TEXAS
WATER
DEVELOPMENT
BOARD

Report 204

ANALYTICAL STUDY OF THE OGALLALA AQUIFER IN LAMB COUNTY, TEXAS

PROJECTIONS OF SATURATED THICKNESS, VOLUME OF WATER IN STORAGE, PUMPAGE RATES, PUMPING LIFTS, AND WELL YIELDS

May 1976

TEXAS WATER DEVELOPMENT BOARD

REPORT 204

ANALYTICAL STUDY OF THE OGALLALA AQUIFER IN LAMB COUNTY, TEXAS

Projections of Saturated Thickness, Volume of Water in Storage, Pumpage Rates, Pumping Lifts, and Well Yields

By

A. Wayne Wyatt, Ann E. Bell,
and Shelly Morrison

May 1976

Published and distributed
by the
Texas Water Development Board
Post Office Box 13087
Austin, Texas 78711

TABLE OF CONTENTS

TABLES AND MAPS PRESENTING RESULTS OF THE STUDY

TABLE OF CONTENTS (Cont'd.)

TABLE OF CONTENTS (Cont'd.)

TABLE OF CONTENTS (Cont'd.)

ANALYTICAL STUDY OF THE OGALLALA AQUIFER IN LAMB COUNTY, TEXAS

Projections of Saturated Thickness, Volume of Water in Storage, Pumpage Rates, Pumping Lifts, and Well Yields

CONCLUSIONS

The Ogallala aquifer in Lamb County contained approximately 10.9 million acre-feet of water in 1974. Historical pumpage has exceeded 250,000 acre-feet annually, which is approximately ten times the rate of natural recharge to the aquifer in the county. This overdraft is expected to continue, ultimately resulting in reduced well yields, reduced acreage irrigated, and reduced agricultural production.

There is a very uneven distribution of ground water in the county. Some areas have ample ground-water resources to support current usage through the year 2020; whereas, in other areas of the county, ground water is currently in short supply.

To obtain maximum benefits from the remaining ground-water resources, Lamb County water users should implement all possible conservation measures so that the remaining ground-water supply is used in the most prudent manner possible and with the least amount of waste.

INTRODUCTION

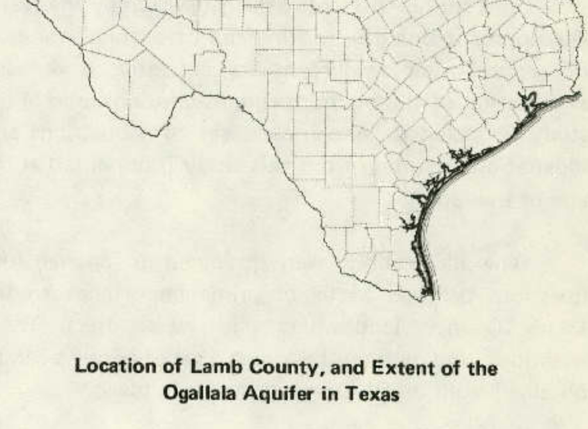
Lamb County is situated in the Southern High Plains of Texas. Littlefield, the county seat, is located approximately 40 miles northwest of Lubbock. The county contains an area of about 1,022 square miles and has a population of approximately 16,000.

Lamb County is one of the leading producers of agricultural crops in the State with a total farm income of over $60 million annually. Leading crops in the county are cotton, grain sorghums, wheat, soybeans, and corn. Numerous agribusinesses, including livestock feeding, sale of irrigation equipment supplies, feed and seed, and fertilizer, also make significant contributions to the total county income.

Ground water is extremely important to the economy of the county inasmuch as most of the crops are irrigated with ground water. Additionally, the water used by rural residents, municipalities, and local industries is mostly ground water.

The principal source of fresh ground water in the county is the Ogallala aquifer. During the past three decades, the withdrawal of ground water has greatly exceeded the natural recharge to the aquifer. If this overdraft continues, the aquifer ultimately will be depleted to the point that it may not be economically feasible to produce water for irrigation.

This is one of numerous planned county studies covering the declining ground-water resource of the Ogallala aquifer in the High Plains of Texas. The report contains maps, charts, and tabulations which reflect



Location of Lamb County, and Extent of the Ogallala Aquifer in Texas

estimates of the volume of water in storage in the Ogallala aquifer in Lamb County and the projected depletion of this water supply by decade periods through the year 2020. The report also contains estimates of pumpage, pumping lifts, and other data related to current and future water use in the county. However, the report does not attempt to project that portion of the volume of water in underground storage which may be ultimately recoverable.

PURPOSE AND SCOPE OF STUDY

This study resulted from an immediate need for information to illustrate to the High Plains water users that the ground-water supply is being depleted. It is hoped that this study will help persuade the water users to implement all possible conservation measures, so that the remaining ground-water supply will be used in the most prudent manner possible and with the least amount of waste.

The study was also conducted to provide information to local, State, and federal officials for their use in implementing plans to alleviate the water-shortage problem in the High Plains of Texas.

These immediate needs for current information have resulted in a concerted effort by the Texas Water Development Board to utilize high-speed computers to conduct evaluation and projection studies of ground-water resources. The results of one of these computer studies is contained in this report.

This report does not represent a detailed ground-water study of the county; rather, the report was prepared using only those data which were readily available in the files of the Texas Water Development Board. Information provided for 1974 is considered reliable; however, the projections of future conditions should be used only as a guide to reasonable expectations.

This study represents a new approach by the Water Development Board in making and presenting appraisals of ground-water resources. Consequently, a detailed explanation of the methods and assumptions used in the study is included. A complete set of tabulations and illustrations resulting from this study is presented at the end of the report.

The illustrations were prepared to answer four questions believed to be of prime importance to the Lamb County landowners and water users. These questions, and methods by which a set of answers can be obtained from the illustrations, are as follows:

1. Question: How much water is in storage under any given tract of land in the county and what is expected to happen to this water in the future?

   Answer: First, determine the approximate location of the tract on the most current (1974) map of saturated thickness. Read the value of the contour line at this location (if midway between two contour lines, take an average of the two). This thickness value can then be converted to the approximate volume of water in storage, in acre-feet per surface acre, by multiplying it by the coefficient of storage of 0.15, or 15 percent. To obtain estimates of what can be expected in the future, the same procedure can be followed by using the maps which illustrate projected saturated thickness in the years 1980, 1990, 2000, 2010, and 2020.

2. Question: What can be expected to happen to well yields if the saturated thickness diminishes as illustrated by the maps?

   Answer: Well yields are expected to decline as the aquifer thins; therefore, a map of estimated well yields has been prepared for each year of the study. The landowner need only find the approximate location of his property on the well-yield map that applies to the year in question and read the well-yield estimates directly from the map.

3. Question: With energy cost increasing, pumping lifts (pumping levels) are becoming more and more important. What are the estimates of current pumping lifts and what are they expected to be in the future?

   Answer: Contour maps depicting estimated pumping lifts have been prepared for each year of the study. These maps are contoured in feet below land surface. The landowner need only find the approximate location of his property on the map that applies to the year in question to read the pumping-lift estimates.

4. Question: If an all-out effort is made to conserve ground-water resources, how can landowners and water users determine how they are doing compared to the projections in the study?

Answer: Using the maps that show rates of water-level declines, the landowners and water users can determine what the changes in water levels are in their area and what they are projected to be in the future. This can be accomplished by finding the approximate location of their property on the map pertaining to the year in question and by reading the estimates of water-level changes which are recorded in feet. To determine how he is doing from year to year, the landowner or water user can make measurements of depth to water in his own wells or obtain copies of measurements made by the Board or the ground-water district for his area. These measurements can then be compared to the projected values on the maps to estimate the effectiveness of conservation efforts.

NATURE OF THE OGALLALA AQUIFER

Because thorough understanding of the Ogallala aquifer is not necessary for the water user, the following discussion of aquifer geology and hydrology is rather general. Readers interested in pursuing the subject in more detail may do so from the numerous reports which have been published on the Ogallala. Most of these publications are included in the list of selected references of this report.

General Geology

Fresh ground water in Lamb County is obtained principally from the Ogallala Formation of Pliocene age. Water in the Ogallala Formation is unconfined and is contained in the pore spaces of unconsolidated or partly consolidated sediments.

The Ogallala Formation principally consists of interfingering bodies of fine to coarse sand, gravel, silt, and clay—material eroded from the Rocky Mountains which was carried southeastward and deposited by streams. The earliest sediments, mainly gravel and coarse sand, filled the valleys cut in the pre-Ogallala surface. Pebbles and cobbles of quartz, quartzite, and chert are typical of these early sediments. After filling the valleys, deposition continued until the entire area that is now the Texas High Plains was covered by sediments from the shifting streams.

The upper part of the formation contains several hard, caliche-cemented, erosionally resistant beds called the "caprock." A wind-blown cover of fine silt, sand, and soil overlies the caprock.

The Ogallala deposits overlie rocks of lower permeability of Triassic and Cretaceous ages. On a broad scale, the erosional surface at the top of the Triassic and Cretaceous rocks dips gently (about 10 feet per mile) toward the southeast, similar to the slope of the land surface. In general, however, this pre-Ogallala surface had greater relief than the present land surface. Low hills and wide valleys which contain deep, narrow stream channels are typical features of the Triassic erosional surface. The Cretaceous rocks, being more resistant to erosion, remain 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. Often this contrast occurs in relatively short distances.

The Triassic rocks, principally shale, serve as a nearly impermeable floor for the aquifer, but the buried mesas or buttes of Cretaceous rocks, where these are present, generally can yield water to wells. At these locations the Ogallala and Cretaceous waters are in hydrologic continuity; therefore, the water-yielding Cretaceous rocks are considered to be part of the Ogallala aquifer.

The Canadian River has cut deeply through the Ogallala Formation in the northern part of the Texas High Plains area. The valley effectively separates the formation geographically into two units having little hydraulic interconnection. Erosion has also removed the Ogallala from much of its former extent to the east, 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 this reason, coupled with the scarcity of local rainfall, water that is being withdrawn from the aquifer cannot be replaced quickly by natural recharge and is in effect being mined.

Storage Properties

The coefficient of storage of an aquifer is defined as the volume of water released from or taken into storage per unit surface area of the aquifer per unit change in the component of head normal to that surface. In water-table aquifers such as the Ogallala, the coefficient of storage is nearly equal to the specific yield, which is defined as the quantity of water that a formation will yield under the force of gravity, if it is first saturated and then allowed to drain, the quantity of water being expressed as a percentage of the volume of material drained.

A coefficient of storage of 15 percent has been selected for use in this study based on past studies and the results of numerous aquifer tests published in Water

Development Board Report 98 (Myers, 1969). The following chart shows the volumes of water corresponding to various amounts of aquifer saturated thickness, based on a storage coefficient of 15 percent. These are the approximate amounts of water that would drain from the aquifer material by gravity flow if the entire saturated thickness could be drained.

SATURATED THICKNESS (feet)	VOLUME OF WATER IN STORAGE (acre-feet, per surface acre)
25	3.75
50	7.50
75	11.25
100	15.00
150	22.50
200	30.00
250	37.50
300	45.00
400	60.00
500	75.00

Natural Recharge and Irrigation Recirculation

Recharge is the addition of water to an aquifer by either natural or artificial means. Natural recharge results chiefly from infiltration of precipitation. The Ogallala aquifer in Lamb County receives natural recharge by precipitation that falls within the county and in adjoining areas.

The amount and rate of natural recharge from precipitation depend on the amount, distribution, and intensity of the precipitation; the amount 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 these factors, it is difficult to estimate the amount of natural recharge to the ground-water reservoir. Estimates of annual natural recharge to the Ogallala aquifer made by Barnes and others (1949, p. 26-27) indicate only a fraction of an inch. Theis (1937, p. 546-568) suggested less than half an inch, and Havens (1966, p. F1), in a study of the Ogallala in New Mexico, indicated about 0.8 inch per year.

The authors of this report believe that recharge from precipitation may be more than these earlier estimates, due to changes in the soil and land surface that have accompanied large-scale irrigation development in the county. Some of the farming practices which are believed to have altered the recharge rate are: clearing the land of deep-rooted native vegetation; deep plowing of fields, which eliminates hard pans, and the plowing of playa lake bottoms and sides; bench leveling, contour farming, and terracing; maintaining a generally higher soil moisture condition by application of irrigation water prior to large rains; and increasing the humus level in the root zone by plowing under a large amount of foliage from crops grown under irrigation.

Obtaining a reliable estimate of the present recharge rate is further complicated by the consideration which must be given to irrigation recirculation. A substantial portion of the water pumped from the Ogallala for irrigation percolates back to the aquifer. This does not constitute an additional supply of water, but reduces the net depletion of the aquifer. As with natural recharge, many factors are involved in making estimates of recirculation. Some of these factors are the rate, amount, and type of irrigation application; the soil type and the infiltration rate of the soil profile in the root zone; 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. Tentative estimates of the actual amounts of recharge and irrigation recirculation in Lamb County will be found in a subsequent section on "Calculating Pumpage."

