to the aquifer after pumping (A. W. Wyatt, High Plains Underground Water Conservation District No. 1, oral commun., 1984). Under this assumption, only natural recharge (water which infiltrates to the aquifer from precipitation) would contribute to the flow of water into the aquifer.

This report describes the results of one of the phase 2 High Plains RASA studies. Phase 2 was conducted to establish and test procedures used to determine return flow from irrigation in Castro and Parmer Counties in Texas and three counties in Nebraska. This study was initiated to quantify the volume of water returning to the aquifer as a result of irrigation return flow. This information is not known in most areas of the High Plains, and it is essential for projecting future water-level changes that result from irrigation pumping. The results of a similar study conducted in Chase, Dundy, and Perkins Counties in Nebraska are the subject of a separate report (Heimes and others, in press).

One of the variables in the water-budget equation for irrigated areas is the quantity of water used for irrigation that infiltrates the land surface and ultimately returns to the saturated zone. The volume of the return flow needs to be investigated in order to improve our understanding of the long-term availability of water. The primary purpose of this investigation is to determine the relationship between irrigation pumpage and change in ground-water storage in the High Plains of Texas. A secondary purpose is to evaluate various methods for estimating irrigation pumpage.

Approach

A grid was established for the study area, with each grid cell measuring 1 minute of latitude by 1 minute of longitude. There were 1,638 cells in the study area, and each cell corresponded to 690.7 acres. Data for a variety of parameters, such as specific yield, saturated thickness, and water-level altitude were assigned to the corresponding cell. For example, a specific-yield map was prepared using data from 816 drillers' logs of water wells in the study area. The drillers' logs were statistically analyzed by a computer program developed by the High Plains RASA project (Gutentag and Weeks, 1981). This program computed specific yield for the center of each grid cell using a weighted-average technique. In a similar manner, a 9-year water-level-change map was prepared by using the sum of the annual water-level changes for each year during 1975-83. This time period was selected because it represented an interval of considerable pumping, and data are available on individual crop acreages for each year.

Water application data for separate crops were collected during the 1983-84 irrigation seasons from about 63 irrigation systems in the study area by using portable flowmeters and time-of-operation sensors (Rettman and McAdoo, 1986). This instrumentation was necessary to provide measured data for use in estimating an irrigation pumpage history.

The Blaney-Criddle formula was used to calculate the optimum volume of water necessary to produce a maximum yield for six of the major crops grown in the study area (U.S. Department of Agriculture, 1967). Effective precipitation was subtracted from the Blaney-Criddle value to get crop-irrigation demand. This demand was calculated for each major crop type for each year of the study. The ratio of the measured application data to the Blaney-Criddle calculated value resulted in a crop adjustment factor.

Acreage values for individual crops were obtained from several sources in the literature: "1975-77 High Plains Irrigation Survey" (New, 1975-77); "1975-84 Texas Field Crop Statistics" (Texas Crop and Livestock Reporting Service, 1975-84); "1982 Census of Agriculture" (U.S. Department of Commerce, 1984); and "Inventories of Irrigation in Texas--1958, 1964, 1969, 1974, and 1979" (Texas Department of Water Resources, 1981a). These were referred to as reported acreage sources. Total crop acreage data also were derived from the interpretation of LANDSAT imagery.

Irrigation pumpage was calculated by multiplying total crop acreage by the crop irrigation demand by the adjustment factor. The net volume of water removed from storage in the aquifer, or change in storage, was calculated for 1975-83. The formula for obtaining the 9-year change in storage is:

$$\text{Change in storage (acre-feet per cell)} = \text{specific yield (dimensionless)} \times \text{9-year water-level change (feet)} \times \text{690.7 (acres per cell)}. \quad (1)$$

This change was computed for each grid cell in the study area and summed for all cells to yield a total change in storage, in acre-feet. The difference between irrigation pumpage and change in storage was then calculated.

Previous Studies

Many hydrologic and geologic investigations have been conducted in the High Plains of Texas during the past 90 years. Some of the investigations were specifically pertinent to Castro and Parmer Counties, but most were conducted on a regional scale encompassing the High Plains in general. The U.S. Geological Survey conducted one of the first studies in the Texas High Plains on water utilization (Johnson, 1901). Baker (1915) examined the geology and ground water in the High Plains. Theis and others (1935) produced some of the most thorough research on ground-water conditions in the southern High Plains in the 1930's. They conducted a reconnaissance survey of the ground-water resources of the southern High Plains, mapped the geology of the area, and described the stratigraphy in detail. Theis (1937) estimated the amount of ground-water recharge in the southern High Plains. The first significant report on ground water in Parmer County was produced by Follet and Bradshaw (1938).

Cronin (1969) described ground-water conditions in the study area in the mid- to late 1960's. Claborn and others (1970) constructed one of the earliest ground-water-flow models of an area which included Castro and Parmer Counties to predict future water-level changes and dewatering effects from estimates of pumpage data. Rayner (1971) analyzed ground-water conditions in Parmer County in 1971.

Rayner and others (1973) prepared a report on the occurrence, quality, and quantity of ground-water supplies of Parmer County. Included in the report is a mathematical-model analysis, which predicts future aquifer dewatering and water-level changes into the 21st century. Wyatt and others (1976) generated reports on both Castro and Parmer Counties in the mid-1970's. These reports gave projections of saturated thickness, volume of water in storage, pumpage rates, pumping lifts, and well yields from 1974 to 2020. McReynolds (1980) and Smith (1980) developed hydrologic atlases for both counties in 1980. The atlases contain maps depicting the approximate altitude of the land surface, the approximate altitude of the water table in 1980, the approximate altitude of the base of the High Plains aquifer, and the saturated thickness of the High Plains aquifer in 1980. Knowles and others (1982) prepared several reports that were designed to improve the data base describing the High Plains aquifer. These reports described the occurrence, operation, and use of the aquifer and a computer model of the aquifer.

The U.S. Geological Survey produced a series of map reports describing the hydrology and geology of the High Plains aquifer, an area which includes Castro and Parmer Counties. Maps include: The water table in the aquifer in 1978 (Weeks and Gutentag, 1981); bedrock geology, altitude of base, and 1980 saturated thickness of the aquifer (Weeks and Gutentag, 1981); and water-level and saturated thickness changes, predevelopment to 1980, in the aquifer (Luckey and others, 1981). Gutentag and others (1984) described in detail the geohydrology of the aquifer. Rettman and McAdoo (1986) collected data on pumpage in Castro and Parmer Counties at 63 sites that were monitored during the 1983 and 1984 irrigation seasons to obtain measurements of discharge and rate of water application to crops. These data were used in making the pumpage calculations used in this report.

Several studies by the U.S. Geological Survey were used in designing the approach and methodology used in this report to estimate irrigation return flow. Luckey and others (1980) described instrumentation for measuring discharge from pumping wells; the authors also investigated various ways to develop the irrigated-cropland maps needed to extend sample-pumpage data. Heimes and Luckey (1982) developed a method to estimate historical pumpage data when pumpage records were not available; and in another study, Heimes and Luckey (1983) used the relationship between irrigation demand (calculated using the Blaney-Criddle formula) and measured application as a way to estimate water application for unsampled areas of the High Plains.

Acknowledgments

A. Wayne Wyatt and the staff at the High Plains Underground Water Conservation District No. 1, Lubbock, Texas, supplied the data from more than 900 drillers' logs of water wells. Their assistance is appreciated. Bernard Baker, Texas Department of Water Resources (currently Texas Water Development Board), Austin, Texas, supplied water levels from almost 200 observation wells in the study area. Comer Tuck, Texas Department of Water Resources, Austin, Texas, supplied data and technical advice on irrigated crops in the two-county area. Their cooperation is greatly appreciated. Paul Rettman of the U.S. Geological Survey, San Antonio, Texas, collected field data on crop water applications, and also provided extensive technical assistance. Brian Eggers of the U.S. Geological Survey, Austin, Texas, helped in the statistical analysis of the data and in the preparation of many contour maps. Their collective efforts helped make this project possible.

GEOGRAPHIC SETTING

Castro and Parmer Counties are located in the southern High Plains of Texas in an area known as the Texas Panhandle (fig. 1). Dimmitt, the Castro County seat, is located about 70 mi southwest of Amarillo and 345 mi northwest of Dallas. The county has an area of about 880 mi^2 and a population of about 10,251 (U.S. Bureau of the Census, 1984). Farwell, the Parmer County seat, is located about 95 mi southwest of Amarillo and 380 mi northwest of Dallas. Parmer County has an area of 859 mi^2 and a population of about 9,496 (U.S. Bureau of the Census, 1984).

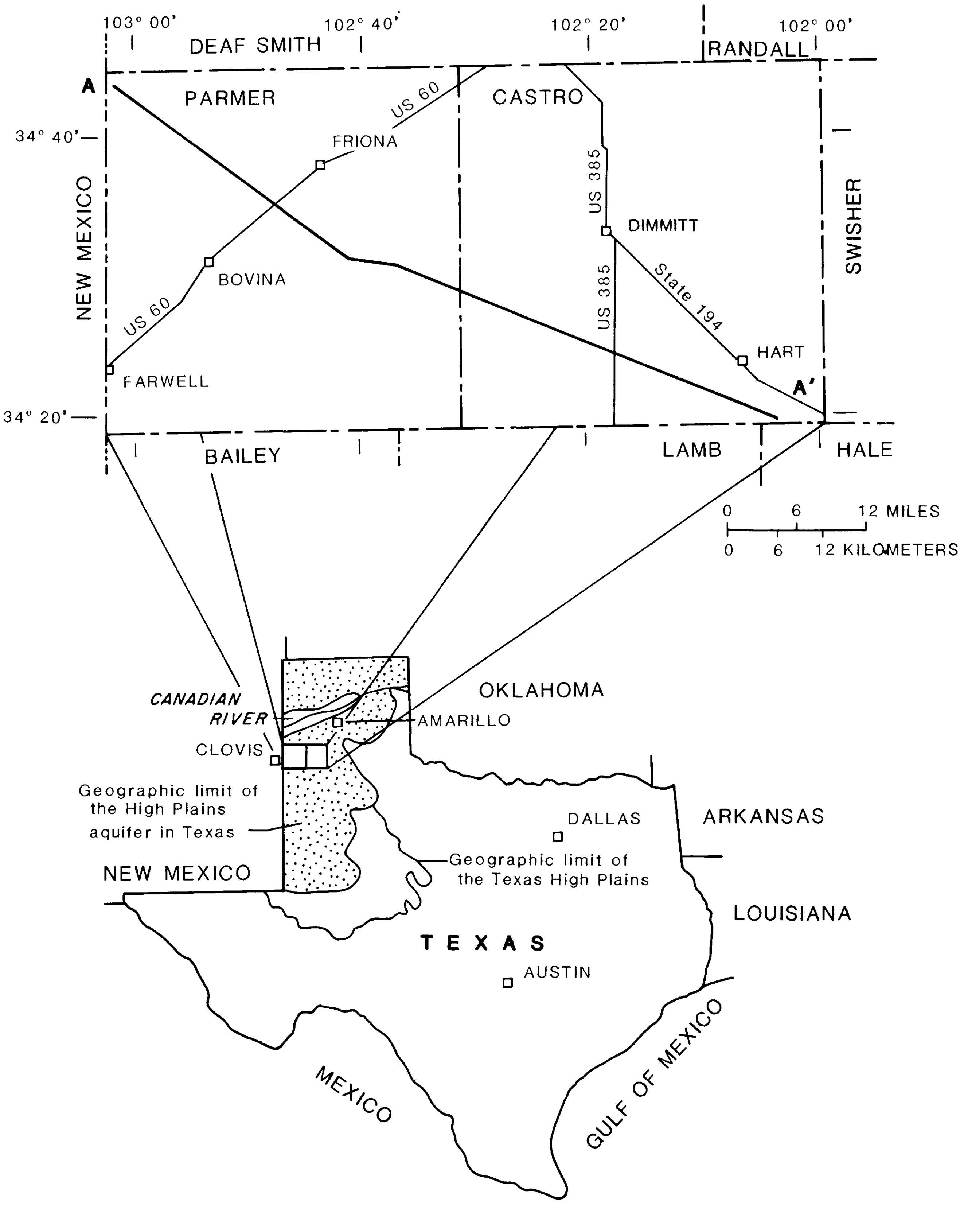


Figure 1.--Location of Castro and Parmer Counties.

Castro County was created in 1876, and ranchers began to move into the area in the 1880's. Homesteaders followed in about 1898, when State land was opended for settlement. From 1912 to 1925, much of the sod in Castro County was plowed, and the county became an area of extensive dryland farming and ranching.

Parmer County was part of the 3,050,000-acre XIT Ranch. It was 1 of the 10 counties that comprised the Capitol Syndicate Land Grant, which built the present Texas State Capital building. In 1898, the Pecos Valley Railway was built from Clovis, New Mexico, to Amarillo, Texas. Several towns gradually became established along the railway in what is now Parmer County. During the first half of the 20th century, the county was transformed from a native grass area to one of ranches and dryland farms.