PROCEDURES USED TO OBTAIN PROJECTIONS

Hydrologic Data Base

The Texas Water Development Board and the High Plains Underground Water Conservation District No. 1 cooperatively maintain a network of water-level observation wells in Lamb County. Records from these wells provided the principal data base used in this study. This data base was supplemented in some areas with records from water well drillers' logs collected by both the District and the Board.

The data base included: (1) measurements of the depth to water below land surface, which have been made annually in the wells in the observation network; (2) the dates these measurements were made; and (3) the depth from land surface to the base of the Ogallala aquifer (In many cases, this was identical to the well depth). To facilitate automatic data processing with modern, high-speed computers, the data base also included a unique number for each well and the geographical coordinates of each well location.

Wells chosen from the data base for use in obtaining projections of future conditions were those in which depth to the base of the aquifer could be determined or estimated, and those needed to provide spaced data coverage in the county. Locations of the wells that were selected and used for control are shown on the various maps in this report.

Projecting the Depletion of Saturated Thickness

The water-use patterns between 1960 and 1972 as reflected in the changes in water levels in wells measured in the High Plains of Texas were used as the principal data source for developing an aquifer depletion schedule. The depletion schedule generally reflects average precipitation and precipitation distribution in the area for the duration of the study period. Additionally, in developing and applying the depletion schedule, adjustments through time were made to reflect the effects of depletion of the aquifer on its ability to yield water. That is, as the aquifer's saturated thickness decreases, its ability to yield water to wells is reduced, the well yields decline, less water is pumped, and there results a lessesed rate of further aquifer depletion.

The aquifer's hydraulics are such that if a well penetrates the total saturated section and the pump is sized to produce the maximum the aquifer will yield, the well yield will decline at a disproportionately greater rate than the reduction in saturated thickness. Actually, the remaining well yield expressed as a percentage of former yield will be only about half of the remaining saturated thickness expressed as a percentage of former thickness. For example, a well with 80 feet of saturated section and a maximum yield of 800 gpm (gallons per minute) will probably yield only 200 gpm when the saturated section is reduced to 40 feet.

The depletion schedule for Lamb and surrounding counties was developed in the following manner:

1. The records for all water level observation wells for the years 1960 through 1972 in Bailey, Lamb, Hale, Floyd, Crosby, and Dickens Counties were separated from the master file. These counties have similar soil types, cropping patterns, depths to water, saturated thickness, and climatic conditions.

2. These well records were then sorted into groups according to the saturated thickness in each well as of 1966 (the middle year). Each group included records of all wells in a 20-foot range of saturated thickness. (Ranges are shown in the tabulation below.)

3. The average decline in water level was calculated for each year for each well group, and these decline values were adjusted to remove the effects of each year's deviation from long-term average precipitation.

4. The average annual decline in water level for the total period (1960-72) was calculated for each well group, incorporating the adjustments for departure from average precipitation.

From the foregoing procedure, the following depletion schedule was developed:

RANGE OF SATURATED THICKNESS (feet)	AVERAGE ANNUAL WATER-LEVEL DECLINE, 1960-72 (feet)
0 to 20	0.35
20 to 40	.75
40 to 60	.95
60 to 80	1.45
80 to 100	1.67
100 to 120	2.08
120 to 140	2.05
140 to 160	2.99
160 to 180	3.00
180 to 200	3.40
200 to 220	3.70
220 to 240	3.67
240 to 260	3.60
260 to 280	4.08

Based on this depletion schedule, a computer program was written to calculate future saturated thickness at individual well sites. The following problem is presented to show the computational procedures used.

Problem: A well has a saturated thickness of 110 feet in 1974 and one wants to project what the saturated thickness will be in this well for every year to the year 2020.

Factors:

1. The beginning saturated thickness is 110 feet in 1974.

2. The average decline rate is 2.08 feet per year for wells with saturated sections of 100 to 120 feet.

3. The average decline rate is 1.67 feet per year for wells with saturated sections of 80 to 100 feet.

4. The average decline rate is 1.45 feet per year for wells with saturated sections of 60 to 80 feet.

5. The average decline rate is 0.95 foot per year for wells with saturated sections of 40 to 60 feet.

6. The average decline rate is 0.75 foot per year for wells with saturated sections of 20 to 40 feet.

7. The average decline rate is 0.35 foot per year for wells with saturated sections of 0 to 20 feet.

8. The time interval is 1974 through 2020.

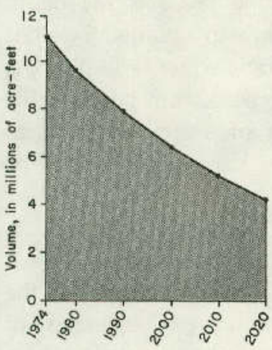
The projected saturated thicknesses in the subject well are calculated and shown in the following table:

YEAR	SATURATED THICKNESS, BEGINNING OF YEAR (feet)	AVERAGE DECLINE RATE (feet)	SATURATED THICKNESS, END OF YEAR (feet)
1974	110.00	2.08	107.92
1975	107.92	2.08	105.84
1976	105.84	2.08	103.76
1977	103.76	2.08	101.68
1978	101.68	2.08	99.60
1979	99.60	1.67	97.93
1980	97.93	1.67	96.26
1981	96.26	1.67	94.59
1982	94.59	1.67	92.92
1983	92.92	1.67	91.25
1984	91.25	1.67	89.58
1985	89.58	1.67	87.91
1986	87.91	1.67	86.24
1987	86.24	1.67	84.57
1988	84.57	1.67	82.90
1989	82.90	1.67	81.23
1990	81.23	1.67	79.56
1991	79.56	1.45	78.11
1992	78.11	1.45	76.66
1993	76.66	1.45	75.21
1994	75.21	1.45	73.76
1995	73.76	1.45	72.31
1996	72.31	1.45	70.86
1997	70.86	1.45	69.41
1998	69.41	1.45	67.96
1999	67.96	1.45	66.51
2000	66.51	1.45	65.06
2001	65.06	1.45	63.61
2002	63.61	1.45	62.16
2003	62.16	1.45	60.71
2004	60.71	1.45	59.76
2005	59.76	.95	58.81
2006	58.81	.95	57.86
2007	57.86	.95	56.91
2008	56.91	.95	55.96
2009	55.96	.95	55.01
2010	55.01	.95	54.06
2011	54.06	.95	53.11
2012	53.11	.95	52.16
2013	52.16	.95	51.21
2014	51.21	.95	50.26
2015	50.26	.95	49.31
2016	49.31	.95	48.36
2017	48.36	.95	47.41
2018	47.41	.95	46.46
2019	46.46	.95	45.51
2020	45.51	.95	44.56

Similar computations were made for each of the selected data-control wells in Lamb County, and the saturated-thickness values for 1974, 1980, 1990, 2000, 2010, and 2020 were extracted from this data set for use in further calculations and mapping.

Mapping Saturated Thickness, and Calculating Volume of Water in Storage

To obtain estimates of the volume of water in storage in the Ogallala aquifer, an electronic digital computer was used to construct maps which reflect the saturated thickness of the aquifer for those years included in the study. These maps were then refined by the computer to reflect the number of acres corresponding to each range of saturated thickness. The number of acres for each range was multiplied by the saturated thickness in feet for that range and then by the coefficient of storage (0.15 or 15 percent), to yield an estimate of the volume of water in storage in each saturated-thickness range. Totaling these volumes produced an estimate of the volume of water in storage in the county. The current (1974) and projected volume estimates are shown in the following graph:



Year	Acre-Feet
1974	10,964,000
1980	9,683,000
1990	7,931,000
2000	6,413,000
2010	5,180,000
2020	4,160,000

Estimated Volume of Water in Storage

Preparing a data base and writing the necessary programs for the computer to use in constructing the saturated-thickness maps and in making the necessary calculations is time consuming; however, once the data base is prepared and programs written, the computer can perform in a few hours calculations that would have required many years of manual effort.

A generalized description of the methodology used in mapping and in computing water volume follows: A base map with a scale of 1 inch equals 2 miles was selected to prepare data for computer processing. All data points (observation wells) were plotted on these base maps by hand and assigned identifying numbers. A machine called a *digitizer* was then used to translate these mapped location data (well locations, county boundaries, etc.) into information processible by the computer. To accomplish this, a latitude and longitude coordinate was recorded on each base map as a central reference point, and all data points and county boundaries were then digitized; that is, measurements were made by the digitizer to reference these data points and boundaries to the initial latitude and longitude coordinate. Then the digitized information was processed by the computer and the maps were re-created by a computer-driven plotter. The computer-plotted image maps were ultimately checked against the hand-constructed maps to verify that the data were plotted accurately.

The assignment of a unique number to each data point (observation well) on the base maps made it possible to machine process the data related to these points and to plot these data back on the maps at the proper location.

To compute the volume of water in storage, the computer was instructed to subdivide the county into units of approximately one-half mile square. The known saturated-thickness values obtained from the data points were filled into the squares in which the data points were located. Based on these known values, the computer filled in a weighted-average value for each remaining square, taking into consideration all known values within a radius of 7 miles. After this step was completed, the computer then counted the numbers of squares having equal values, thus obtaining the approximate area in square miles (later converted to acres) corresponding to each range of saturated thickness. As previously stated, the number of acres in each 25-foot range of saturated thickness was multiplied by the corresponding saturated-thickness value and the storage coefficient (0.15 or 15 percent), to obtain the approximate volume of water in acre-feet in that saturated-thickness range.

Although the calculations were made by the computer from information stored in its image field, the data in the image field were printed out in the form of contoured saturated-thickness maps, which are reproduced in this report. Facing each saturated-thickness map in the report is a corresponding tabulation of the approximate volume of water in storage.

Calculating Pumpage

Estimates of current pumpage were obtained in this study by calculating the storage capacity of the dewatered section of the Ogallala aquifer as reflected in changes in the annual depth-to-water measurements made in the water level observation wells. Factors for natural recharge and irrigation recirculation were then added to these volumetric figures to obtain more realistic pumpage estimates.

The step-by-step procedure involved in making pumpage estimates is similar to the procedures used in calculating the estimates of volume of water in storage; therefore, a more general explanation follows.

Change in water level (decline) maps for the aquifer were made by the computer for the years considered. From these maps, the volume of desaturated material was multiplied by the number of acres corresponding to each 0.25-foot range of decline and then multiplied by the storage coefficient of the aquifer (0.15 or 15 percent), which resulted in an estimate of the volume of water taken from storage for each decline range. Estimates for natural recharge and irrigation recirculation were added to these values to obtain estimates of pumpage.

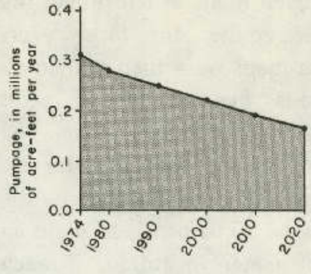
An attempt was made to obtain a reliable estimate of the natural recharge and recirculation for use in this study. This involved obtaining an estimate of the amount of water required by each of the major crops grown in the area. These values, generally referred to as "duty of water," were obtained from Texas Agricultural Experiment Stations located in the High Plains area. The duty of water figure for each major crop was multiplied by the number of crop acres, and the resulting numbers were added together to yield an estimate of the total crop water demand.

The amount of precipitation which fell just prior to and during the growing season was subtracted from the total water demand estimate. The difference between these values should equal that amount which would have been supplied by irrigation, which will be referred to as irrigation makeup water.

The volume figure represented by the dewatered section was then compared to the volume of water which should have been supplied to crops by irrigation makeup water. In all tests, the volume of water represented by the depletion of the aquifer was considerably less than the makeup water estimate. This difference was attributed to irrigation recirculation and natural recharge.

Various combinations of estimates for natural recharge and recirculation were added to the volume represented by aquifer depletion, in an attempt to obtain comparable values with the makeup water estimated for the test years. One inch per year of natural recharge, and 20 percent recirculation added to the volume represented by the depletion of the aquifer, most nearly equaled the makeup water estimated in the largest number of instances in Lamb County and in adjoining counties with similar conditions.

These amounts were added to the previously calculated storage capacity of the dewatered section to obtain estimates for current (1974) and future pumpage. The following graph shows the current and projected estimates of pumpage:



Year	Acre - Feet
1974	313,000
1980	277,000
1990	250,000
2000	217,000
2010	194,000
2020	173,000

Estimated Pumpage

Calculating Pumping Lifts

The pumping lift (pumping level) is the depth from land surface to the water level in a pumping well; it is equal to the depth of the static water level plus the drawdown due to pumping. The amount of pumping lift largely determines the amount of energy required to produce the water, and thus strongly affects the pumping costs.

In calculating pumping lifts, procedures were used that are similar to those used in making estimates of the volume of water in storage and the estimates of pumpage. Again, the computer and original data base were used as previously described.