Physiography

The topography of Castro and Parmer Counties is mostly flat with some areas of gently rolling terrain. Land-surface altitude ranges from 3,500 ft in Castro County to 4,430 ft in Parmer County. The landscape is dotted with hundreds of small playa lakes and basins which contain water part of the year. The lakes have no significant external drainage, and range in depth from about 10 to 50 ft (Rayner and others, 1973). The surface-water drainage network is ill-defined and consists almost entirely of intermittent streams, locally known as draws. The draws are not hydraulically connected to the High Plains aquifer because the water table is at least 100 ft below the bed of the draws.

Climate

Castro and Parmer Counties are located in a cool-temperate climatic zone. The climate is dry, steppe continental and is characterized by mild winters and large variations in annual extremes of temperature. Precipitation averages 17 in. annually (U.S. Department of Commerce, 1975-77, 1978-84), although it varies considerably from month to month and year to year. More than 80 percent of the average total annual precipitation falls during the 7-month warm season of April through October. Warm-season precipitation occurs most frequently as a result of thundershowers. Monthly precipitation decreases significantly during the cold season because frequent cold fronts accompanied by strong northerly winds block the supply of moisture from the Gulf of Mexico. Prevailing winds are southerly to southwesterly throughout the year, but northerly winds are frequent in the colder months (November through March). Occasionally, strong winds, usually from the southwest through the north, cause blowing dust. The strongest sustained winds are in March and April and are associated with intense low-pressure centers.

The dry area, high altitude, and usually clear skies are ideal conditions for solar radiation; consequently, the daily range between maximum and minimum temperatures is large. Midafternoon temperatures are high in summer, but decrease rapidly after sundown. Average daily minimum temperatures during midsummer are in the range of 64 to 66 °F, and average daily maximum midsummer temperatures are in the range of 71 to 78 °F.

Low relative humidity (35 to 40 percent) is observed during most of the year. High summer temperatures, dry winds, and low humidity combine to produce a net free-lake surface-evaporation rate of about 65 in. of water per year (Rayner and others, 1973). A summary of the climatic conditions in the two counties is given in table 1.

Economy

Castro and Parmer Counties are almost totally dependent economically on agriculture and agribusiness. Irrigation is used extensively in the area to obtain better crop yields. Irrigated corn, cotton, grain sorghum, and wheat are the main crops, but irrigated vegetables and sugar beets also are grown. Grain sorghum and wheat also are dryfarmed, and nearly all dryfarmed areas are in the northwestern and northeastern corners of the study area. These two counties are among the leading counties in the State in total farm income, crop income, and livestock income. They are leading producers of cattle, corn, sugar beets, sunflowers, potatoes, sorghum, cotton, wheat, hay, barley, vegetables, and soybeans. In 1983, cash receipts for all crops marketed from both counties totaled $132,380,000 (Texas Crop and Livestock Reporting Service, 1983). Owing to the major dependence on irrigation, the farming economy in the two counties is greatly affected by the ground-water supply.

The earliest attempts to utilize ground water in the area began in the early 1900's when windmill-equipped wells were drilled primarily for stock watering on the XIT Ranch. Irrigation development suffered a setback during the severe drought of the 1930's. The resulting duststorms, lack of precipitation, and low market prices forced many farmers to leave the area. With the advent of new irrigation methods and improved equipment, irrigated agriculture became firmly established by the late 1940's. Since the beginning of the mid-1940's, the farms have converted almost completely to irrigation because of the unreliability of dryland farming. The ensuing drought of the early 1950's accelerated the development of irrigation wells. By the end of 1952, there were an estimated 573 wells in Parmer County (Rayner and others, 1973). Ground water supplies almost all the irrigation water in the counties. The number of irrigation wells has increased significantly during the past 25 years as evidenced by the following: 1958--5,010 wells; 1969--6,752 wells; and 1979--7,923 wells (Texas Department of Water Resources, 1981a).

Beef production is an important enterprise in the county, and livestock operations include cow-calf and stocker cattle operations. Seven commercial feedlots are located in Parmer County (Bruns, 1978). Numerous agribusinesses, including livestock feeding and sale of irrigation-equipment supplies, feed, seed, and fertilizer, also make significant contributions to the total county income. Cash receipts from marketing livestock and livestock products from both counties increased from a total of $103,180,000 in 1975 to $164,512,000 in 1983 (Texas Crop and Livestock Reporting Service, 1975, 1983).

GEOHYDROLOGY

The High Plains aquifer consists mainly of near-surface sand and gravel deposits of Miocene and younger age. The principal geologic unit in the High Plains aquifer, which underlies Castro and Parmer Counties, is the Ogallala

Table 1.--Summary of climatic conditions 1/

Annual weather element	Mean annual value
Precipitation (mostly rain)	17 inches
Temperature	55.3 °Fahrenheit
Estimated lake-surface evaporation	65 inches
Relative humidity (at 6 p.m. daily)	40 percent
Growing season	199 days
Days of sunshine (no cloud cover)	75 percent of time
First killing frost	November 1
Last killing frost	April 15

1/ From U.S. Department of Commerce (1984).

Formation of Miocene age. The Ogallala consists of poorly sorted clay, silt, sand, and gravel which generally are unconsolidated. Within the Ogallala, zones cemented with calcium carbonate are resistant to weathering and form ledges in outcrops. The most distinctive of these layers, the Ogallala cap rock (commonly called caliche or mortar bed), is near the top of the Ogallala Formation. The cap rock underlies large areas in Texas and New Mexico, and may be as thick as 60 ft (Gutentag and others, 1984).

Geologic Framework

The Ogallala Formation unconformably overlies rocks of Triassic and Cretaceous age that dip about 10 ft/mi toward the southeast, similar to the slope of the land surface (Wyatt and others, 1976). In general, however, this pre-Ogallala surface had larger relief than the present land surface; low hills and wide valleys which contained deep, narrow stream channels were typical features of the Triassic erosional surface. The Cretaceous rocks, being more resistant to erosion, remained as small buried mesas or buttes. Because the Ogallala was deposited on top of this irregular surface, the formation is very thin in some areas and very thick in others (fig. 2). Commonly, the thickness varies over relatively short distances. The Triassic rocks, principally shale, serve as a nearly impermeable basal confining bed for the High Plains aquifer in the study area, but the buried mesas or buttes of Cretaceous rocks generally can yield limited amounts of water to wells. At these locations, water in the Ogallala and Cretaceous rocks is in hydraulic continuity; therefore, the water-yielding Cretaceous rocks are considered to be part of the High Plains aquifer.

The Ogallala Formation consists of clay, silt, fine to coarse sand, and gravel. The lithology varies within short distances, both vertically and horizontally, and individual beds or lenses are not continuous over wide areas. Instead, the individual beds or lenses generally pinch out or grade into finer or coarser material. In the study area, silt commonly is associated with the fine to medium sand in the upper part of the formation; coarse sand generally occurs in the lower part of the formation; gravel is present in many places at the base of the formation where it is commonly associated with sand and silt and may be cemented; at other horizons, gravel also is present as lenses or is interbedded with sand.

Most of the Ogallala is unconsolidated, although near the top and locally within the formation, the sediments have been cemented, chiefly by calcium carbonate, to form beds of caliche. The degree of cementation varies largely from well cemented to partly cemented. The caliche occurs in single or multiple layers in the uppermost part of the formation throughout much of the southern High Plains. Because it is resistant to erosion, it forms the "cap rock" of the escarpment and the topographic prominences of the plains surface. The Ogallala Formation ranges in thickness from zero where the formation wedges out against older rocks to 500 ft in places in east-central Parmer County (Cronin, 1969).

Hydrologic Characteristics

The Canadian River has eroded through the Ogallala Formation in the Texas High Plains about 60 mi north of the study area (fig. 1). The valley effec-

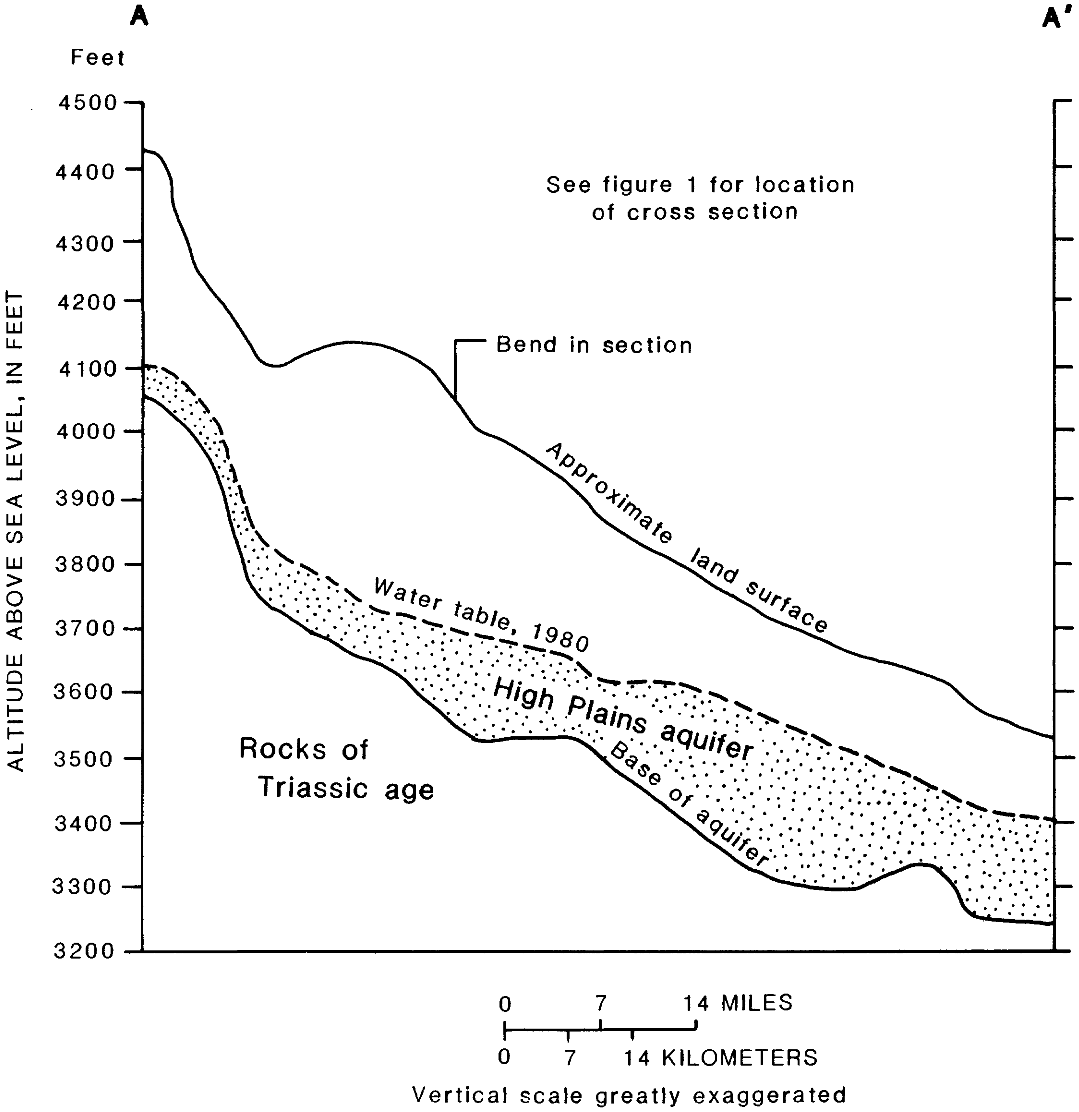


Figure 2.--Generalized geohydrologic section through the High Plains aquifer, northwest to southeast.

tively separates the High Plains aquifer into two units having little hydraulic interconnection. Erosion also has removed the Ogallala from much of its former extent to the east in Texas and to the west in New Mexico. As a result, the southern High Plains, although relatively flat, stands in high relief and is hydraulically independent of adjacent areas. For these reasons, coupled with the scarcity of local precipitation, water that is being withdrawn from the aquifer cannot be replaced quickly by natural recharge.

A map showing altitude and configuration of the water table in 1980 was constructed by plotting the altitude of water levels from a network of observation wells maintained by the Texas Department of Water Resources (fig. 3). The configuration of the water-table contours is affected by several factors, including: (1) Slope of the bedrock base of the aquifer; (2) variations in the thickness and hydraulic conductivity of saturated materials; (3) distribution and intensity of ground-water pumpage; (4) recharge to the aquifer from streams and playa lakes, and (5) recharge by infiltration of water through permeable soils. Ground-water flow in the study area generally is from northwest to southeast in the general direction of the hydraulic gradient or slope of the water table. Ground water in the study area moves at an average rate of about 7 in./d (Knowles and others, 1982).

Water Budget

Recharge to and discharge from the High Plains aquifer control the long-term availability of ground water in Castro and Parmer Counties. For example, when recharge exceeds discharge, the quantity of water in storage increases, and the water table rises. Conversely, when discharge exceeds recharge, the quantity of water in storage decreases and the water table declines. Prior to human activities, the ground-water system operated under natural conditions--that is, the water table was near equilibrium and the quantity of water stored in the aquifer was relatively constant, varying only in response to changes in annual precipitation, streamflow, and vegetation.