In making estimates of pumping lifts, it was assumed: (1) that the yield of each pumping well is 800 gpm except as limited by the capacity of the aquifer (this conforms with the historical trend of equipping new wells with 8-inch or smaller pumps); (2) that the specific well yield is 10 gpm per foot of drawdown; and (3) that once the well yield equals the capacity of the aquifer, the well will continue to be produced at a rate near the capacity of the aquifer until pumping lifts are within 10 feet of the base of the aquifer. After that time, it is assumed that the pumping lift will remain constant because of greatly diminished well yields. It should be noted that this 10-foot minimum is somewhat arbitrarily chosen, as one cannot predict accurately the minimum saturated thickness that will be feasible for producing irrigation water under future economic conditions.

The above assumptions restrict the drawdown in wells to a maximum of 80 feet (maximum well yield of 800 gpm divided by specific well yield of 10 gpm per foot equals 80 feet of maximum drawdown).

Based on the above assumptions, pumping lifts were calculated separately for each of the selected data-control wells in the county. The factors involved were the historical and projected saturated-thickness values, the historical and projected static water levels, and the drawdown value assigned to the Lamb County area.

In all areas where the aquifer's saturated thickness was 90 feet or greater (areas where a well, pumped at full capacity, would be drawn down 80 feet to yield 800 gpm), the computer was instructed to add 80 feet (the drawdown) to the static water level to determine pumping lift. For a well with a saturated thickness of less than 90 feet, the pumping lift was calculated by subtracting 10 feet from the depth of the well (base of the aquifer). These calculations were made for each year of record to be reported (1974, 1980, 1990, 2000, 2010, and 2020) for each well. The pumping-lift values were stored in the computer and printed out in the form of contour maps. Additionally, the surface area corresponding to each interval between the mapped contours was calculated and printed out in tabular form.

Well-Yield Estimates

Estimates of the rate, in gallons per minute, at which the Ogallala aquifer should be capable of yielding water to wells in various areas of the county are presented on maps for each year of record reported (1974, 1980, 1990, 2000, 2010, and 2020). These well-yield estimates are based on capabilities of the aquifer to yield water to irrigation wells of prevailing construction as reflected by the very large number of pumping tests which have been conducted in various saturated-thickness intervals in the Texas High Plains. The estimates are adjusted to reflect the expected decreases in well yields through time due to the reduced saturated thickness as depletion of the aquifer progresses.

The well-yield estimates are subject to deviations caused by localized geological conditions. The Ogallala is not a homogeneous formation; that is, silt, clay, sand, and gravel which generally comprise the formation vary from place to place in thickness of layers, layering position, and grain-size sorting. The physical composition of the formation material can drastically affect the ability of the formation to yield water to wells. As an example, in areas where the saturated portion of the formation is comprised of thick beds of coarse and well-sorted grains of sand, the well yields probably will exceed the estimates shown on the maps. In other localized areas, the saturated portion of the formation may be comprised principally of thick beds of silt and clay which can be expected to restrict well yields to less than those shown on the maps.

The following can be used as a general guide in the Texas High Plains in estimating well yields based on saturated thickness:

SATURATED THICKNESS (feet)	WELL YIELD (gallons per minute)
Less than 20	Less than 100
20 to 40	100 to 250
40 to 60	250 to 500
60 to 80	500 to 800
80 to 100	800 to 1,000
More than 100	More than 1,000

The maps presented in this report are intended for use as general guidelines only and are not recommended for use in determining water availability when buying and selling specific tracts of land. Inasmuch as the availability of ground water constitutes a large portion of the price of land bought and sold in this area, it is recommended that a qualified ground-water hydrologist be consulted to make appraisals of ground-water conditions when such transactions are contemplated.

DISTINCTION BETWEEN PROJECTIONS AND PREDICTIONS

The actions of the Lamb County water user will determine whether the projections of this study come to pass, as the rate of depletion of the ground-water resource is determined by the rate of water use. The authors have not made predictions of what will occur, but have furnished projections based on past trends and presently available information.

There are many unpredictable factors which can influence the future rates of withdrawal of ground water from the Ogallala aquifer for irrigation farming. These factors include: (1) the amounts and distribution of precipitation which will be received in the area in the future; (2) federal crop acreage controls or the lack of these; (3) the price and demand for food and fiber grown in the area; (4) the cost and availability of energy to produce water from the aquifer; (5) farm labor cost and availability of farm labor; (6) results of continuing research that seeks to develop more frugal water-application methods for irrigation, crops having less water demand, and methods for inducing clouds to yield more water as rain; and (7) most important, the degree to which feasible soil and water conservation measures are employed by the High Plains irrigator. Any of these factors could appreciably influence the rate of use of ground water in the future; however, the projections in this study provide a reasonable set of general expectations on the further depletion of the aquifer.

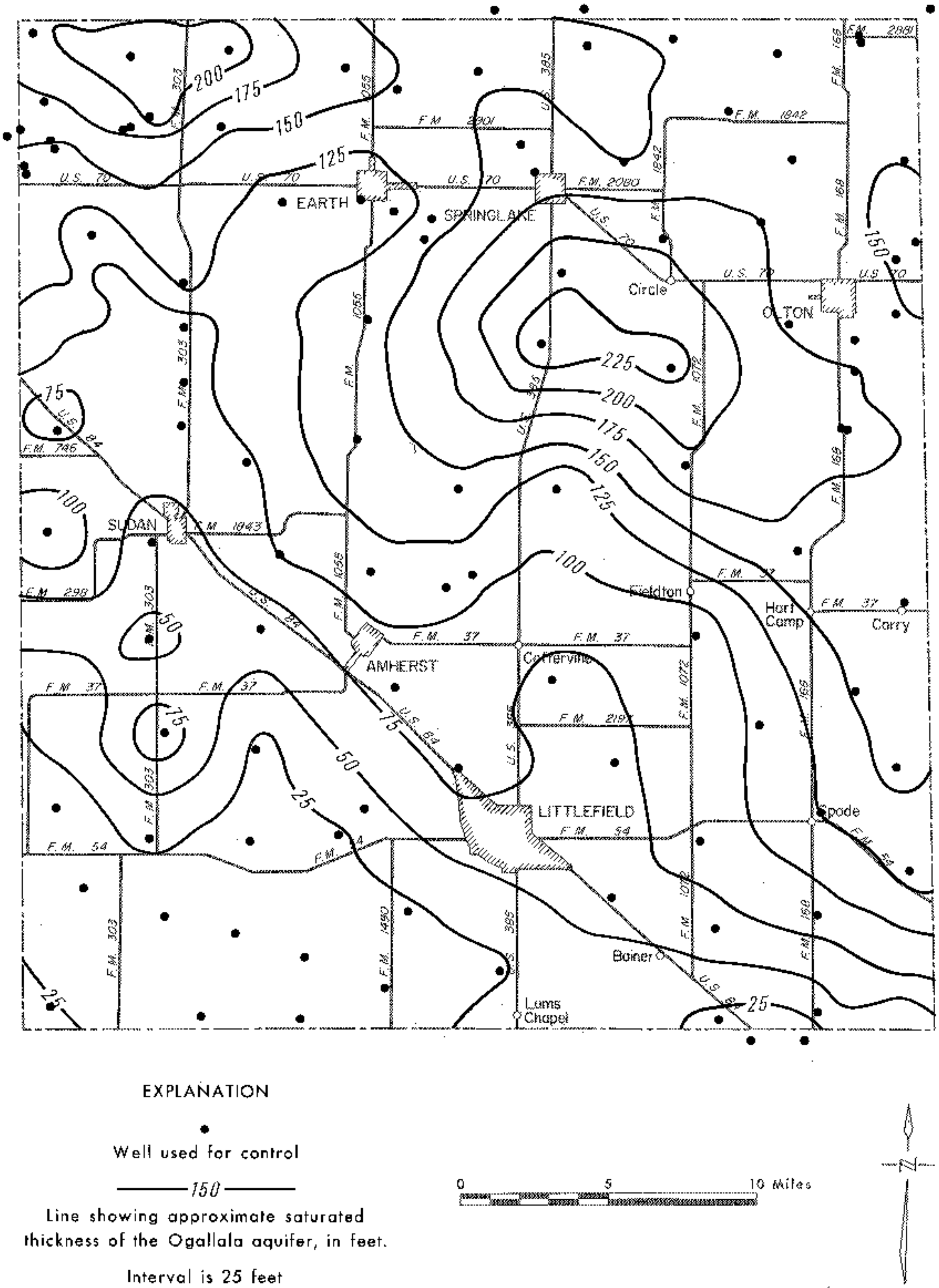
SATURATED THICKNESS AND VOLUME OF WATER IN THE OGALLALA AQUIFER

1974

Volume of Water in Storage Corresponding to Mapped Saturated-Thickness Intervals

(Coefficient of Storage: 15 percent)

MAPPED SATURATED-THICKNESS INTERVAL (feet)	SURFACE AREA (acres)	VOLUME OF WATER IN STORAGE (acre-feet)
0– 25	64,963	168,190
25– 50	53,843	304,461
50– 75	73,336	700,507
75–100	93,459	1,219,720
100–125	75,978	1,278,477
125–150	92,922	1,938,003
150–175	119,324	2,889,601
175–200	50,495	1,405,545
200–225	27,720	876,797
225–250	5,320	182,998
TOTAL	657,355	10,964,223



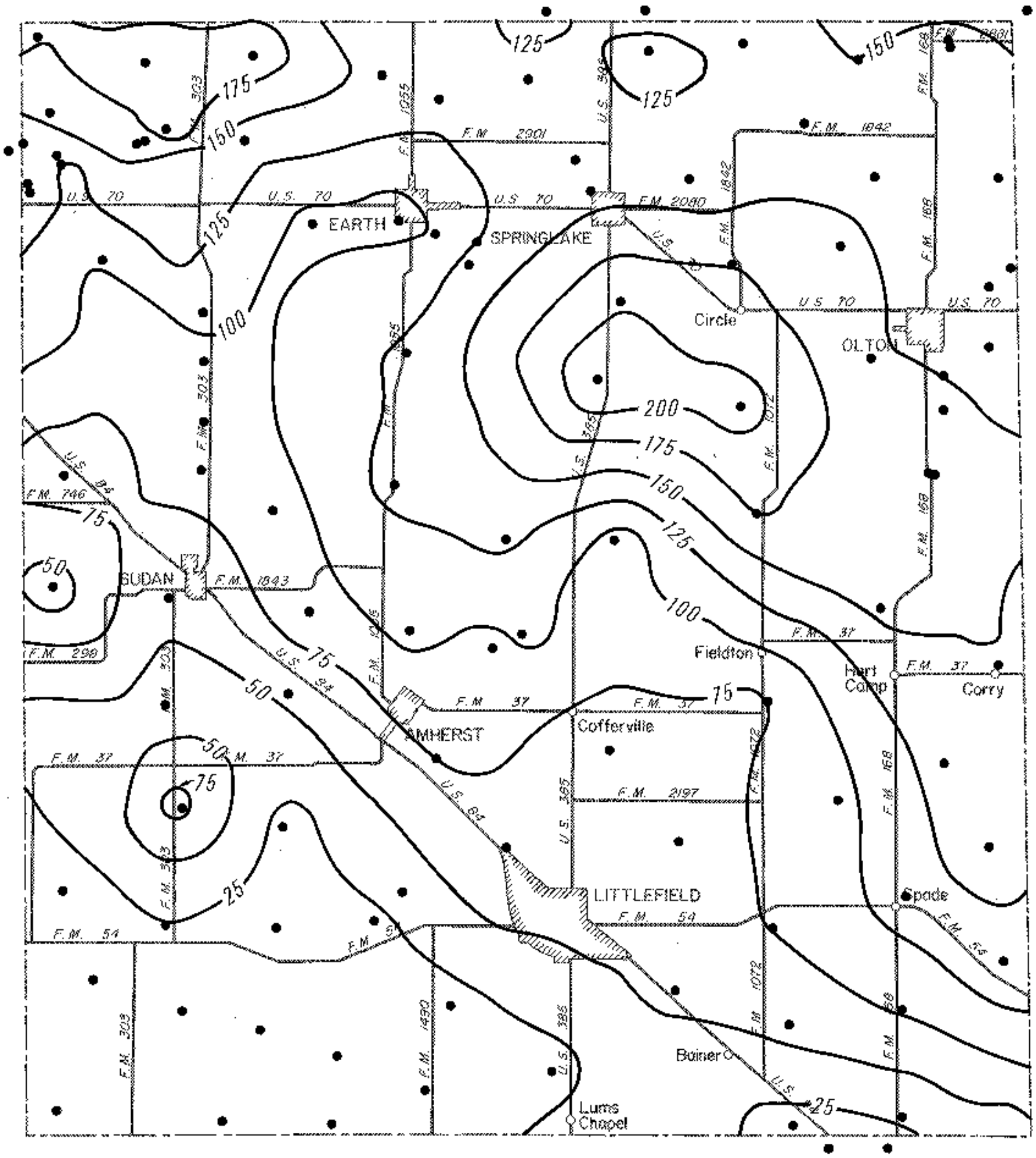
1974
Estimated Saturated Thickness

1980

Volume of Water in Storage Corresponding to Mapped Saturated-Thickness Intervals

(Coefficient of Storage: 15 percent)

MAPPED SATURATED-THICKNESS INTERVAL (feet)	SURFACE AREA (acres)	VOLUME OF WATER IN STORAGE (acre-feet)
0– 25	71,944	174,967
25– 50	62,655	362,367
50– 75	92,718	887,060
75–100	90,801	1,188,031
100–125	85,385	1,443,235
125–150	132,076	2,713,434
150–175	57,728	1,398,521
175–200	43,163	1,201,927
200–225	9,691	300,488
225–250	380	13,254
TOTAL	646,541	9,683,211



EXPLANATION

•
Well used for control

——150——
Line showing approximate saturated thickness of the Ogallala aquifer, in feet.

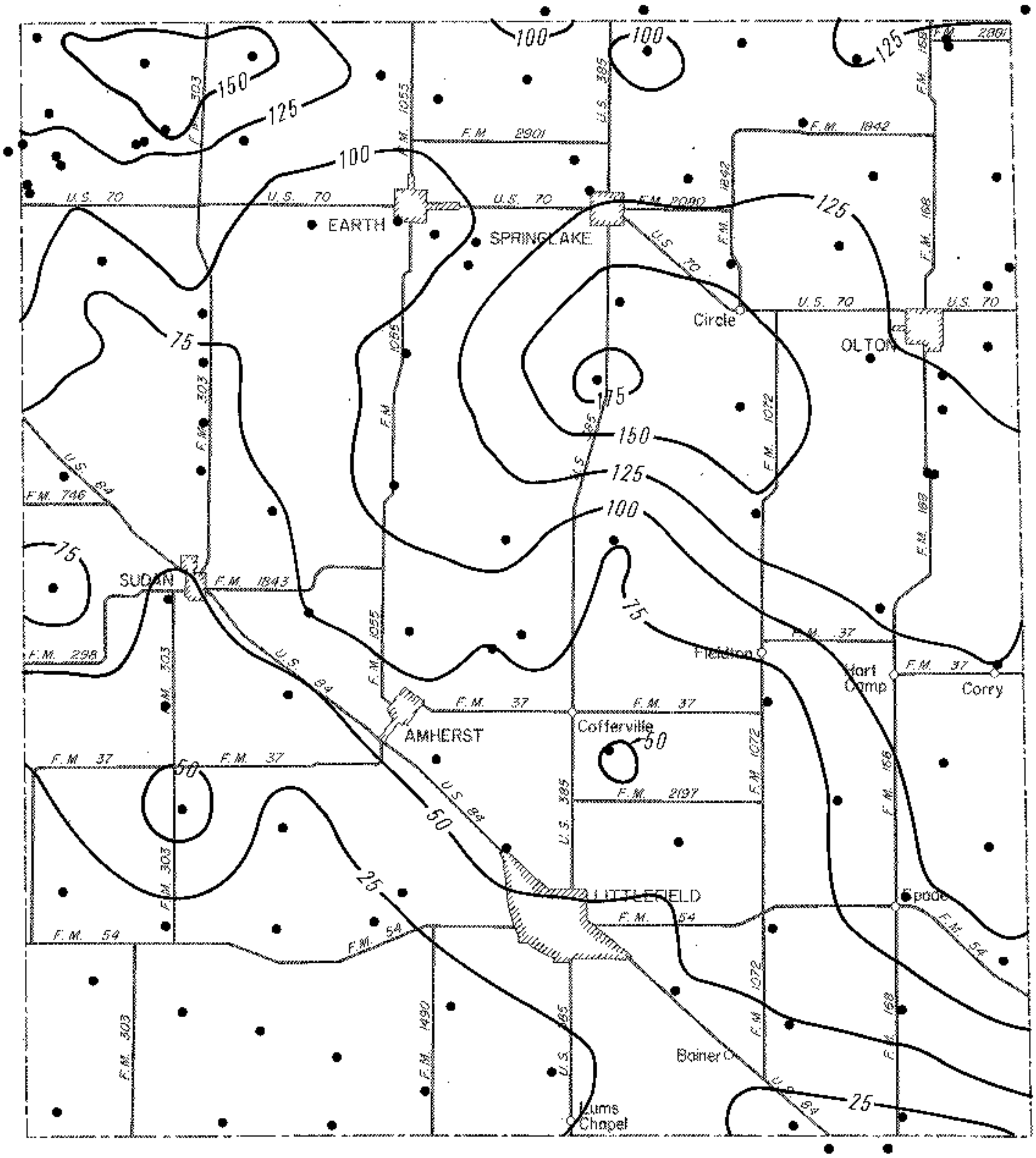
Interval is 25 feet

1980
Projected Saturated Thickness

Volume of Water in Storage Corresponding to Mapped Saturated-Thickness Intervals

(Coefficient of Storage: 15 percent)

MAPPED SATURATED-THICKNESS INTERVAL (feet)	SURFACE AREA (acres)	VOLUME OF WATER IN STORAGE (acre-feet)
0– 25	82,381	181,078
25– 50	90,975	524,953
50– 75	117,031	1,085,493
75–100	99,420	1,301,833
100–125	155,612	2,623,648
125–150	63,312	1,303,656
150–175	35,340	843,353
175–200	2,470	67,349
TOTAL	646,542	7,931,319



EXPLANATION

• Well used for control

——150—— Line showing approximate saturated thickness of the Ogallala aquifer, in feet.

Interval is 25 feet

0 5 10 Miles

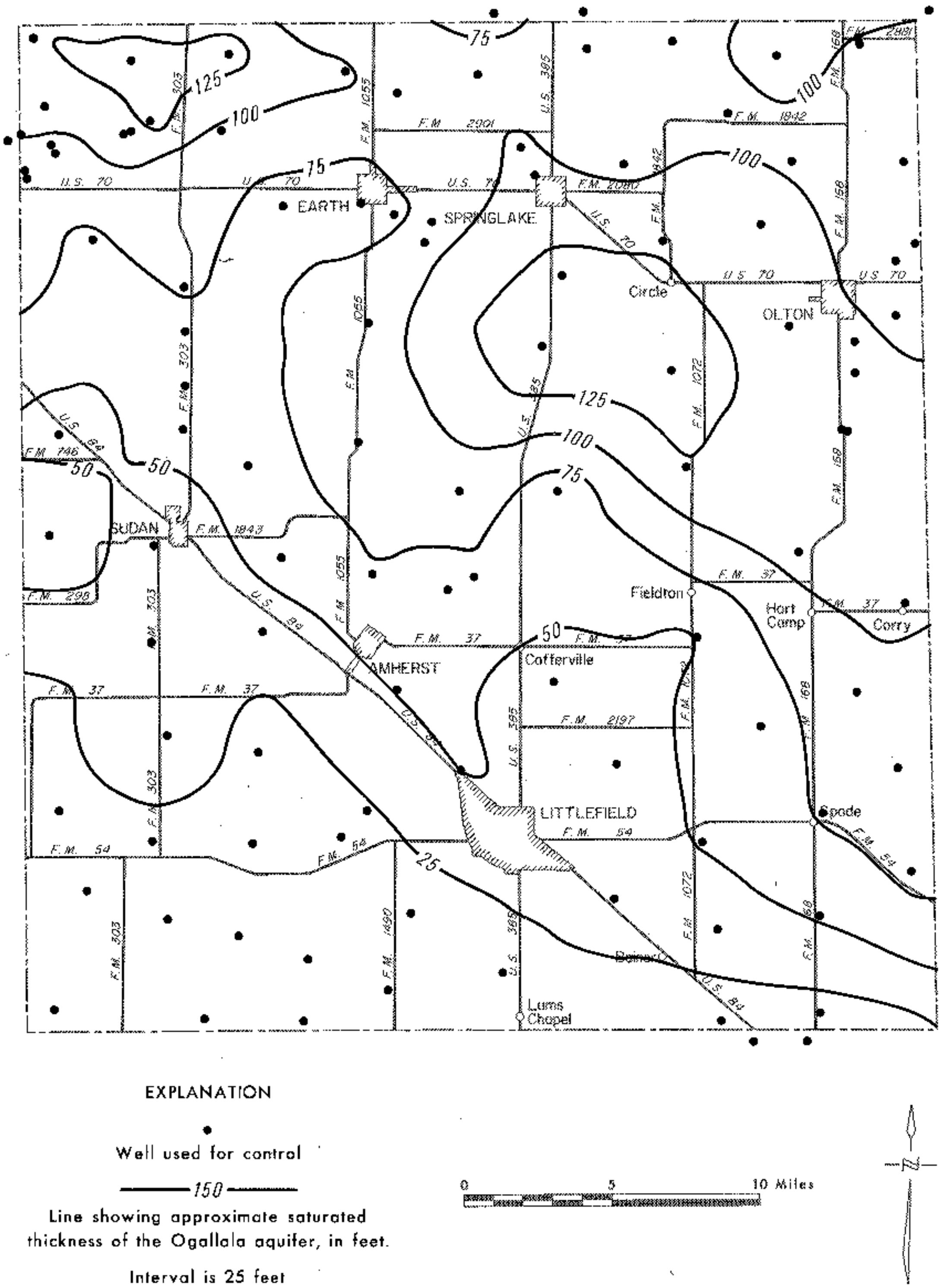
N

1990
Projected Saturated Thickness

Volume of Water in Storage Corresponding to Mapped Saturated-Thickness Intervals

(Coefficient of Storage: 15 percent)

MAPPED SATURATED-THICKNESS INTERVAL (feet)	SURFACE AREA (acres)	VOLUME OF WATER IN STORAGE (acre-feet)
0– 25	105,145	228,639
25– 50	136,235	794,691
50– 75	120,925	1,128,389
75–100	173,542	2,307,100
100–125	80,100	1,342,516
125–150	29,454	585,262
150–175	1,140	26,694
TOTAL	646,542	6,413,254



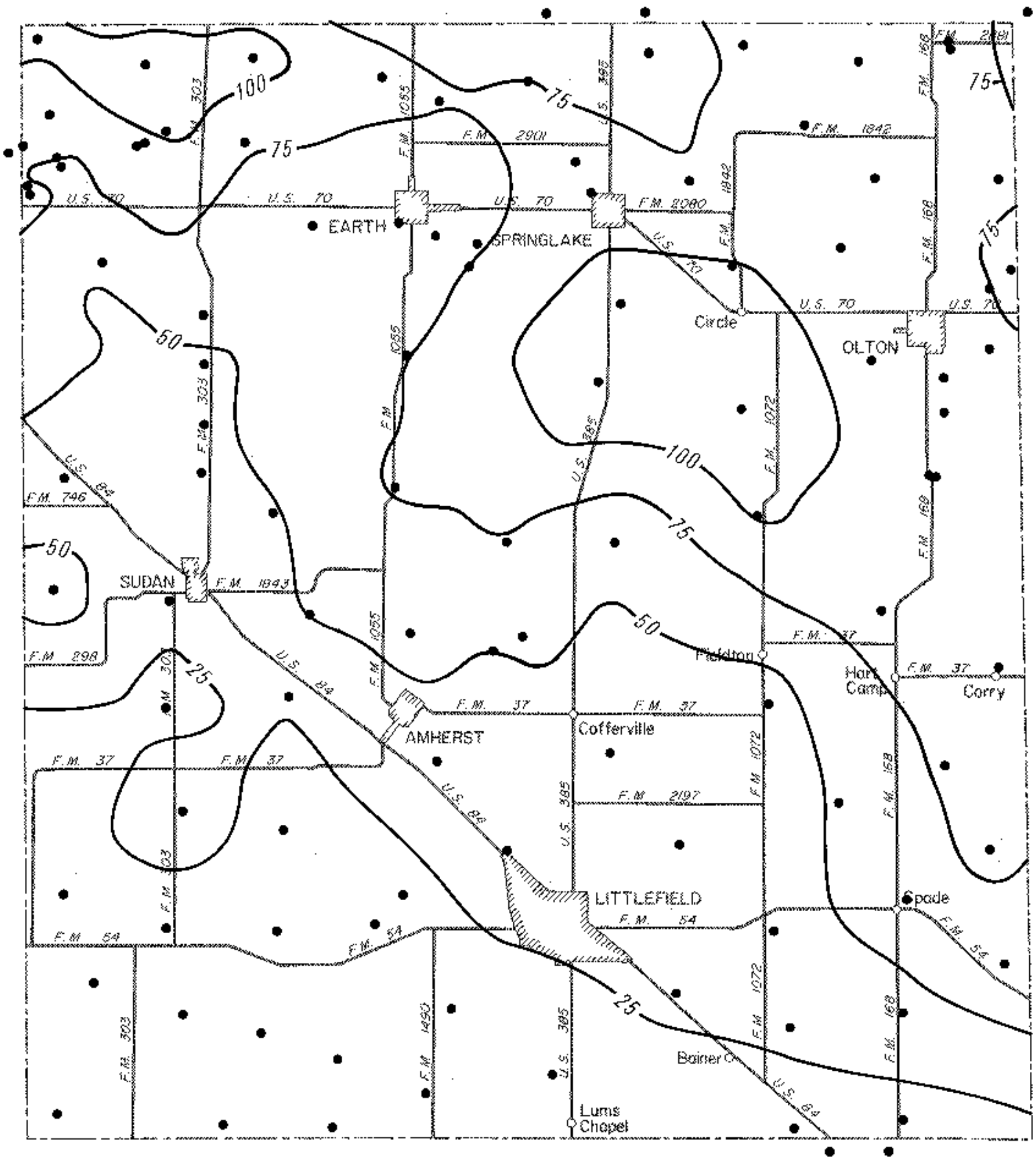
2000
Projected Saturated Thickness

2010

Volume of Water in Storage Corresponding to Mapped Saturated-Thickness Intervals

(Coefficient of Storage: 15 percent)

MAPPED SATURATED-THICKNESS INTERVAL (feet)	SURFACE AREA (acres)	VOLUME OF WATER IN STORAGE (acre-feet)
0– 25	135,360	296,630
25– 50	167,570	945,550
50– 75	169,599	1,611,925
75–100	137,148	1,734,443
100–125	36,296	580,150
125–150	570	11,228
TOTAL	646,542	5,179,896



EXPLANATION

•
Well used for control

——150——
Line showing approximate saturated thickness of the Ogallala aquifer, in feet.