Recharge and discharge consist of a variety of components. The components of recharge are the infiltration and percolation of precipitation, percolation through playa lake bottoms, ground-water inflow from the upgradient areas of the High Plains aquifer, and percolation of irrigation return flow. The components of discharge are pumpage from municipal and farm wells, evapotranspiration, ground-water outflow, and pumpage from irrigation wells.

Recharge from precipitation depends on the volume, distribution, and intensity of the precipitation; the volume of moisture in the soil when the rain or snowmelt begins; and the temperature, vegetative cover, and permeability of the materials at the site of infiltration. Because of the wide variations in the factors, it is difficult to estimate the volume of precipitation recharge to the aquifer. Nevertheless, a variety of precipitation recharge estimates for the High Plains aquifer have been made. Theis (1937) used the water-budget method on the southern High Plains of Texas and New Mexico to estimate precipitation recharge at "somewhat less than 0.5 in./yr." White and others (1946) used the water-budget method to determine precipitation recharge at 0.06 in./yr for the southern High Plains. W. F. Guyton, cited by Rayner and others (1973), used the water-budget method in Parmer County to get a precipitation recharge estimate of 0.175 in./yr. Brown and Signor (1973) used the water-budget method

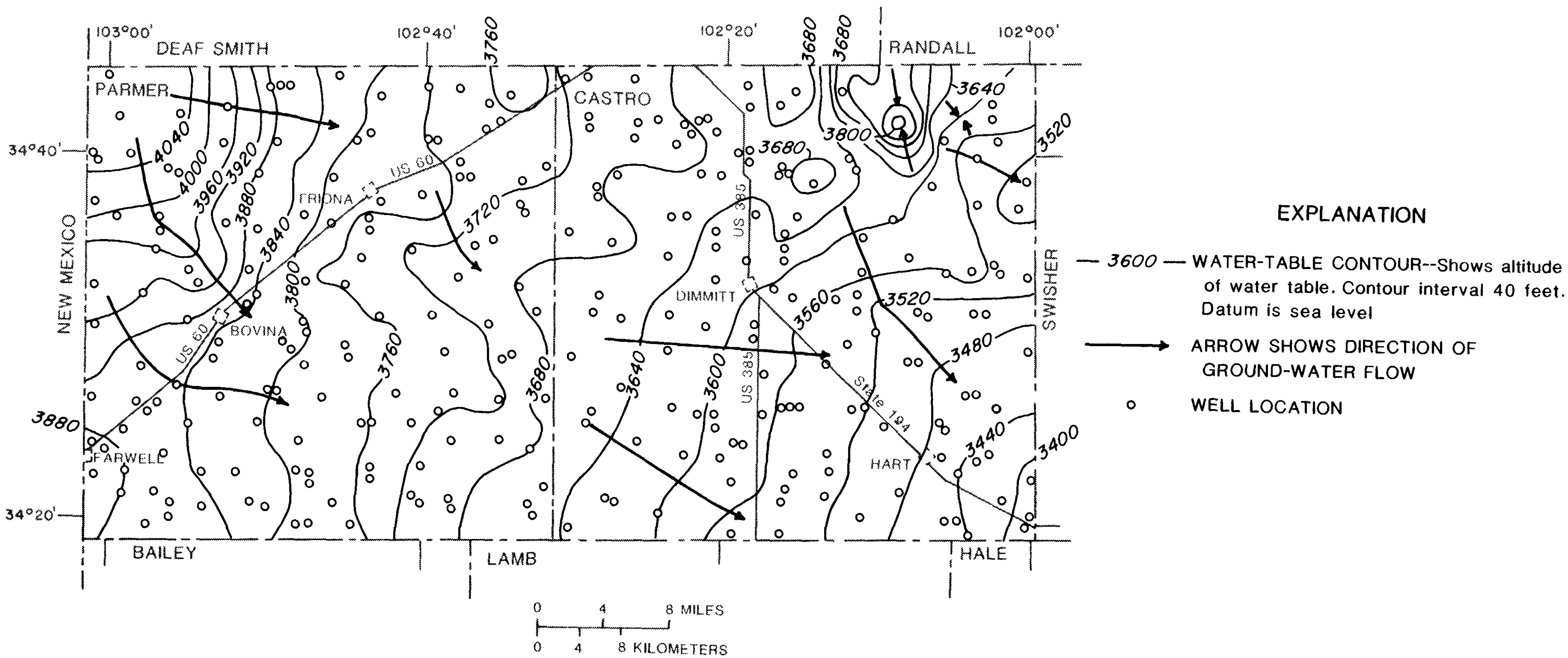


Figure 3.--Altitude of the water table, 1980, direction of ground-water flow, and location of water-level observation wells.

in the southern High Plains of Texas and New Mexico to get a range of precipitation recharge estimates from 0.024 to 0.072 in./yr. Brutsaert and others (1975) used C. E. Jacob's analysis for a tax depletion court case in the southern High Plains to arrive at a recharge rate of 0.183 in./yr. The Texas Department of Water Resources (1981b) county reports used an estimate of 1.0 in./yr precipitation recharge rate for their ground-water flow-model analysis of the High Plains. Although there are a variety of precipitation-recharge estimates for the High Plains aquifer, all the estimates indicate that recharge from precipitation is very small.

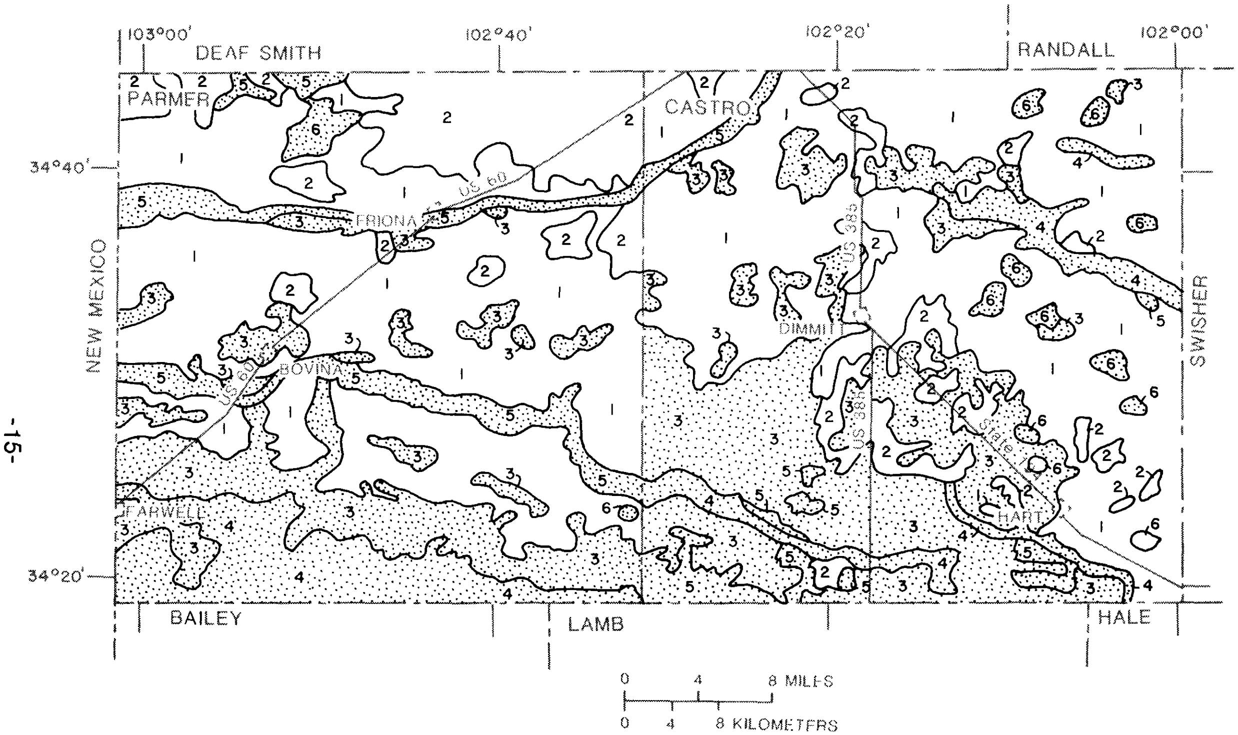
Recharge through playa lake bottoms was found to be more significant than recharge from precipitation over large land areas, as stated in a report by Wood and Osterkamp (1984). They concluded that most recharge of water to the High Plains aquifer in Texas is through the ring immediately surrounding the floors of playa lakes. They also stated that very little recharge occurs in the areas between the playa lake basins. They estimated the average recharge rate through playa lake bottoms to be about 1.57 in./yr.

Recharge from ground-water inflow occurs in the study area in the northwest and west parts of Parmer County. This inflow is in the direction of ground-water movement as shown in figure 3. Ground water flows from New Mexico east and southeast into the study area. Rayner and others (1973) determined the average inflow to be 1,070 acre-ft/yr through the aquifer from New Mexico into Parmer County.

In the final component of recharge, irrigation return flow, part of the water pumped from the High Plains aquifer for irrigation percolates back to the aquifer. Many factors are involved in the occurrence of irrigation return flow. Some of these factors include: The rate, amount, and type of irrigation application; the soil type and the infiltration rate of the soil profile; the amount of moisture in the soil prior to the irrigation application; the type of crop being grown, its root development, and its moisture extraction pattern; and the climatic conditions during and following the irrigation application.

One of the most important factors affecting the quantity of water recharged to the High Plains aquifer is the type of soil present. A generalized map of soil types in the study area is shown in figure 4. Most of the major soil types in the area (2, 4, 5, and 6) have moderate infiltration rates (2.0 in./hr). Areas 1 and 3 have very slow to slow infiltration rates--maximum of about 0.6 in./hr (Bruns, 1974, 1978). Most of the moderate infiltration rates occur in the central and southern areas of the counties. The factors which affect infiltration rate are porosity, permeability, grain size, sorting, composition, soil structure, and slope. Infiltration governs the rapidity with which water can percolate through the unsaturated zone and recharge the water table.

Discharge through the pumping of municipal and domestic farm wells and all non-irrigation wells was estimated to be 6,757 acre-ft in 1984, according to water-use estimates by the State (W. J. Moltz, Texas Water Development Board, oral commun., 1986). This pumpage is small compared to estimated irrigation pumpage for 1983 which will be discussed later (only 1 percent of irrigation pumpage calculated using reported acreage). Discharge through evapotranspiration includes evaporation from the soil and transpiration through plants. Pan evaporation in Castro and Parmer Counties is three to four times larger than the precipitation (Gutentag and others, 1984). Therefore, most precipitation



EXPLANATION

SOIL ASSOCIATIONS AND INFILTRATION RATES:

☐ Very slow to slow rate--Maximum of 0.6 inch per hour

- 1 Olton
- 2 Pullman

▒ Moderate rate--2.0 inches per hour

- 3 Acuff
- 4 Amarillo
- 5 Berda-Estacado-Bippus
- 6 Estacado-Tulia

Modified from Bruns, 1974; 1978

Figure 4.--Soil types.

which falls during the growing season returns to the atmosphere by evapotranspiration. Discharge through ground-water outflow appears to balance ground-water inflow during the 1975-83 study (R. R. Luckey, U.S. Geological Survey, oral commun., 1985). Rayner and others (1973) also believed that outflow balances inflow from New Mexico. The pumping of irrigation wells is by far the largest component of discharge. The total estimated pumpage from these wells is discussed later in this report. It also will be shown that discharge from the aquifer is larger than the volume of water recharging the aquifer.

Saturated Thickness

In the study area, the High Plains aquifer contains water under water-table, or unconfined, conditions. Two of the principal components of ground-water storage in the High Plains aquifer are saturated thickness and specific yield.

Eight hundred and sixteen drillers' logs of irrigation wells obtained from the files of the High Plains Underground Water Management District No. 1 in Lubbock, Texas, were analyzed to determine the saturated thickness, sand and gravel thickness, and specific yield. The drillers' logs contained descriptions of the material penetrated while drilling the well and the depths to the top and bottom of each lithologic unit. Along with these descriptions was information such as: Static water level, final pumping water level, sustained yield (metered), and the distance from the land surface to the base of the aquifer. The logs were all completed by water-well drilling contractors; they were not done under the supervision of professional geologists. The geologic data obtained from the logs were the only data available on the High Plains aquifer in the study area.

Gutentag and Weeks (1981) developed a computer program to analyze the data from the logs and calculate the following properties: Distance above base of aquifer, sand and gravel thickness, saturated thickness, aggregate sand and gravel thickness, and statistics related to distribution of aquifer properties.

The saturated thickness of the aquifer is the vertical distance between the water table and the base of the High Plains aquifer. The distribution of saturated thickness of the High Plains aquifer for 1980 is shown in figure 5. The map was constructed using saturated-thickness values calculated from drillers' logs. Saturated thickness varies considerably over the area and ranges from zero in the northeast corner of Castro County to 320 ft in a well in the center of the study area near the Castro-Parmer County line. The average saturated thickness throughout the study area is 129 ft.