Interval is 25 feet

0 5 10 Miles

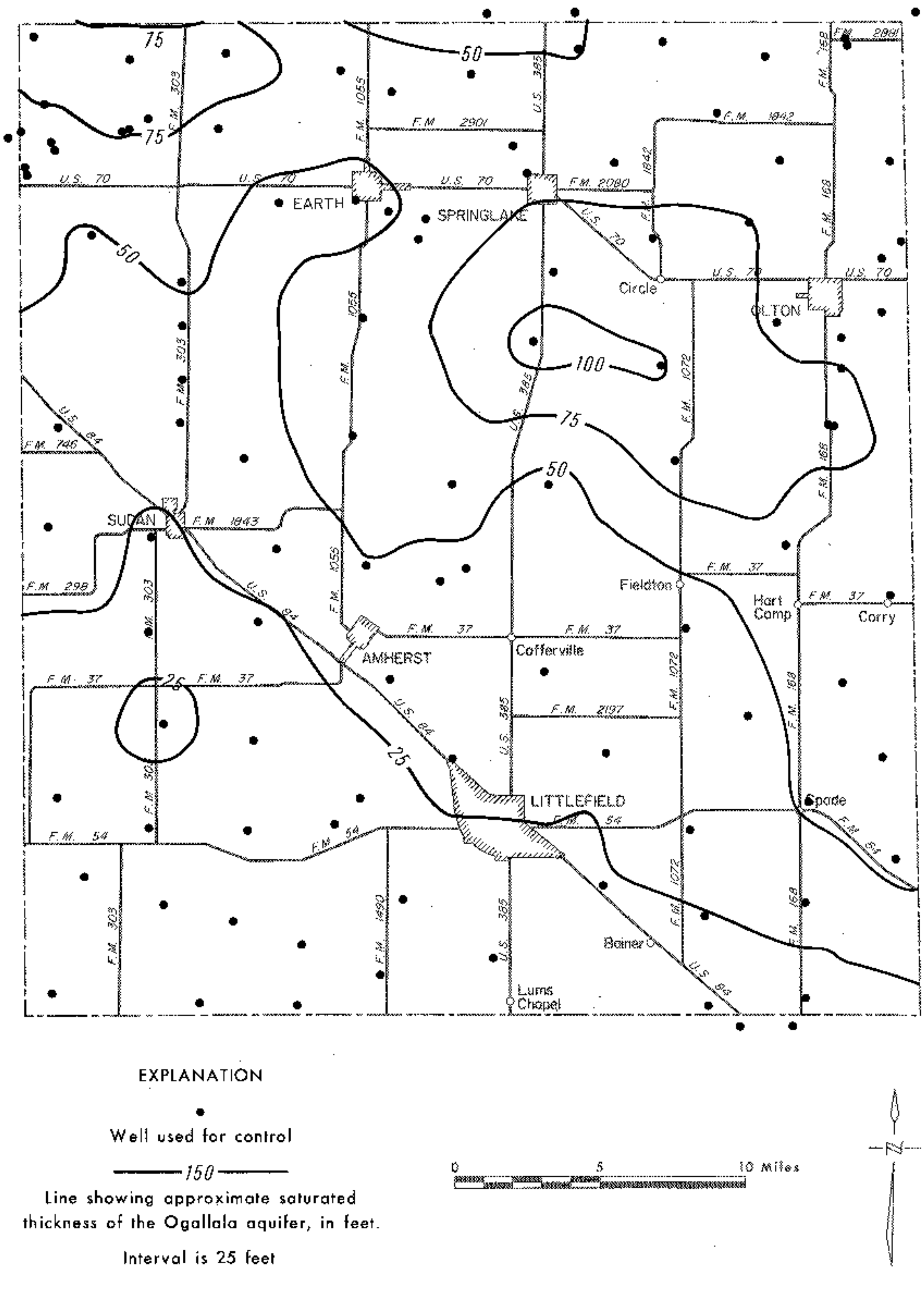
N

2010
Projected Saturated Thickness

Volume of Water in Storage Corresponding to Mapped Saturated-Thickness Intervals

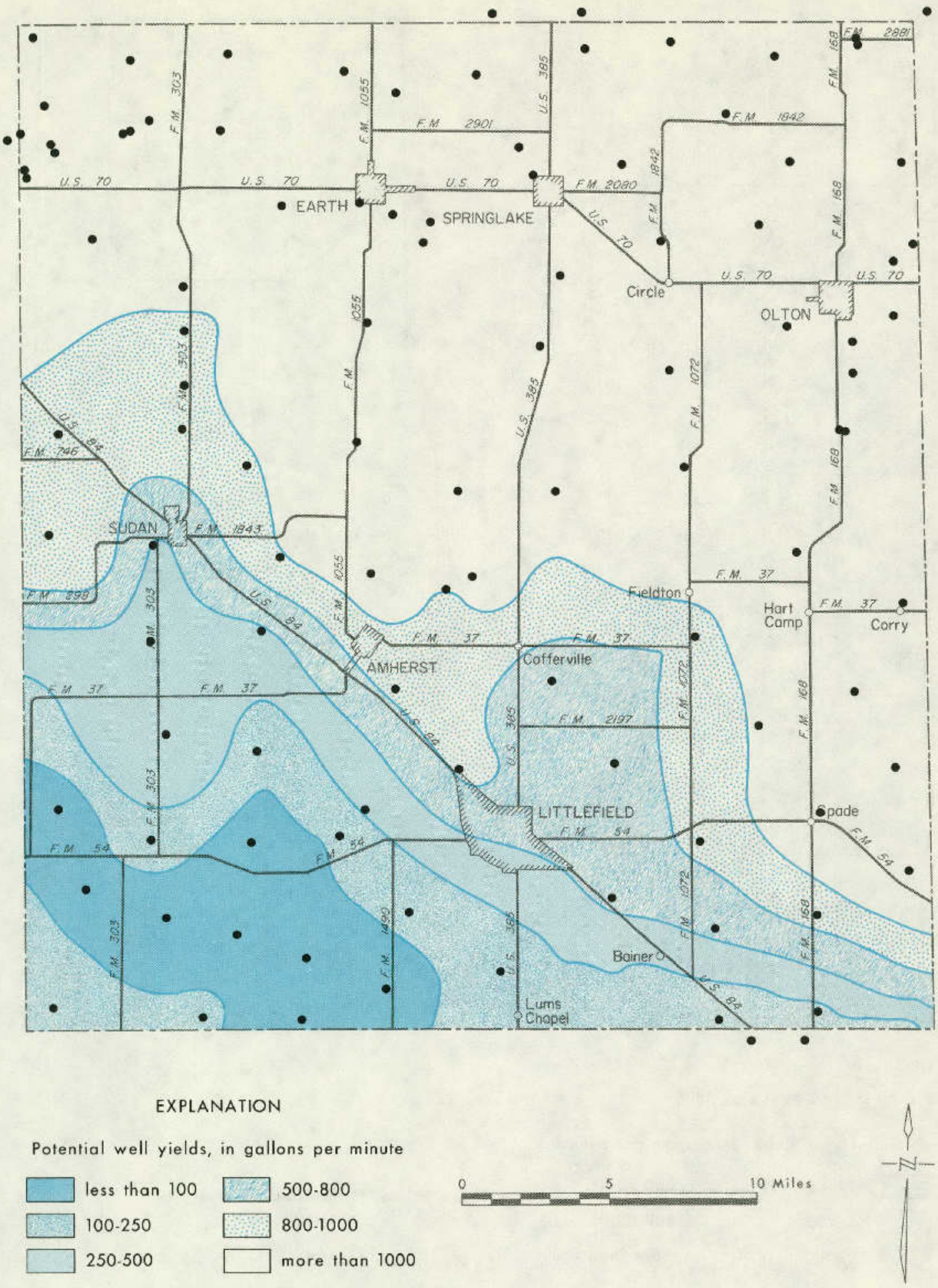
(Coefficient of Storage: 15 percent)

MAPPED SATURATED-THICKNESS INTERVAL (feet)	SURFACE AREA (acres)	VOLUME OF WATER IN STORAGE (acre-feet)
0– 25	176,593	398,433
25– 50	205,564	1,134,831
50– 75	202,344	1,850,848
75–100	61,281	763,505
100–125	760	11,961
TOTAL	646,542	4,159,559

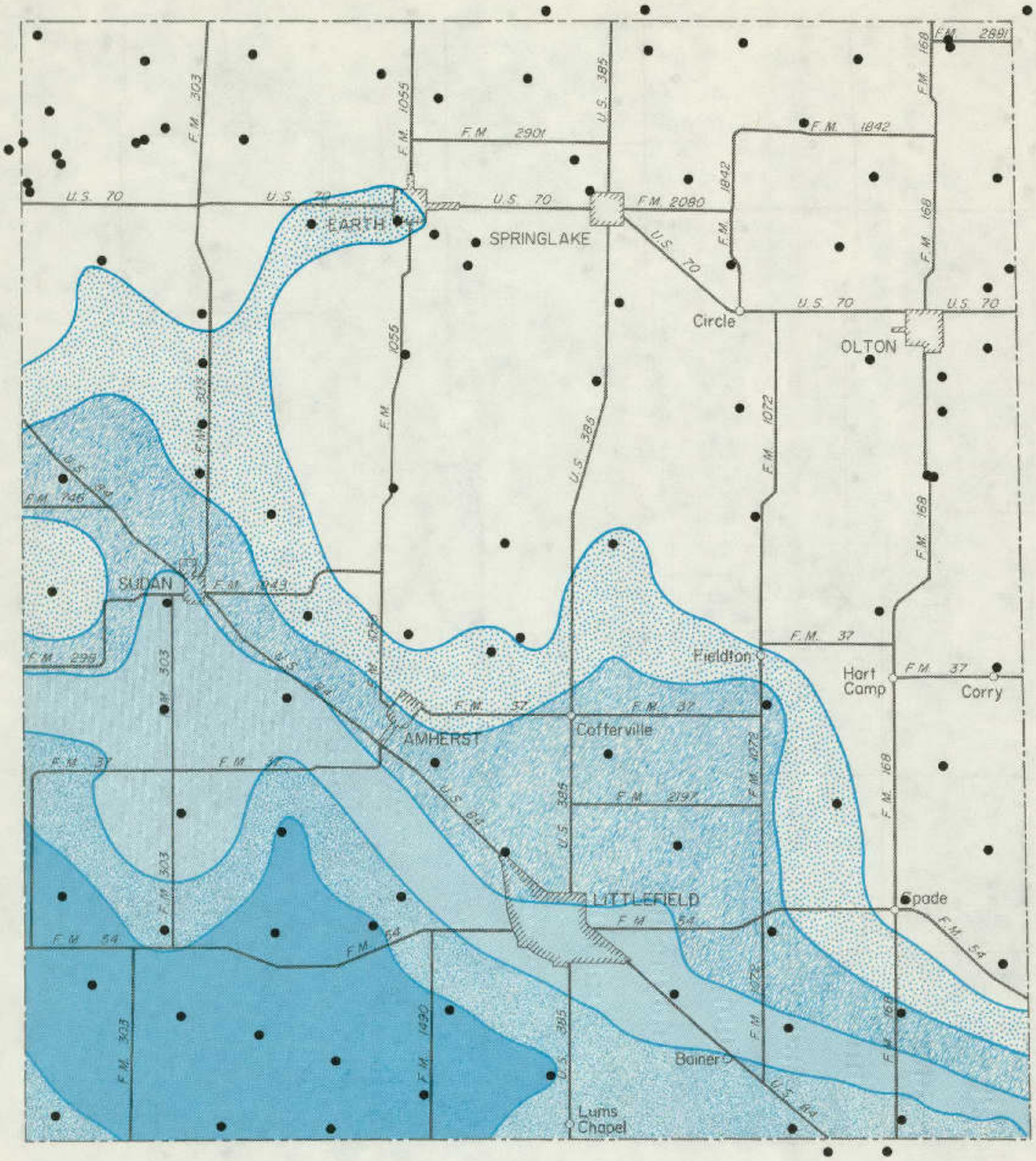


2020
Projected Saturated Thickness

POTENTIAL WELL YIELD OF THE OGALLALA AQUIFER



1974
Estimated Potential Yield



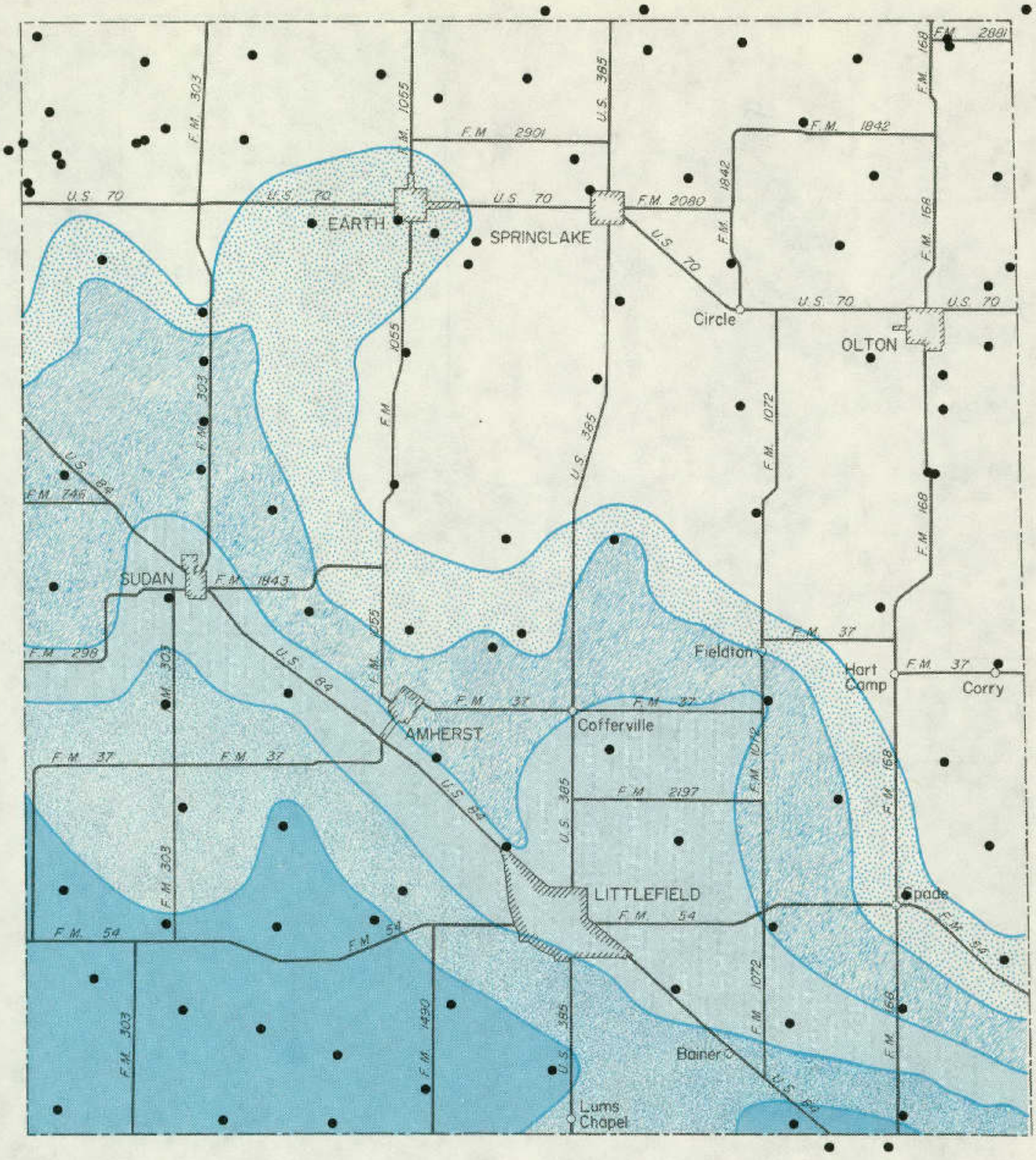
EXPLANATION

Potential well yields, in gallons per minute

- less than 100
- 100-250
- 250-500
- 500-800
- 800-1000
- more than 1000

1980

Projected Potential Yield



EXPLANATION

Potential well yields, in gallons per minute

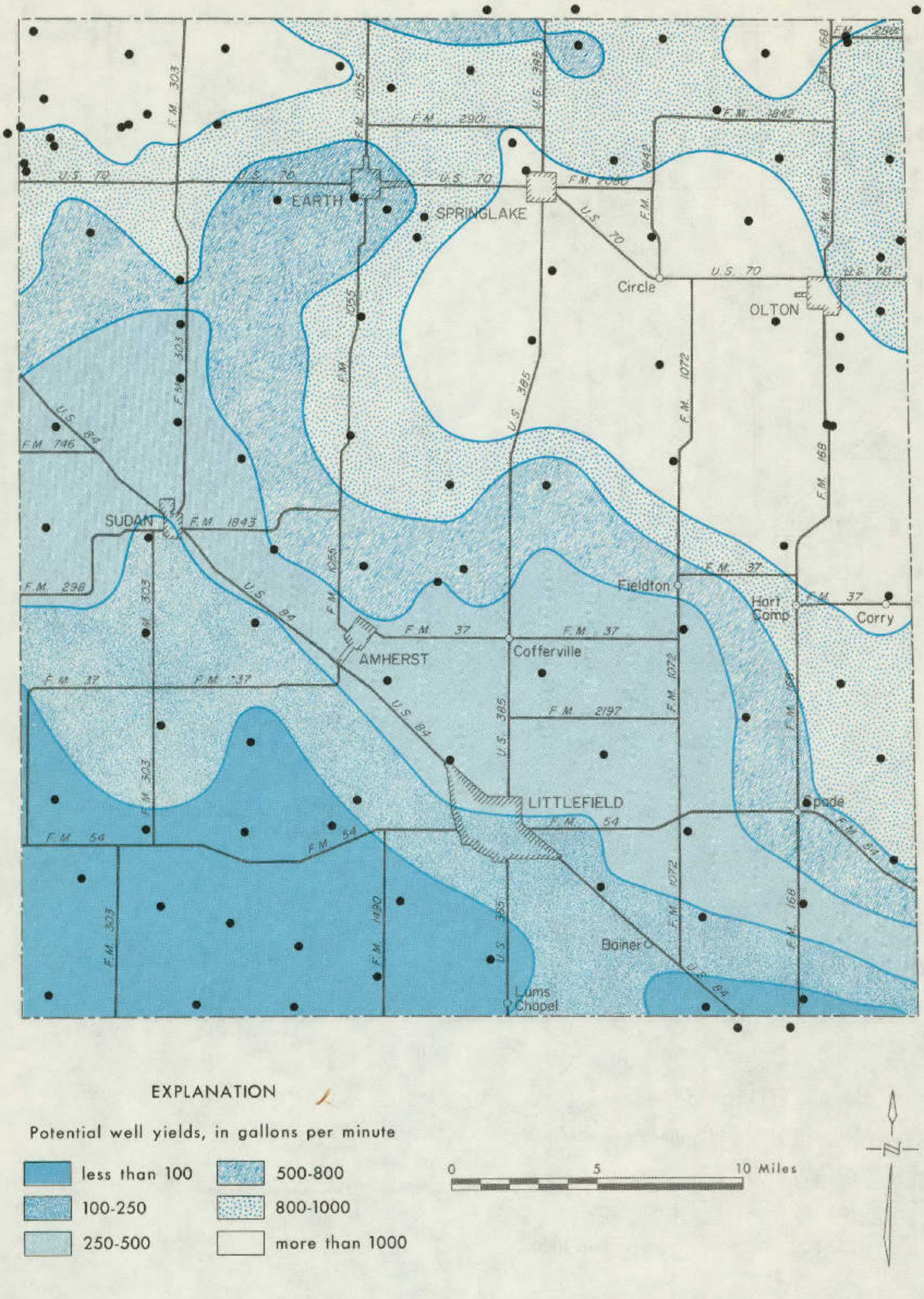
- less than 100
- 100-250
- 250-500
- 500-800
- 800-1000
- more than 1000