Saturated Sand and Gravel Thickness

Thickness of the saturated sand and gravel lenses in the aquifer is a factor affecting the movement and storage of ground water in the study area. The thickness of each sand and gravel lens below the 1980 water table in each driller's log was totaled, and a map of the areal distribution of saturated sand and gravel thickness was created (fig. 6). The largest saturated sand and gravel thickness areas generally are in the southern half of the study area. Saturated sand and gravel thickness ranged from 0 to 294 ft, with an average thickness of about 120 ft.

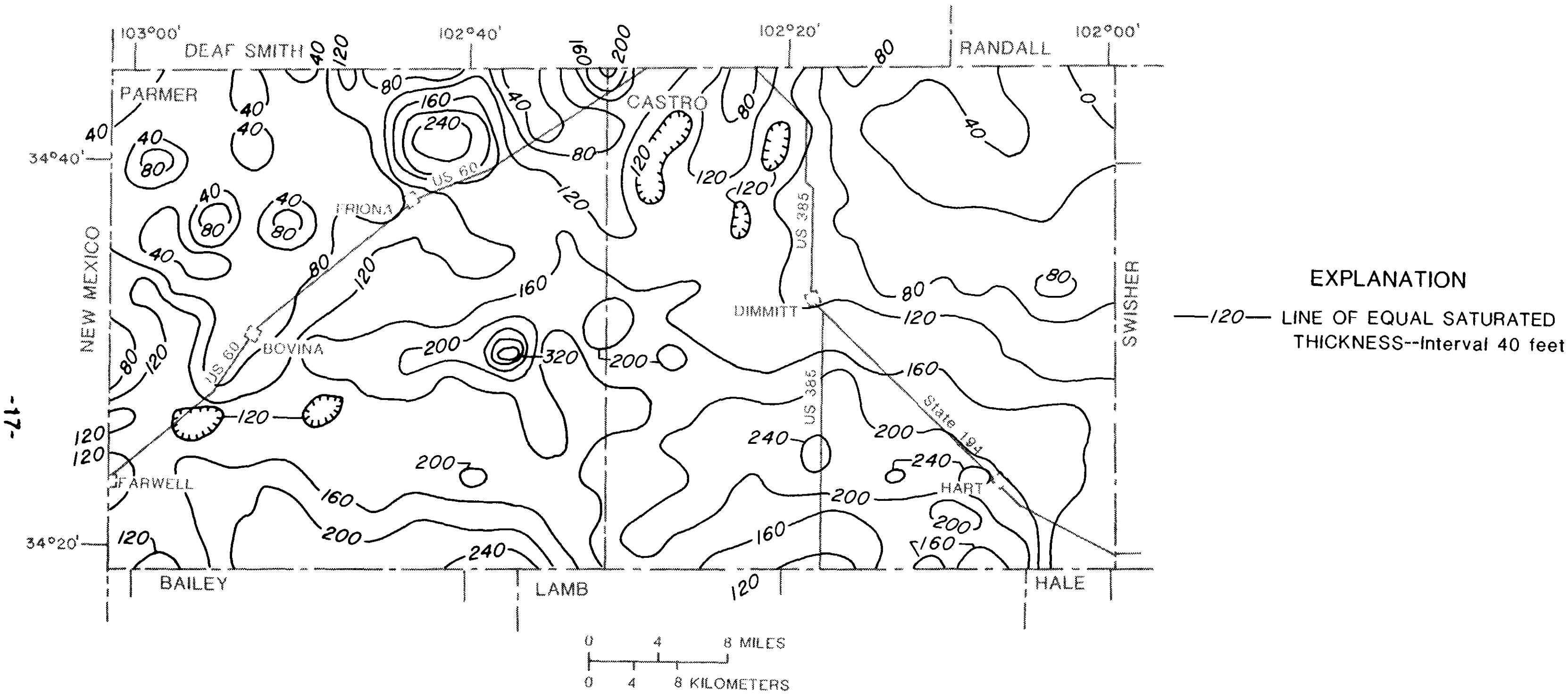
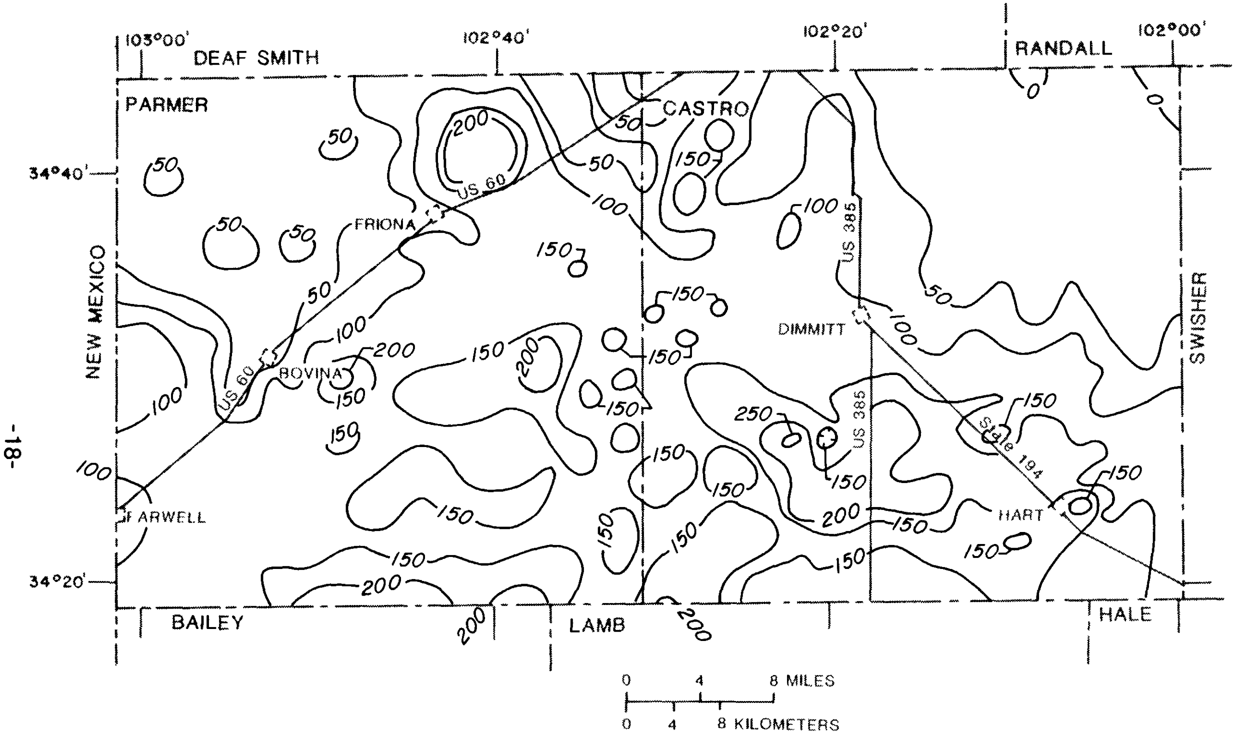


Figure 5.--Distribution of saturated thickness of the High Plains aquifer, 1980.



EXPLANATION

—200— LINE OF EQUAL SATURATED THICKNESS OF SAND AND GRAVEL--Interval 50 feet

Figure 6.--Distribution of saturated thickness of sand and gravel, 1980.

Specific Yield

Specific yield is defined as the ratio of the volume of water that the saturated material will yield by gravity drainage to the total volume of saturated material. Conversely, specific retention is defined as the ratio of the volume of water retained in the material after gravity drainage to the total volume of the saturated material. Specific-yield and specific-retention values are expressed as dimensionless fractions or percentages. The specific yield is dependent on particle size, shape, sorting, and cementation of the aquifer material. Fine-grained deposits, such as silt and clay, have a smaller specific yield than coarse-grained deposits, such as sand and gravel because specific retention increases as grain size decreases.

Specific-yield estimates were made from 816 drillers' logs of the study area. The specific-yield data were obtained by a method requiring the calculation of statistics which described the vertical variability of aquifer properties determined from lithologic descriptions reported by the driller (Gutentag and Weeks, 1981). A single specific-yield value was determined for a well log by assigning specific-yield values to each lithologic unit within the saturated interval of the aquifer and calculating a weighted-mean value. The weighted-mean specific yield (Sy) can be expressed as:

$$Sy = [(Sy_1)(t_1) + (Sy_2)(t_2) + \ldots + (Sy_n)(t_n)]/(t_1 + t_2 + \ldots + t_n) \qquad (2)$$

where Sy_1 = estimated specific yield of layer 1; and

t_1 = thickness of layer 1.

Specific yield for the study area (fig. 7) ranged from 4.1 to 24.9 percent with an average of 19.0 percent. This average compares favorably to a specific yield of 20.0 percent calculated for the southern High Plains of Texas by Rayner and others (1973).

The data set was extrapolated from 816 point values to 1,638 cell values by a computer smoothing program (R. R. Luckey, U.S. Geological Survey, written commun., 1985). The smoothing program computes the specific yield for a cell weighting all the data points within the effective radius of the cell. The effective radius could be varied by any amount.

The weight function is given by:

$$W = \frac{R^2+D^2}{S^2+D^2} \qquad (3)$$

where W = weight of the data point at the cell;

R = effective radius of the data point, in feet;

D = distance between the data point and the center of the cell, in feet; and

S = smoothing factor, in feet.

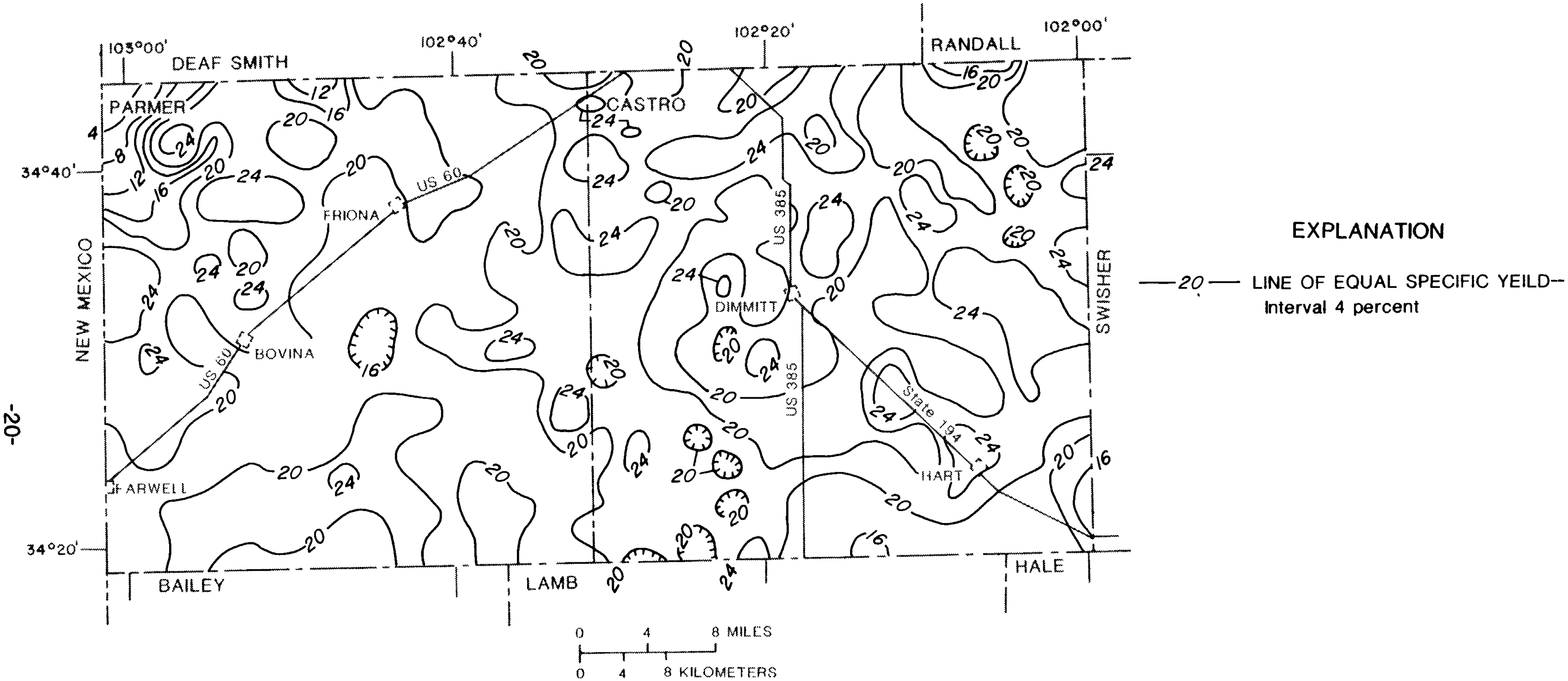


Figure 7.--Distribution of specific yield of the High Plains aquifer.

After all input data points are extended to all cells within their effective radii, the program computes a weighted average at each node using the formula:

$$G = \frac{\Sigma(WV)}{\Sigma W} \tag{4}$$

where G = the smoothed value at the cell;

W = the weighting computed by formula (3); and

V = the input value.

The summations are completed for all data points within the effective radii of the cells. The procedure outlined above was used in the construction of the maps presented in this report: Saturated thickness, saturated sand-and-gravel thickness, specific yield, water-level decline, and change in storage.