0 5 10 Miles

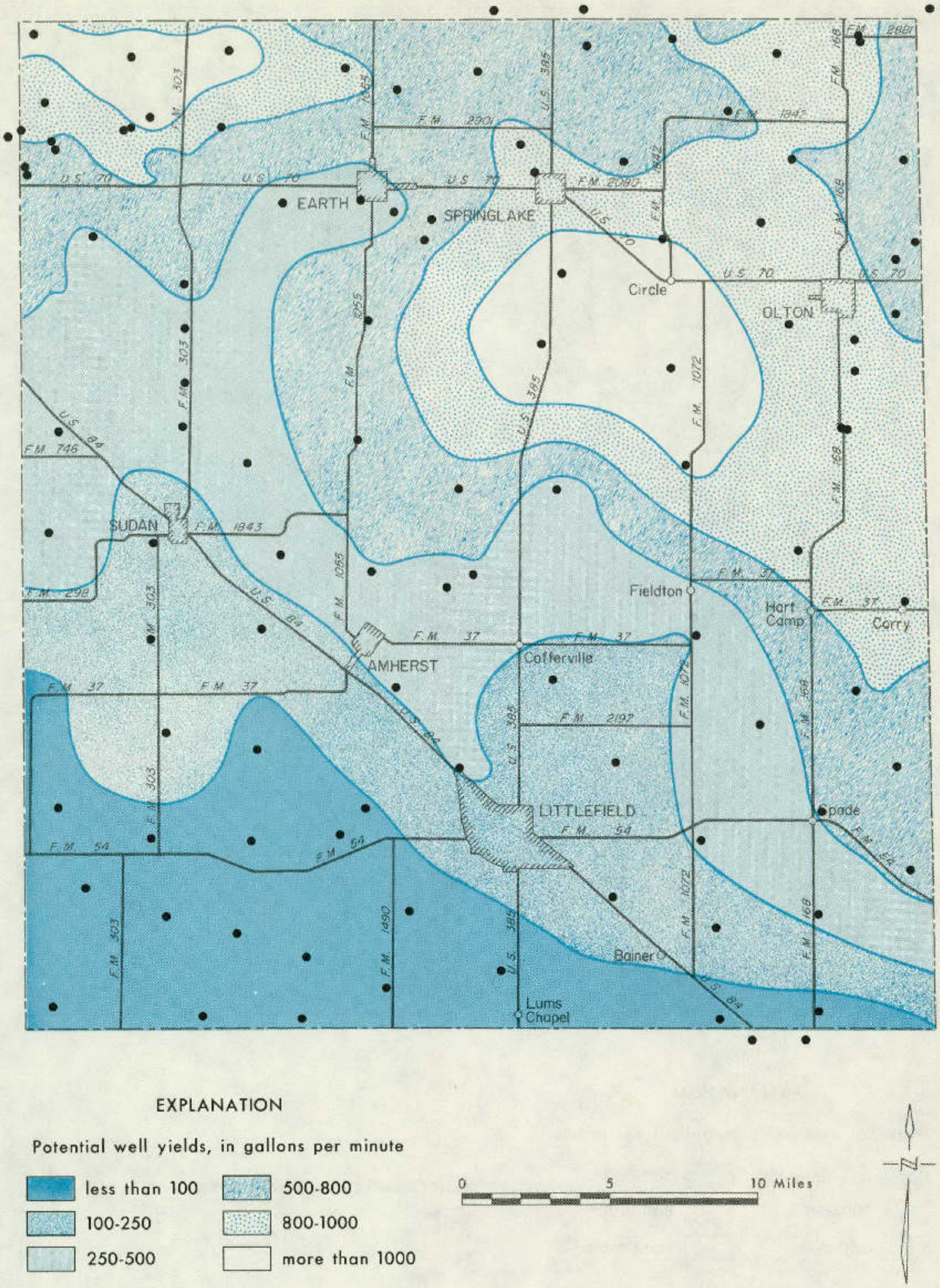
N

1990

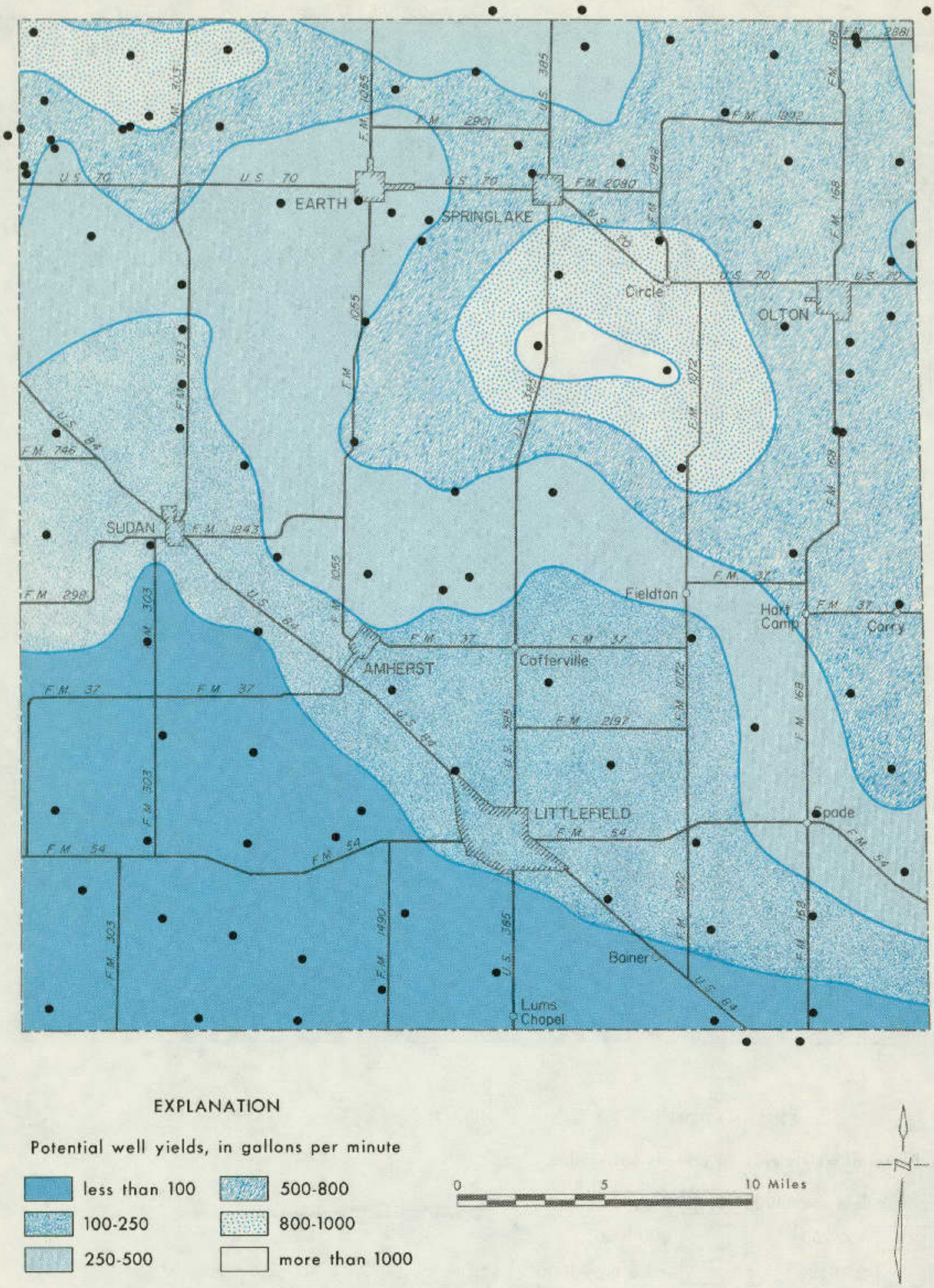
Projected Potential Yield



2000
Projected Potential Yield



2010
Projected Potential Yield



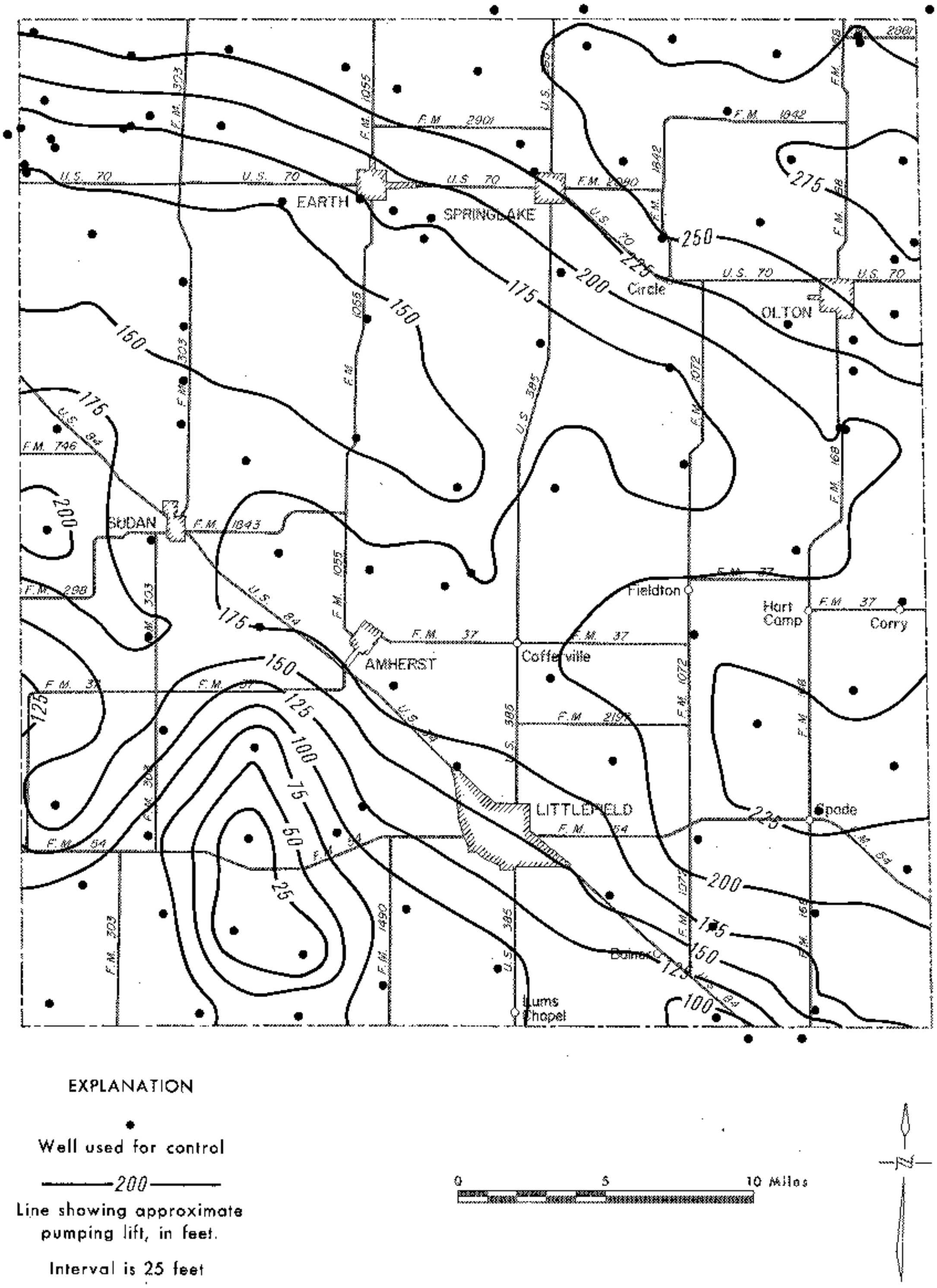
2020
Projected Potential Yield

PUMPING LIFTS IN THE OGALLALA AQUIFER

1974

Surface Area Corresponding to Mapped Pumping-Lift Intervals

MAPPED PUMPING-LIFT INTERVAL (feet)	SURFACE AREA (acres)
0– 25	7,966
25– 50	9,294
50– 75	13,269
75–100	42,396
100–125	27,027
125–150	79,782
150–175	130,272
175–200	131,494
200–225	91,999
225–250	72,139
250–275	44,020
275–300	6,389
TOTAL	656,048

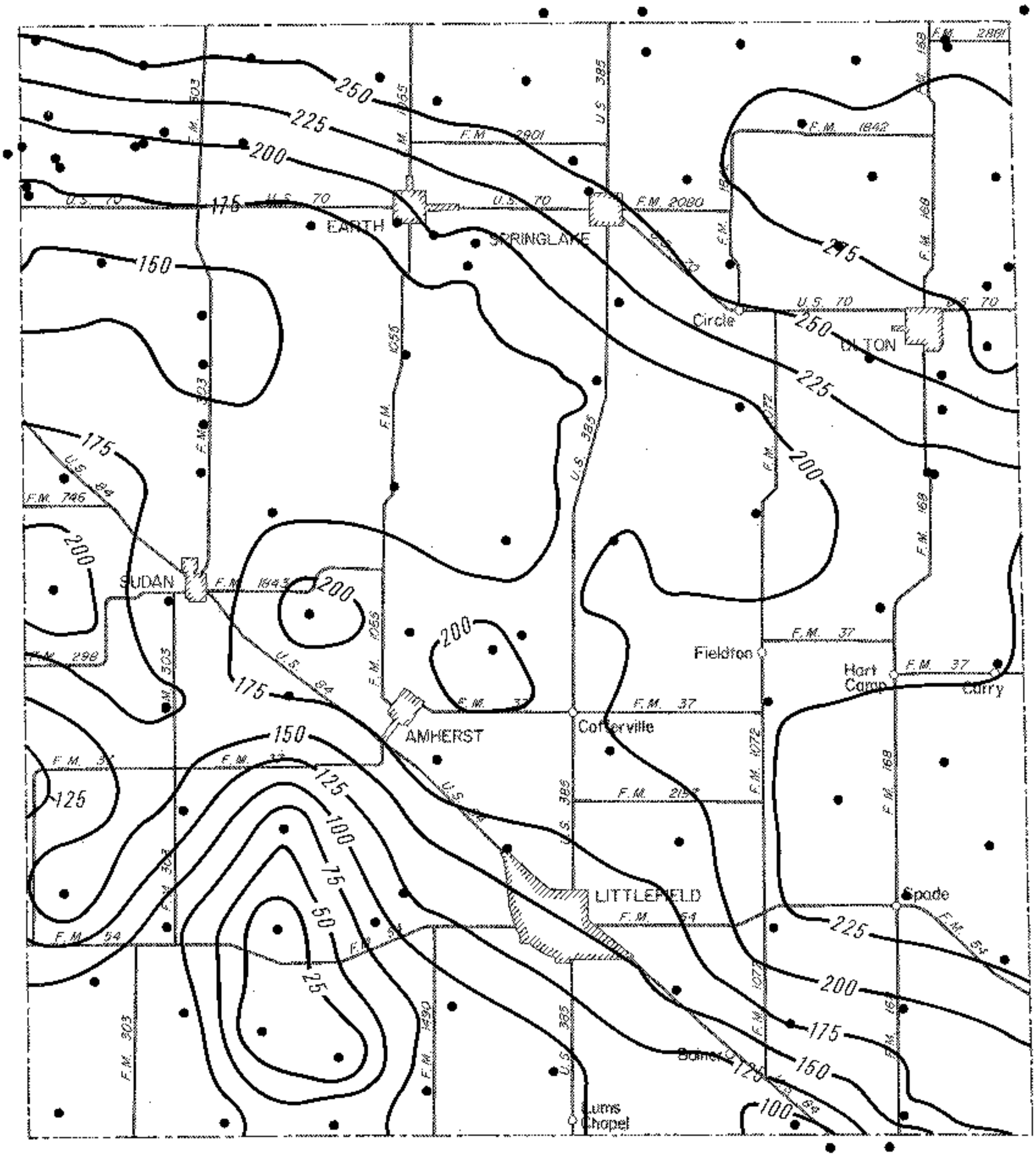


1974
Estimated Pumping Lifts

1980

Surface Area Corresponding to Mapped Pumping-Lift Intervals

MAPPED PUMPING-LIFT INTERVAL (feet)	SURFACE AREA (acres)
0– 25	7,411
25– 50	9,501
50– 75	13,492
75–100	41,226
100–125	24,704
125–150	45,987
150–175	124,851
175–200	125,421
200–225	103,757
225–250	66,467
250–275	68,310
275–300	17,859
TOTAL	648,988



EXPLANATION

• Well used for control

—200— Line showing approximate pumping lift, in feet.