Different radii and smoothing factors were applied to the data. Each smoothed data set was statistically analyzed to determine which radius and smoothing factor resulted in the best "fit" of data. The best smoothed specific-yield data set resulted from an effective radius of 20,000 ft and a smoothing factor of 1 percent of the effective radius. The average specific yield from the smoothed data set was only 0.2 percent different than the average specific yield of the original data set. Thus, the smoothing techniques aided in extending the existing data to areas of sparse data without disturbing the overall data accuracy.

Even though specific-yield values shown in figure 7 may not be accurate in local areas, the map is useful for comparing specific-yield trends with maps showing depositional environments and sand and gravel thickness. Aquifers identified as channel deposits generally have specific-yield values of 18 percent or more, whereas sediments deposited in lower-energy environments have a markedly smaller average specific yield (Nordstrom, 1984). Other methods of specific-yield determination seem to corroborate the validity of these trends (Knowles and others, 1982). Statistics on hydrologic characteristics of the aquifer are summarized in table 2.

IRRIGATION PUMPAGE

The use of flowmeters on irrigation wells is not required in Texas; therefore, reliable historical records of irrigation pumpage are not available. Heimes and Luckey (1983) estimated pumpage by using the relationship between the theoretical irrigation demand for individual crops and field-measured pumpage. The field-measured data were collected by monitoring both pumpage and crop acreage for randomly selected irrigation wells for 3 years (Rettman and McAdoo, 1986).

The first step in determining irrigation pumpage was to calculate irrigation demand for each major crop for each year of the study. The Blaney-Criddle formula was used to compute the optimum volume of water for maximum yield for each crop type for each of the 9 years, and an adjustment was made for precipitation to permit computation of irrigation demand. By using direct measurements of irrigation pumpage from randomly selected wells for 1980, 1983, and 1984, a weighted-average measured application rate was calculated for each crop for

Table 2.--Hydrologic characteristics of the aquifer

Hydrologic characteristic	Number of values 1/	Minimum	Maximum	Average
Saturated thickness (feet)	816	0.0	320.0	129.0
Saturated sand and gravel thickness (feet)	818	0.0	294.0	118.0
Specific yield (percent)	816	4.1	25.0	19.0

1/ These values are based on original unsmoothed data. The number of values does not total the number of drillers' logs (more than 900) because some closely spaced wells would have created a duplication of data.

each year. The calculated irrigation demand for each crop was compared with measured applications to arrive at a factor which related irrigation demand and measured application. Pumpage for each crop was estimated by multiplying the factor, the irrigation demand, and the crop acreage for each year. The total estimated irrigation pumpage is the sum for all crop types for each year.

Irrigated Acreage

Reported acreage data were available for some or all years included in this study (1975 through 1983) from the "1982 Census of Agriculture" (U.S. Department of Commerce, 1984), "1975-84 Texas Field Crop Statistics" (Texas Crop and Livestock Reporting Service, 1975-84), "1975-77 High Plains Irrigation Survey" (New, 1975-77), and "Inventories of Irrigation in Texas--1958, 1964, 1969, 1974, and 1979" (Texas Department of Water Resources, 1981a). These data sources also were used to obtain irrigated acreages on various crop types. The Texas Field Crop acreage statistics were used in the pumpage calculations because they provided the only set of consistent crop acreage data for the 9 years. Other data are reported in table 3 for comparison.

LANDSAT imagery also was used to determine the number of irrigated acres in the study area. The LANDSAT imagery was analyzed at the Ames Research Center, Moffett Field, California, by the National Mapping Division of the U.S. Geological Survey. The imagery was taken for even-numbered years (1976, 1978, 1980, 1982) and for 1983. These years were selected because of cost considerations and the fact that year-to-year irrigation acreage pattern changes were minimal and odd-numbered year data could be interpolated from the even-year data. Two imagery bands were used in the analysis: Band 5 (red or chlorophyll band) and band 7 (infrared). A ratio of the chlorophyll band to the infrared band was taken to determine which areas on the image were irrigated.

This type of LANDSAT imagery data interpretation also was used for the RASA study in Nebraska. The use of LANDSAT imagery to detect irrigated acreage was more successful in Nebraska than Texas, because in Texas the imagery tends to underestimate acreage owing to the wider diversity of crop types grown there (F. J. Heimes, U.S. Geological Survey, oral commun., 1986). The procedures for analyzing LANDSAT imagery data for irrigated cropland are described in a report by Thelin and Heimes (in press). The imagery was interpreted by means of a computer program to determine acres irrigated in each grid cell. The total irrigated acreages from both reported and LANDSAT sources are presented in table 3.

The difference between reported irrigated acres and irrigated acres determined from LANDSAT can be explained by one or several of the following factors: (1) Summer LANDSAT imagery was used to estimate irrigated acreage and many crops such as cotton and sorghum are "stressed" during the summer by not receiving the optimum amount of water. Farmers purposely "stress" crops because they can still achieve good yields but at a smaller unit cost. Therefore, these crops might show on satellite images as being in dryland farm areas; (2) many of the U.S. Soil Conservation Service agents who compile data for the reports consider an acreage to be irrigated even if water was applied only once or twice during the growing season; and (3) irrigated acreages may have appeared to be dryland on LANDSAT imagery because irrigation water had not been applied recently.

Table 3.--Total irrigated acreage by year from various sources

Year	Census of agriculture	Texas field crop statistics 1/	High Plains irrigation survey	Inventories of irrigation in Texas	LANDSAT imagery
1975	618,941	712,000	760,653	--	2/510,820
1976	--	720,000	740,300	--	531,857
1977	--	727,000	763,620	--	2/524,980
1978	--	654,000	--	--	518,129
1979	--	609,000	--	689,636	2/496,840
1980	--	626,000	--	--	475,611
1981	--	584,000	--	--	2/488,445
1982	503,039	523,000	--	--	501,361
1983	--	371,000	--	--	376,073

1/ These are sums of the acreages of the six major crop types plus hay and vegetables.

2/ Acreage for these years was not taken from actual LANDSAT imagery, but is a linear interpolation calculated from previous and/or subsequent years of imagery data.

The areas of irrigated agriculture estimated from LANDSAT data collected in the summer of 1980 are presented in figure 8. This irrigated-acreage map shows the areas that are most intensely irrigated. The areas most intensely irrigated exhibit the largest pumping and, therefore, the largest change in water level and storage. Many of the most intensely irrigated areas also are in locations of largest saturated thickness.

Consumptive Use and Irrigation Demand

Consumptive use, also called evapotranspiration, is the amount of water in a specified time that is: (1) used by vegetation in transpiration and building of plant tissue and (2) evaporated from adjacent soil or from intercepted precipitation on the foliage. Blaney and Criddle (U.S. Department of Agriculture, 1967) found that the amount of water consumptively used by crops during their normal growing season was closely correlated with mean monthly temperatures and daylight hours. They developed coefficients that can be used to transfer the consumptive-use data for a given area to other areas for which only climatological data are available. Consumptive use for different crop types can be calculated using the Blaney-Criddle consumptive-use formula (U.S. Department of Agriculture, 1967).

The Blaney-Criddle formula frequently is used to estimate seasonal or monthly crop consumptive use in arid or semiarid areas, but it tends to overestimate irrigation requirements on stress-tolerant crops such as cotton and sorghum (F. J. Heimes, U.S. Geological Survey, oral commun., 1986). The method is used extensively by the U.S. Soil Conservation Service and was used in several studies conducted by the U.S. Geological Survey (Heimes and Luckey, 1982, 1983). The only parameters needed for Blaney-Criddle calculations are temperature and precipitation, and these data were obtained from six weather stations in the area (fig. 9)--Hart, Dimmit 6E, Hereford, Friona, Muleshoe, and Clovis 13N (New Mexico). By using a mean-weighted areal distribution, six weather zones were created for these stations.

Annual consumptive use was calculated by the Blaney-Criddle formula for each weather zone for each of six major crop types--corn, cotton, sorghum, soybeans, sugar beets, and winter wheat. The values for each of the zones were then averaged to arrive at a consumptive-use value for the study area.

The Blaney-Criddle formula is:

$$U = \sum_{i=1}^{n} (K_i F_i) \tag{5}$$

where $K_i = (0.0173t - 0.314)(KC)$;

$F_i = \frac{tp}{100}$

U = seasonal consumptive use of the crop, in inches;

n = number of months in growing season of a particular crop;

i = index for month;

K_i = empirical consumptive-use crop coefficient for a given crop and month;

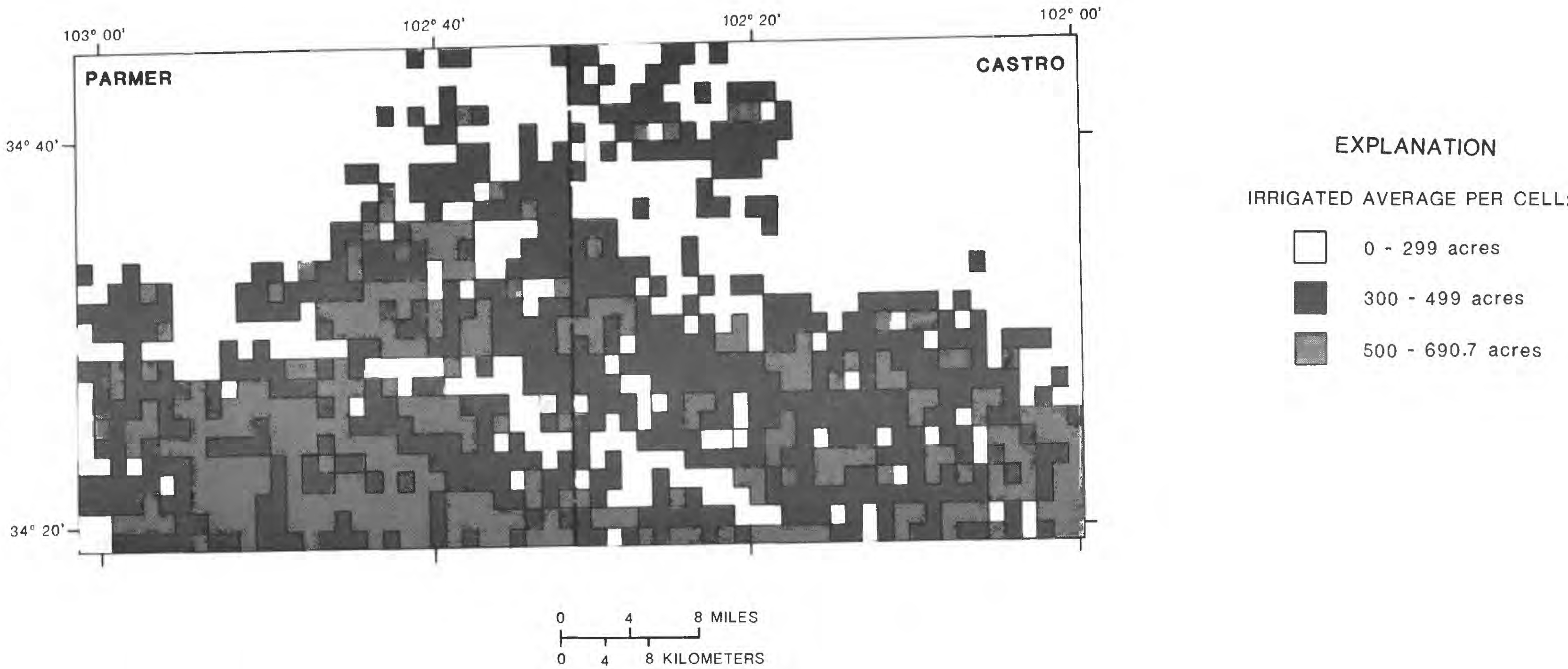


Figure 8.--Density of irrigated agriculture, summer 1980.

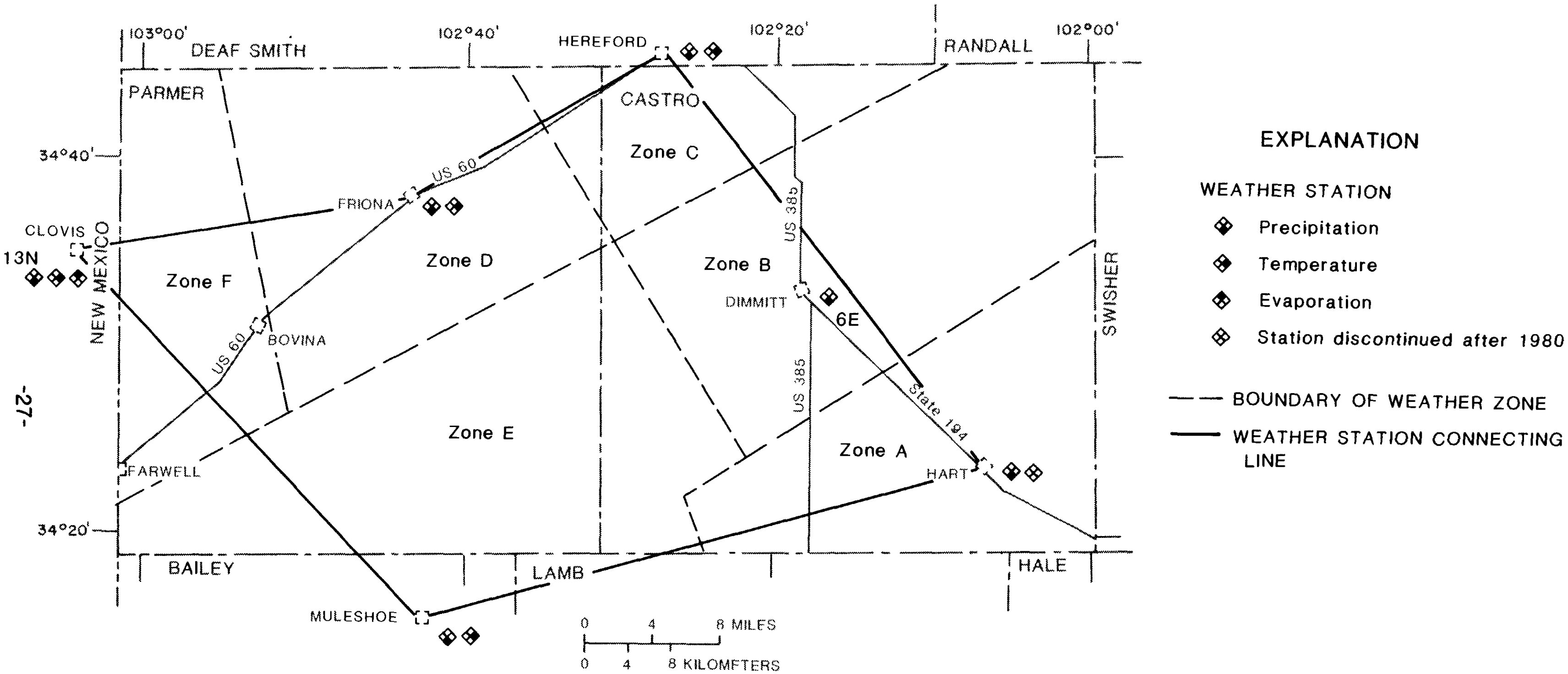


Figure 9.--Location of weather stations and weather zones.

F_i = monthly consumptive-use factor;

t = monthly mean air temperature, in degrees Fahrenheit;

KC = coefficient reflecting the growth stage of the crop; and

p = monthly percentage of daylight hours.

Values for the crop coefficient (KC) and the percentage of daylight hours (p) were interpreted from graphs and tables in a report by the U.S. Department of Agriculture (1967). Monthly mean air temperature (t) and precipitation for the 1980 growing season were compiled for the six weather stations (U.S. Department of Commerce, 1975-77, 1978-84).

Irrigation demand is the estimated depth of irrigation water required by a crop during the growing season. Demand needed to be calculated so it could be compared to measured water applied to crops. Irrigation demand is calculated from consumptive-use values by the formula:

$$I = \sum_{i=1}^{n} (U_i - ep_i) \qquad (6)$$

where I = seasonal irrigation demand for a particular crop, in inches;

n = number of months in growing season of a particular crop;

i = index for month;

U_i = monthly consumptive use of the crop, in inches; and

ep_i = monthly effective precipitation, in inches.

Monthly effective precipitation (ep_i) was calculated using a formula in a report by the U.S. Department of Agriculture (1967). Effective precipitation during the growing season is a function of total precipitation and the consumptive-use requirement of the crop. For this study, effective precipitation also included that part of non-growing-season precipitation that could be stored as soil moisture and then subsequently used by a crop during the growing season. The non-growing-season effective precipitation is a function of total precipitation, soil type, and the rooting depth of the crop. A more detailed discussion of the formulas and precedures used in the calculations is contained in a report by Heimes and Luckey (1982).

Results of the calculated irrigation demand for each year from 1975 through 1984 are presented in table 4. The average difference between irrigagation demands calculated by the Blaney-Criddle method and the field-measured application as collected by Rettman and McAdoo (1986) ranged from 18 percent for soybeans to 37 percent for cotton, and the average for all crop types was 30 percent.

The difference between the calculated irrigation demand and the measured application rate could be explained by the fact that Blaney-Criddle calculates only the optimum amount of water needed for plant growth. Also, these "ideal" water requirements are seldom used in the actual process of farming.

Table 4.--Calculated irrigation demand and measured application rate by crop type

[Units in inches per year; C, calculated irrigation demand; M, measured application rate; --, missing measurement]

Year	Corn		Cotton		Sorghum		Soybeans		Sugar beets		Winter wheat	
	C	M	C	M	C	M	C	M	C	M	C	M
1975	18.1	--	13.3	--	15.2	--	12.8	--	21.5	--	10.8	--
1976	17.7	--	13.1	--	13.8	--	11.9	--	20.8	--	10.5	--
1977	20.9	--	15.9	--	16.9	--	14.6	--	24.3	--	11.5	--
1978	19.2	--	14.4	--	16.6	--	14.5	--	22.6	--	10.9	--
1979	15.4	--	10.9	--	12.0	--	10.5	--	18.4	--	10.3	--
1980	22.5	31.8	17.5	10.3	20.0	14.9	17.3	10.0	26.4	--	9.1	26.1
1981	16.4	--	12.4	--	11.4	--	8.2	--	19.2	--	10.0	--
1982	16.7	--	11.7	--	14.1	--	12.8	--	19.6	--	12.2	--
1983	21.7	35.1	16.3	12.4	19.5	19.6	18.0	13.4	24.2	34.1	10.5	11.0
1984	14.7	31.5	10.2	13.7	8.9	11.4	6.9	10.5	17.5	26.6	9.4	15.5

Irrigation Application Rate

Measured field-application rates for the six major crop types were collected for three growing seasons (1980, 1983, and 1984). The techniques used to collect these field data are described in the following section and the results of the field measurements are given in table 4.

Because the calculated irrigation demand did not indicate a close correlation to the measured application rate, the relationship between the two was mathematically described. It also proved useful in calculating estimated irrigation pumpage.

Field Determination

Irrigation pumpage data were collected by the Geological Survey at 54 sites in Parmer County in 1980 (fig. 10), and additional data were collected for both counties at 63 randomly selected sites in 1983 and 1984 (fig. 11). These data included well yields, hours of operation, fuel consumption, crop type, and irrigated acreage (Rettman and McAdoo, 1986).

Well sites were visited prior to the irrigation season to obtain an initial reading on energy (natural gas or electric) meters and on inline flowmeters and engine-hour meters, if available. Vibration Time Totalizers (VTT's) were installed to provide additional information about operating times of the wells. These devices are electronic timers that record the total pumping time of a well by sensing vibration. The sites were visited periodically during the irrigation season to obtain data on crop types and acreage, well discharge, energy consumption, time of operation, and water application. Well discharge was measured with a portable flowmeter that uses a high-pitched sound to penetrate the pipe material and measure water flow. To ensure that the water application data were as accurate as possible, considerable care was taken in collecting the well discharge and time-of-operation data. Personal interviews were conducted with some farm operators when additional information was needed. However, the measured irrigation applications are considered as estimates because well discharge varied and operating hours were not always known with a large degree of confidence (Rettman and McAdoo, 1986).

Adjustment Factor

Because of the large variation between calculated irrigation demand and measured application rate, a factor relating irrigation demand to measured application rate was needed. Based on the reported acreage of each crop, an acreage-weighted composite irrigation demand was calculated for each of the 3 years (1980, 1983, and 1984) using the following formula:

$$CID = \sum_{i=1}^{n} A_i I_i \Big/ \sum_{i=1}^{n} A_i \qquad (7)$$

where CID = composite irrigation demand, in inches;

I_i = irrigation demand of crop i, in inches;

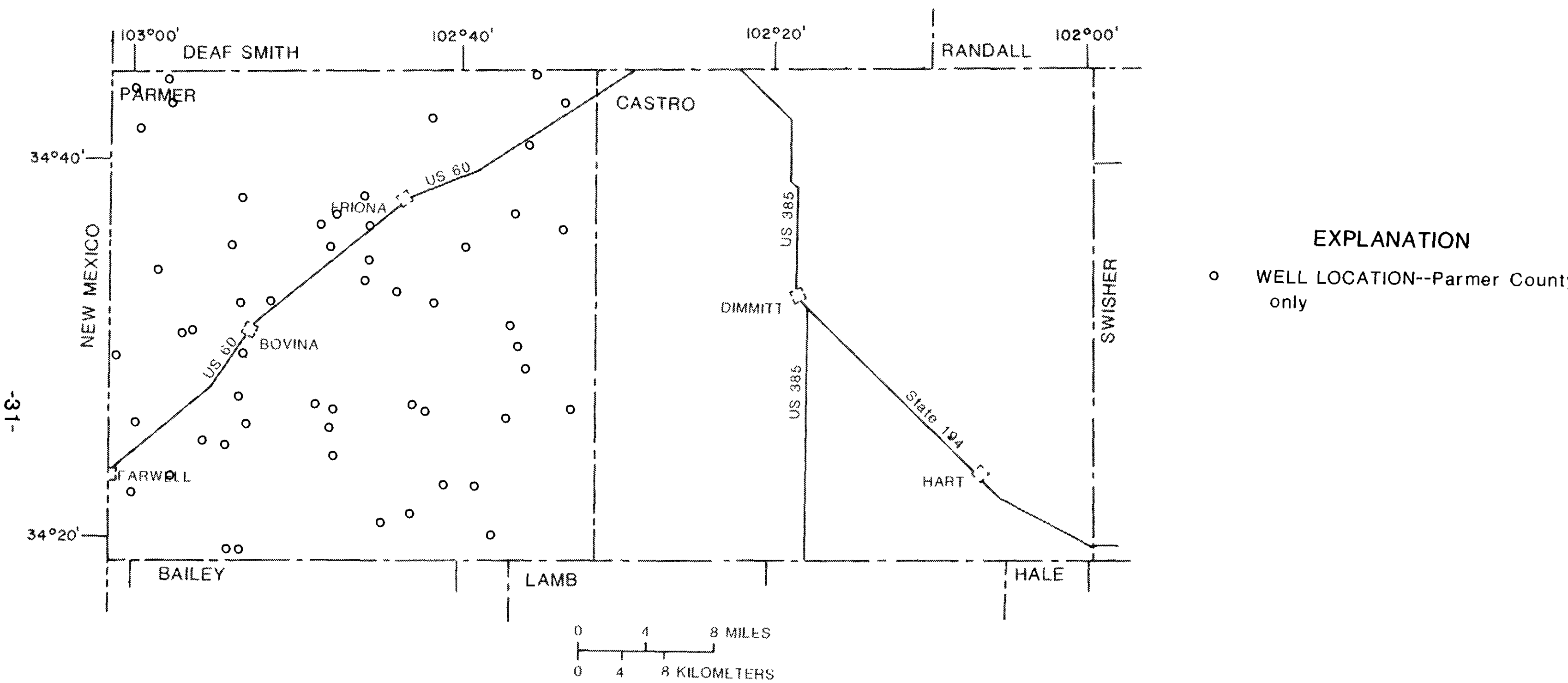


Figure 10.--Location of irrigation-pumpage measurement sites, 1980.

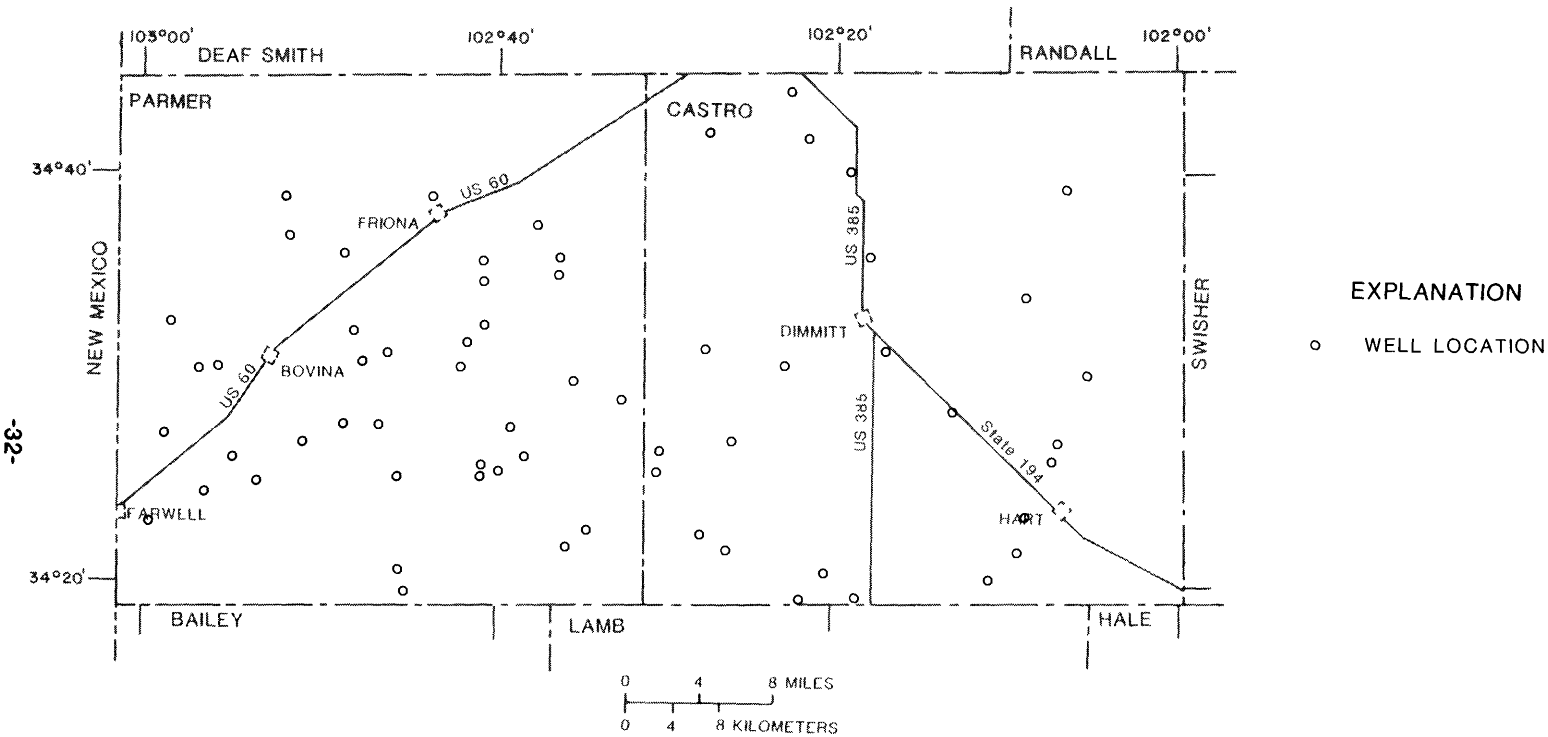


Figure 11.--Location of irrigation-pumpage measurement sites, 1983-84.

A_i = reported acreage of crop i in the study area; and

n = number of crop types.

Similarly, an acreage-weighted application for each of the 3 years of measured data (1980, 1983, and 1984) was calculated from the formula:

$$WA = 12 \sum_{i=1}^{n} Q_i \;/\; \sum_{i=1}^{n} A_i \qquad (8)$$

where WA = acreage-weighted application, in inches;

Q_i = pumpage at site i, in acre-feet;

A_i = acreage at site i; and

n = number of field sites in the study area.

The composite irrigation demand and the acreage-weighted application rate are listed in table 5. Total acreage-weighted application rate is 1.53 (72.4/ 47.2) times larger than total composite irrigation demand for the 3 years.

Estimated Irrigation Pumpage

Irrigation pumpage was estimated for each year of the study by using the following formula:

$$Q = (TA)(CID)(1.53) \;/\; 12 \qquad (9)$$

where Q = total estimated pumpage for each year, in acre-feet;

TA = total irrigated acreage; and

CID = composite irrigation demand for each year, in inches.

The results of the estimated irrigation pumpage calculations are presented in table 6.

Because of the large differences between total irrigated acreages from reported data sources and from LANDSAT imagery (table 3) and a lack of information as to which is more accurate, both data sources were used in the pumpage estimates. The reported acreages are larger than those estimated from LANDSAT imagery except in 1983. Pumpage computed using acreage provides a range of values with the "correct" value believed to be somewhere in between.

Three major factors could account for the pumpage fluctuations from year to year. They are: (1) Total precipitation, (2) energy and commodity prices, and (3) government payments programs.

In general, the amount and frequency of pumping were related to the amount of precipitation received during the growing season. In years of less than normal precipitation (about 17 in.), pumpage tended to increase. Conversely, if precipitation was more than normal, especially during critical growing periods, pumpage decreased.

Table 5.--Composite irrigation demand and acreage-weighted application for 3 years

Year		Composite irrigation demand (inches)	Acreage-weighted application (inches)
1980		18.5	25.3
1983		16.9	25.7
1984		11.8	21.4
	TOTAL	47.2	72.4

Table 6.--Estimated irrigation pumpage by year for reported acreage data sources and LANDSAT acreage

[acre-feet]

Year	Calculated using reported acreage	Calculated using LANDSAT acreage
1975	1,424,000	1,022,000
1976	1,460,000	1,078,000
1977	1,715,000	1,238,000
1978	1,416,000	1,056,000
1979	1,040,000	849,000
1980	1,474,000	1,120,000
1981	983,000	823,000
1982	958,000	918,000
1983	799,000	810,000
TOTAL	11,269,000	8,914,000
AVERAGE	1,252,000	990,000

Rising energy prices during the mid- to late 1970's also influenced pumpage. As fuel costs increased, pumpage tended to decline slightly. Annual pumpage was larger from 1975 to 1980 than from 1981 to 1983, primarily because high commodity prices for agricultural products tended to offset the high energy prices. Only after commodity prices declined steeply in 1980-81, did pumpage significantly decline (table 6). A study by the Texas Water Resources Institute established the relationship between energy and commodity prices with agricultural production (including pumpage for irrigation) on a typical farm in the Texas High Plains (Petty and others, 1980).

There was a strong relationship between government agriculture payments to farmers and pumpage. When government payments were large, pumpage decreased proportionately because farmers took land out of production. When more land was placed in production, pumpage increased somewhat proportionately. In 1983, the Department of Agriculture initiated a payment-in-kind (PIK) program whereby farmers would be paid for taking land out of production by the use of warehouse receipts rather than checks. The warehouse receipt entitled the bearer to claim an equivalent quantity of an agricultural commodity which he might have otherwise grown on the fallow land. The receipt could be converted to cash by turning it over to a broker or commodity exchange. The PIK program seemed to be popular throughout the country and especially in Castro and Parmer Counties. The amount of irrigated land in the study decreased significantly in 1983 (table 3). There also was a substantial decrease in computed pumpage in the same year (table 6).

Besides the three main factors affecting pumpage, farming techniques and traditions also are important. Many farmers are changing from large water-use crops such as corn and vegetables to crops which require less water. Farms that traditionally grew sorghum and cotton changed to corn and vegetables in the 1960's. When energy prices increased and commodity prices decreased in the early 1980's, there was a movement away from large water-use crops to the more traditional crops which could be stressed with little water without suffering substantial yield declines. This trend seems to have been established in the Texas High Plains (C. Tuck, Texas Department of Water Resources, oral commun., 1985).

CHANGE IN GROUND-WATER STORAGE

Change in ground-water storage is the net change in the volume of water in the aquifer over a specific time period. The change would be positive if the volume of water increased and negative if the volume of water decreased. It was necessary to determine the change in ground-water storage for the aquifer. To calculate the change in storage, water-level changes needed to be determined on an annual basis during the study from 1975 to 1983. The annual water-level change was multiplied by the specific yield and the area in calculating change in storage.

Water-Level Changes

Water levels for each year of the 1975-83 study, were obtained for each well in the observation-well network maintained by the Texas Department of Water Resources. Water-level change was the difference between water levels measured at different times in each observation well. The difference was plotted on maps and entered into the computer. The data were analyzed using the smoothing program, and the result was a change in water level at each of the 1,638 grid cells in the study area. Maps showing the annual water-level change were then prepared.

Summary statistics of the average annual water-level changes are presented in table 7. Almost the entire study area experienced water-level declines, with the exceptions of the northeast and northwest corners. From 1975 to 1977, the average rate of water-level decline increased from 3.10 to 3.47 ft per year. After 1977, the average rate of water-level decline generally decreased each year to 1.85 ft in 1983. Much of this decrease in average annual water-level decline can be attributed to a progressive decrease in acres irrigated (table 3). Annual water-level changes also reflect the variability within the study area due to pumping density, pumping rates, total saturated thickness, and farming techniques.

The water-level decline for 1975-83 is depicted in figure 12. Many areas have experienced a water-level decline of more than 30 ft, and one area had a decline of more than 50 ft. The maximum decline for the study period was 63 ft in the center of the study area, about 14 mi west of Dimmitt. The average decline for the 9 years was 25.3 ft. This water-table surface indicates that most of the study area is undergoing a significant water-level decline. Individual cones of depression from pumping wells have coalesced in many areas to produce a regional pumping surface of significant drawdown. This condition is the consequence of a large number of wells per unit area, large rate of water withdrawal, and a small rate of recharge.

In general, the areas of largest saturated thickness also were the areas of largest water-level decline. The largest capacity wells are in areas of largest saturated thickness and cause the largest drawdowns or water-level declines.

Calculations

Change in storage was calculated from the following formula:

$$C = (SY)(WLC)(690.7) \qquad (10)$$

where C = change in storage, in acre-feet;

SY = specific yield, dimensionless;

WLC = annual water-level change, in feet; and

690.7 = acreage of each grid cell.

Because specific yield is extremely variable, it can greatly affect the calculation for change in storage. The effect of change in specific-yield values on specific-yield values for a given data point is indicated in table 8. If the area of the cell and the 9-year water-level change remain constant and the specific yield is varied by 0.05, the change in storage will vary in direct proportion to the change in specific yield. For the values in table 8, a 0.05-error in specific yield can cause a 20-50 percent error in change in storage.

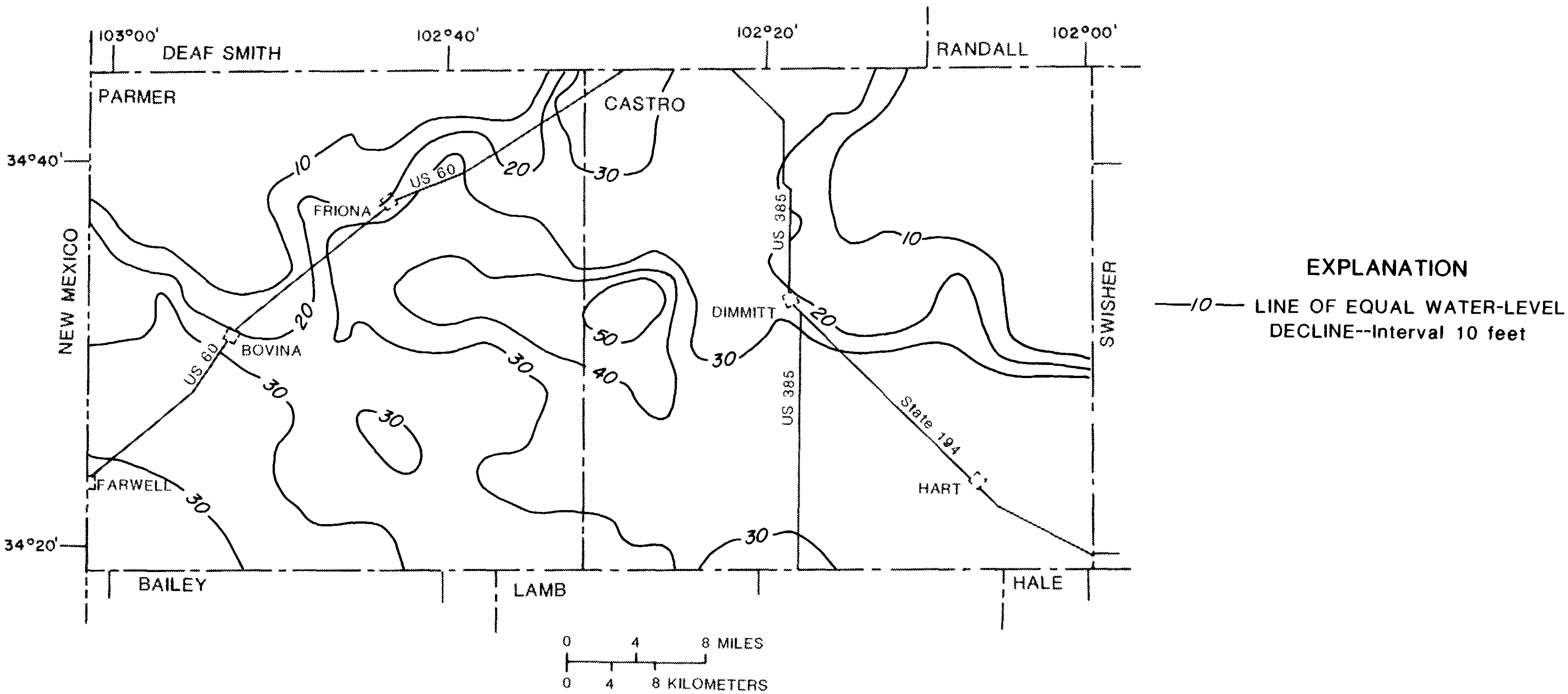


Figure 12.--Water-level decline, 1975-83.

Table 7.--Summary statistics of average annual water-level decline, 1975-83

Year	Minimum decline (feet)	Maximum decline (feet)	Average decline (feet)
1975	0.0	6.0	3.10
1976	.0	6.5	3.46
1977	.0	6.5	3.47
1978	.0	6.5	3.26
1979	.0	6.0	2.65
1980	.0	6.0	2.59
1981	.0	6.0	2.93
1982	.0	5.2	2.01
1983	.0	5.5	1.85
TOTAL	0.0	54.2	25.32

Table 8.--Change in storage as a function of specific yield

Area of cell (acres)	1975-83 water-level decline (feet)	Specific yield (dimensionless)	Change in storage (acre-feet)
690.7	35	0.10	2,417
690.7	35	.15	3,626
690.7	35	.20	4,835
690.7	35	.25	6,044
690.7	35	.30	7,252

Thus, small differences in specific yield can result in large differences in the change in storage. For the purposes of this study, only one specific-yield value was associated with each 690.7-acre cell. In an area as large as 690.7 acres, specific yield could vary significantly.

The change in storage estimates for each year of the study period are presented in table 9. The change in storage increased from 1975 to 1977. Thereafter, change in storage decreased progressively each year, with the exception of 1981. The total change in storage for the 9 years was 5,168,000 acre-ft. Change in storage correlates directly with estimated irrigation pumpage (table 6) because when pumpage was large, change in storage increased correspondingly. A map depicting change in storage per unit area is shown in figure 13. The largest change in storage per unit area occurred in the southern half of the study area, in an area southeast of Friona, and in areas northwest of Dimmitt. These areas correspond to areas of largest pumpage and density of agriculture--400 to 690 acres irrigated per cell (fig. 8).

COMPARISON OF IRRIGATED PUMPAGE AND CHANGE IN GROUND-WATER STORAGE

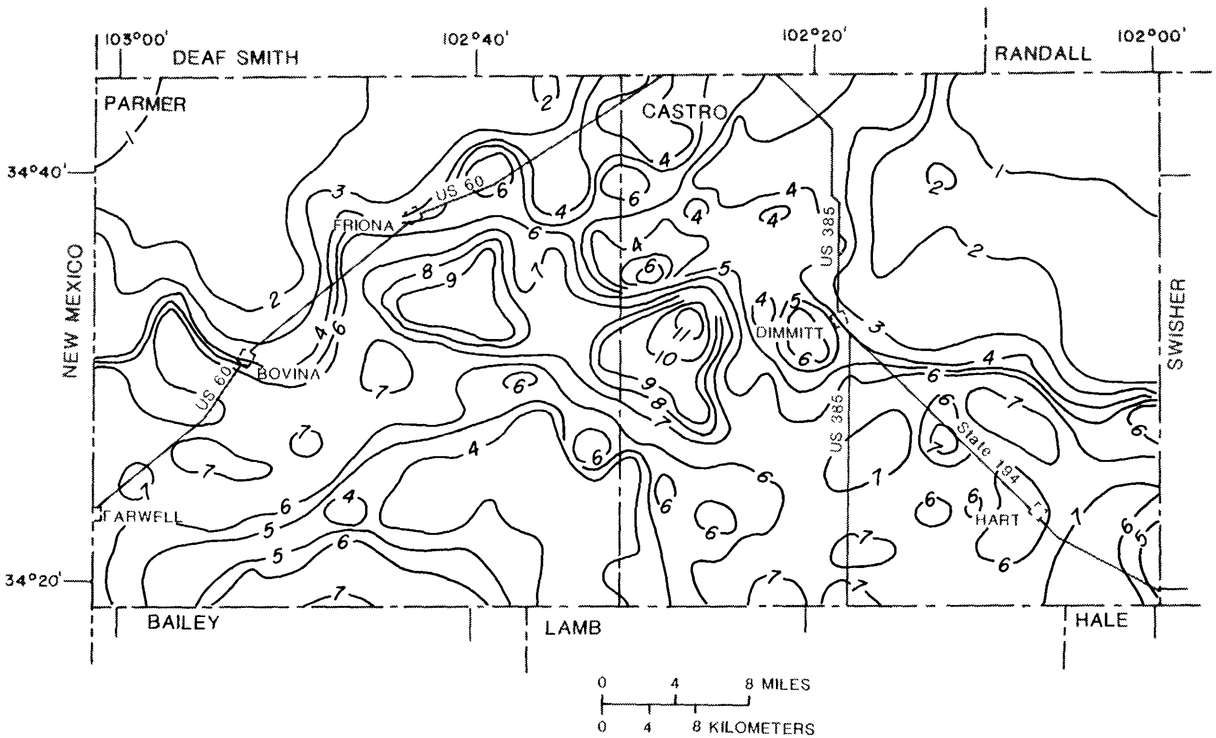
Change in ground-water storage was subtracted from irrigated pumpage for each year of the study (1975-83). The results are given in table 10. The difference between pumpage and change in storage for the 9 years was 6,101,000 acre-ft using reported acreage data and 3,746,000 acre-ft using LANDSAT data. In every year except 1983, the difference was larger using reported data than using LANDSAT data. For the 9 years, pumpage exceeded change in storage by 118.3 in. based on reported data and 76.4 in. based on LANDSAT data.

The difference between irrigation pumpage and change in storage as a percentage of pumpage is given in table 10. The difference averaged 54 percent of pumpage for reported data and 42 percent for LANDSAT data. From the results in table 10, it is readily apparent that in Castro and Parmer Counties, pumpage is significantly larger than the change in ground-water storage.

In a similar study conducted by the U.S. Geological Survey in Chase, Dundy, and Perkins Counties, Nebraska, the difference between pumpage and change in storage as a percentage of pumpage was estimated to be 70 percent (Heimes and others, in press). The difference between that study and the one in Texas can be partly explained because the soils in much of the study area of Nebraska are more sandy than those in Texas, and therefore, percolation rates would be larger. Also, historical pumpage records were available in Nebraska, and irrigation pumpage could be calculated more accurately than in Texas.

Essentially, change in ground-water storage equals recharge minus discharge. The major components of recharge, as outlined in this report, are recharge from precipitation, recharge from playa lake bottoms, recharge from ground-water inflow, and recharge from irrigation return flow. The major components of discharge, as outlined in this report, are pumpage from municipal, industrial and domestic farm wells, evapotranspiration, ground-water outflow, and irrigation pumpage. Change in storage can be calculated by the following formula:

$$\Delta S = (Rp + Rpi + I + Rf) - (P + ET + O + Q) \qquad (11)$$



EXPLANATION

—8— LINE OF EQUAL CHANGE IN STORAGE PER UNIT AREA--Interval 1 acre-foot per acre

Figure 13.--Change in storage per unit area, 1975-83.

Table 9.--Change in storage estimates by year

Year	Change in storage (acre-feet)
1975	633,000
1976	706,000
1977	708,000
1978	665,000
1979	541,000
1980	529,000
1981	598,000
1982	410,000
1983	378,000
TOTAL	5,168,000

Table 10.--Comparison of irrigation pumpage and change in ground-water storage by year

Year	Pumpage minus change in storage (acre-feet)		Pumpage minus change in storage per irrigated acre (inches)		Pumpage minus change in storage as a percentage of pumpage	
	Reported data	LANDSAT data	Reported data	LANDSAT data	Reported data	LANDSAT data
1975	791,000	389,000	13.3	6.6	55	38
1976	754,000	372,000	12.6	6.2	52	35
1977	1,007,000	530,000	16.6	8.7	59	43
1978	751,000	391,000	13.8	7.2	53	37
1979	499,000	308,000	9.8	6.1	48	36
1980	945,000	591,000	18.1	11.3	64	53
1981	385,000	225,000	7.9	4.6	39	27
1982	548,000	508,000	12.6	11.7	57	55
1983	421,000	432,000	13.6	14.0	53	53
TOTAL	6,101,000	3,746,000	118.3	76.4	--	--
AVERAGE	678,000	416,000	13.1	8.5	54	42

where ΔS = change in ground-water storage;
Rp = recharge from precipitation;
Rpi = recharge from playa lake bottoms;
I = ground-water inflow;
Rf = irrigation return flow;
P = municipal, industrial, and domestic farm well pumpage;
ET = evapotranspiration;
O = ground-water outflow; and
Q = irrigation pumpage.

Therefore, irrigation return flow can be calculated by the formula:

$$Rf = \Delta S + (P + ET + O + Q) - (Rp + Rpi + I). \tag{12}$$

Rayner and others (1973) stated that ground-water inflow balances ground-water outflow (inflow = outflow). Also, for purposes of simplification, evapotranspiration can be considered negligible, so ET = 0. The formula can be simplified to:

$$Rf = \Delta S + (P + Q) - (Rp + Rpi). \tag{13}$$

Change in storage (ΔS) from table 9 is -5,168,000 acre-ft for the 9-year study. Municipal, industrial, and domestic farm pumpage for the study area was estimated to be 6,757 acre-ft in 1984 (W. J. Moltz, Texas Water Development Board, oral commun., 1986). The total for P for the 9-year study is about 61,000 acre-ft. This was based on the assumption that water use did not change significantly during this time because population did not change by more than a few percent. From table 6, the total irrigation pumpage by year for the 9-year study was 11,269,000 acre-ft using reported acreage and 8,914,000 acre-ft using LANDSAT acreage (Q). Recharge from precipitation could be 0.183 in./yr based on Brutsaert and others (1975) analysis. This is equivalent to 0.015 ft/yr. This value times the study area of 1,739 mi^2 (1,112,960 acres) would be 16,694 acre-ft/yr of recharge from precipitation (Rp); or about 150,000 acre-ft of recharge for the 9-year study. Recharge from playa lake bottoms was estimated to be a rate of 1.57 in./yr based on a study by Wood and Osterkamp (1984). This rate times a playa-lake basin recharge area of 18,931 acres for the study area resulted in a recharge rate of 2,477 acre-ft/yr. For 9 years, the recharge through playa lake bottoms would be about 22,000 acre-ft (Rpi). Solving the formula for Rf would give:

Rf = -5,168,000 + (61,000 + 11,269,000) - (150,000 + 22,000);
Rf = 5,990,000 acre-ft, using reported acreage data; and
Rf = 3,635,000 acre-ft, using LANDSAT interpreted acreage data.

Therefore, irrigation return flow, for the 9-year study, could be in the range of 3,635,000 to 5,990,000 acre-ft. These values are 97-98 percent of the respective values for the total of pumpage minus change in storage as given in the first two columns in table 10. The difference between irrigation pumpage and change in ground-water storage is almost the same as irrigation return flow, excluding slight differences for municipal, industrial, domestic, and farm well pumpage, recharge from precipitation, and recharge from playa lake bottoms. The two most significant components of the water budget in Castro and Parmer Counties are irrigation pumpage and change in ground-water storage.

SUMMARY AND CONCLUSIONS

A study of the relationship between irrigation pumpage and change in ground-water storage was conducted. Two counties were selected in the High Plains of Texas because water levels have declined significantly because of a large density of irrigation wells. Castro and Parmer Counties are essentially flat with some areas of gently rolling terrain. The surface-water drainage network is composed almost entirely of intermittent streams. Water from the High Plains aquifer is the only source of water for irrigation.

The principal geologic unit of the High Plains aquifer is the Ogallala Formation of Miocene age. The Ogallala consists of randomly distributed lenses of poorly sorted clay, silt, sand, and gravel, which generally are unconsolidated. In Castro and Parmer Counties, the Ogallala is underlain by impermeable rocks and is hydraulically independent of formations in adjacent areas, except where it is directly underlain by rocks of Cretaceous age. The High Plains aquifer is under water-table conditions, and the flow of ground water is from the northwest to the southeast. Saturated thickness of the aquifer ranges from 0 to 320 ft and averages 129 ft in the study area.

Specific yield has an average value of 19.0 percent in the study area. Sand and gravel lenses compose a fairly large percentage of the materials in the aquifer in the study area. The average sand and gravel thickness is about 120 ft. In general, areas of large sand and gravel thickness also are areas of large specific yield.

Ground water does not discharge to the intermittent streams or playa lakes, and flow across boundaries into and out of the study area does not change significantly from year to year. Natural recharge accounts for only a very small volume of water entering the aquifer.

Irrigated acreage from reported sources (published reports and surveys) and LANDSAT imagery were used in this study. Acreages obtained from LANDSAT were always smaller than reported acreages. Irrigation pumpage was estimated for the study area from calculated irrigation demand, irrigated acreage, and measured crop-application rates. Pumpage was calculated for each year using reported acreage and acreage from LANDSAT imagery. From 1975 through 1983, total pumpage was 11,269,000 acre-ft using reported acreage data and 8,914,000 acre-ft using LANDSAT acreage data. Pumpage decreased significantly from 1980 to 1983.

Water-level changes for a 9 years (1975-83) were calculated and mapped. Annual water-level changes also were obtained for the study period. Almost all water-level changes for the 1,638 grid cells in the study area were declines. Average water-level decline increased from 1975 to 1977. After 1977, the rate of average water-level decline decreased. The average water-level decline was 16.6 ft for the 5-year period (1975-79) and 25.3 ft for the 9-year period (1975-83). The only locations which did not experience significant water-level declines were the northwest and northeast corners of the study area.

The change in ground-water storage was calculated by multiplying specific yield, water-level change, and the area of each grid cell. The total change in storage from 1975 to 1983 was 5,168,000 acre-ft. Many of the areas of largest change in storage also were areas of the largest density of irrigated acreage.

The difference between estimated pumpage and change in storage was 6,101,000 acre-ft based on reported acreage data and 3,746,000 acre-ft for LANDSAT acreage data. These volumes represent 54 percent of total pumpage based on reported acreage data and 42 percent of total pumpage based on LANDSAT acreage.

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