Interval is 25 feet

0 5 10 Miles

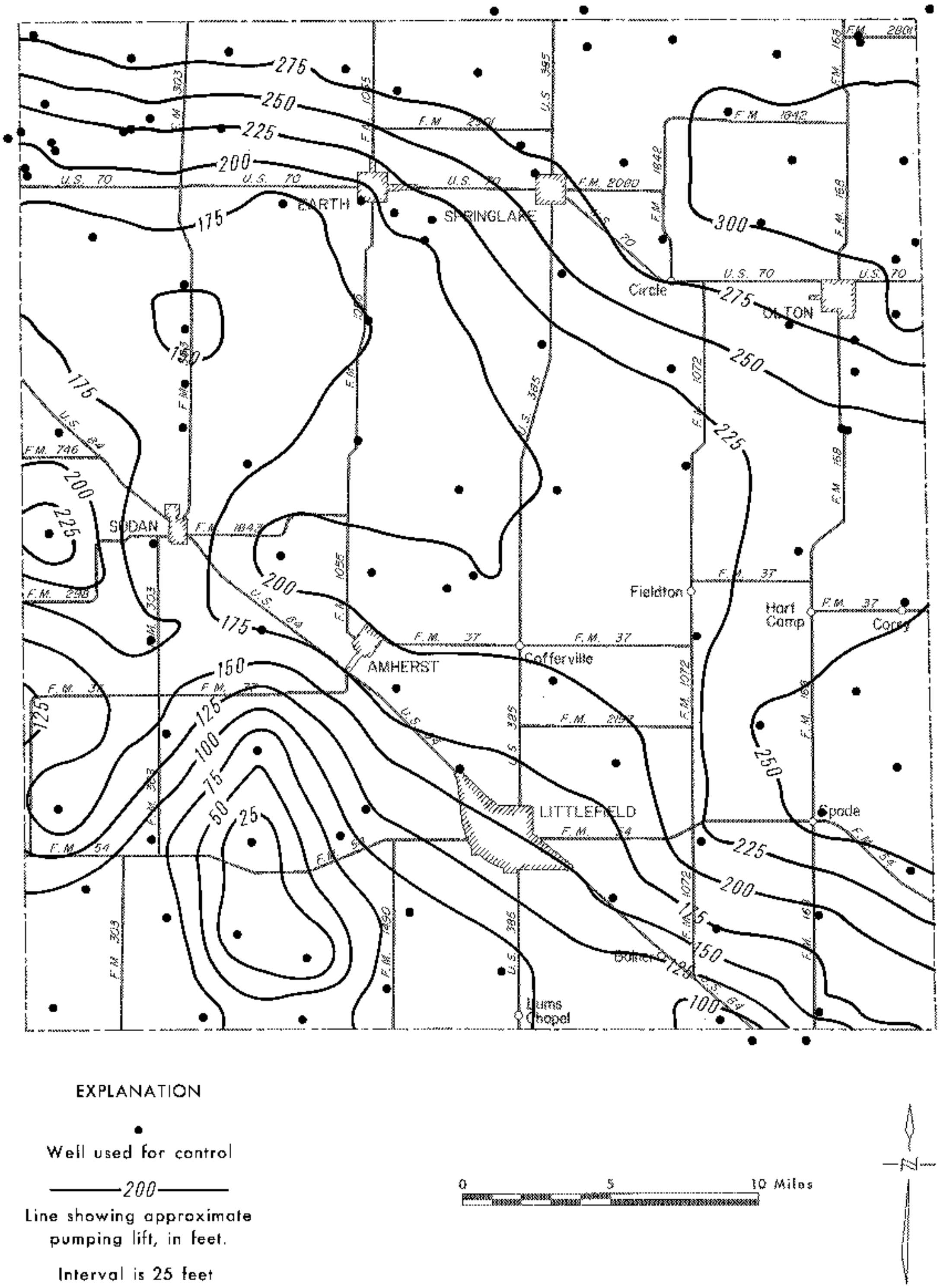
1980

Projected Pumping Lifts

1990

Surface Area Corresponding to Mapped Pumping-Lift Intervals

MAPPED PUMPING-LIFT INTERVAL (feet)	SURFACE AREA (acres)
0– 25	7,411
25– 50	9,501
50– 75	13,492
75–100	41,226
100–125	24,704
125–150	33,065
150–175	90,265
175–200	101,477
200–225	103,567
225–250	72,212
250–275	57,769
275–300	69,648
300–325	24,649
TOTAL	648,988

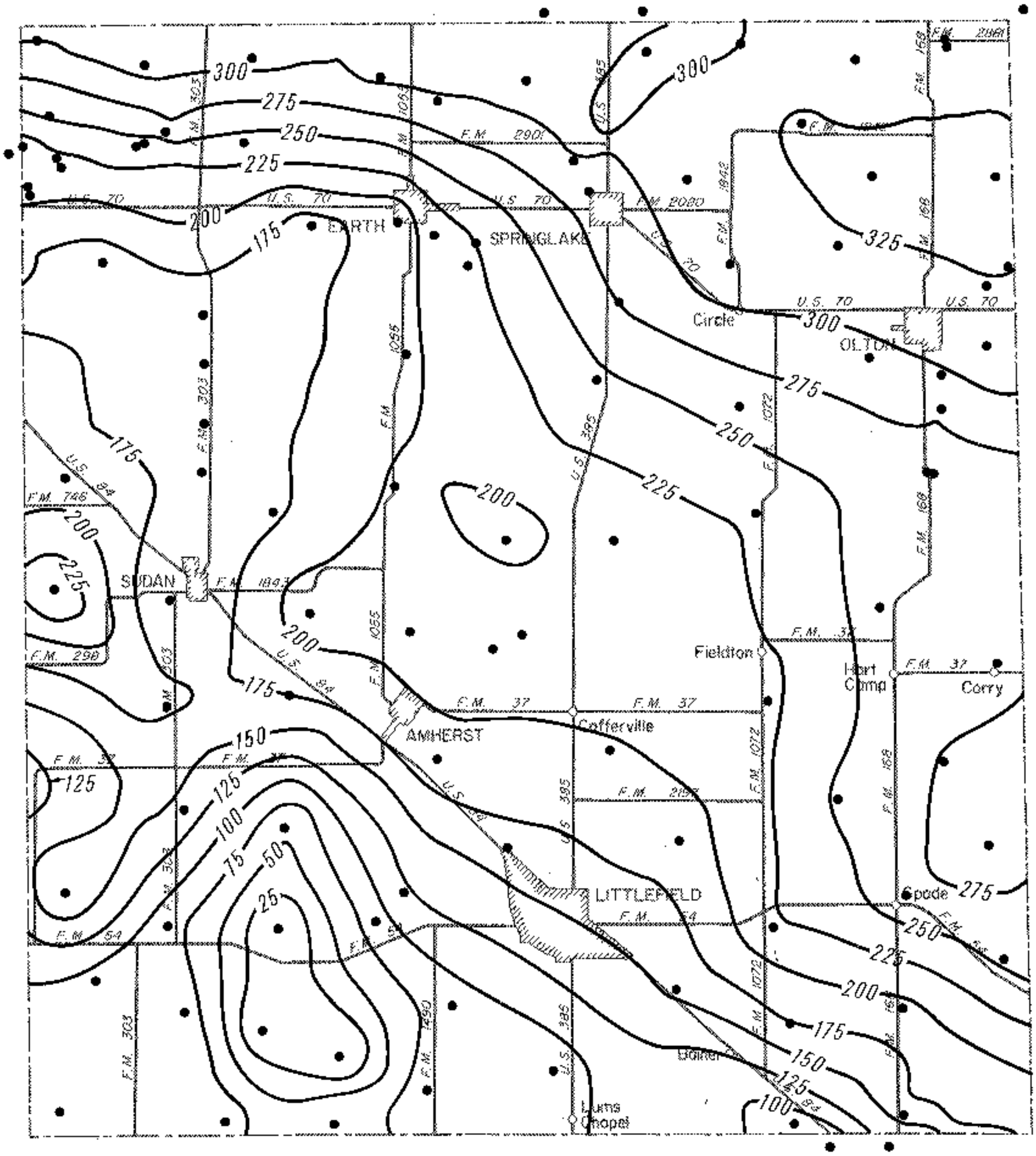


1990
Projected Pumping Lifts

2000

Surface Area Corresponding to Mapped Pumping-Lift Intervals

MAPPED PUMPING-LIFT INTERVAL (feet)	SURFACE AREA (acres)
0– 25	7,411
25– 50	9,601
50– 75	13,492
75–100	41,226
100–125	24,704
125–150	32,495
150–175	78,293
175–200	84,944
200–225	97,106
225–250	54,539
250–275	66,701
275–300	49,408
300–325	72,297
325–350	16,869
TOTAL	648,988



EXPLANATION

•
Well used for control

———200———
Line showing approximate pumping lift, in feet.

Interval is 25 feet

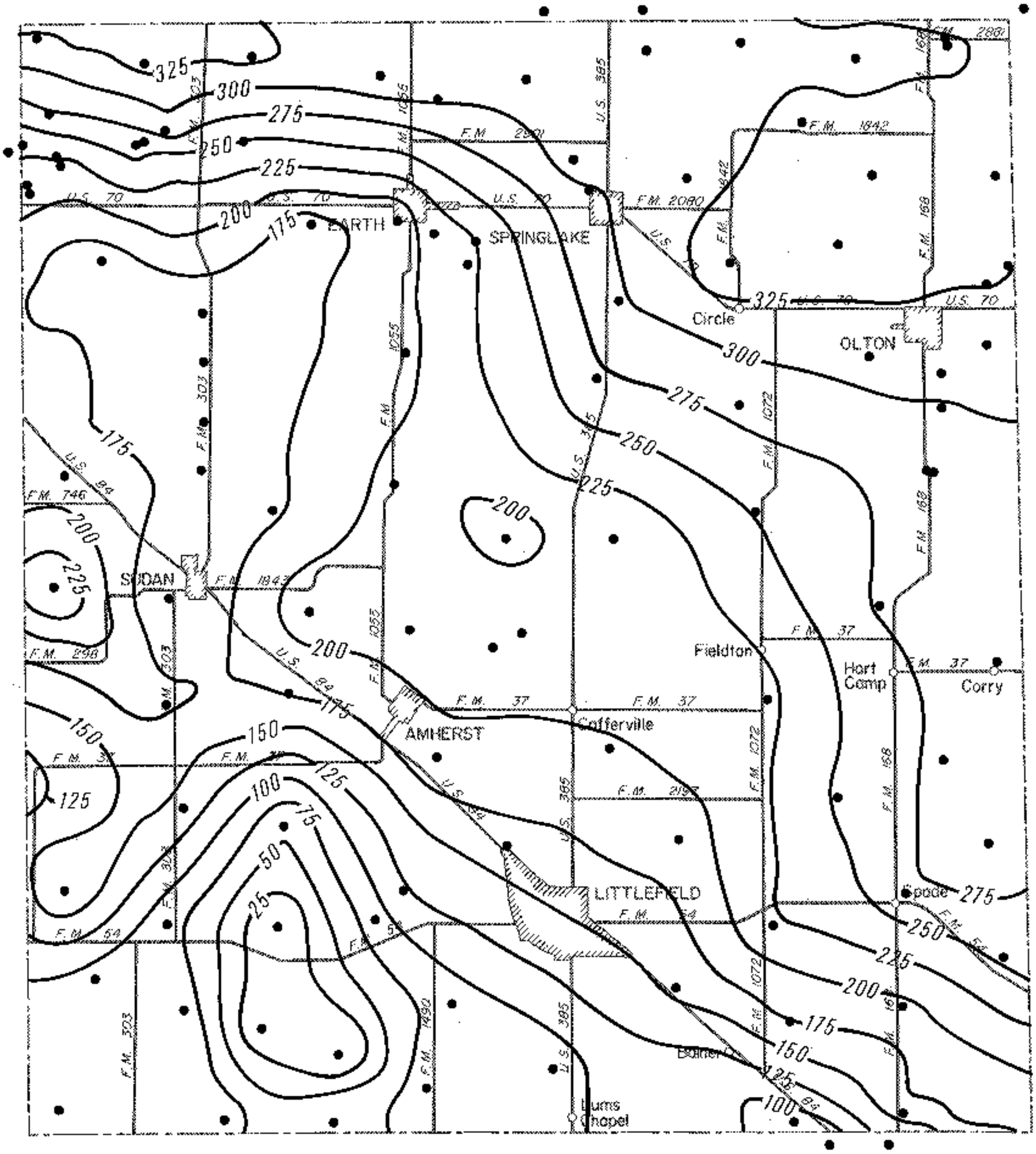
0 5 10 Miles

N

2000
Projected Pumping Lifts

Surface Area Corresponding to Mapped Pumping-Lift Intervals

MAPPED PUMPING-LIFT INTERVAL (feet)	SURFACE AREA (acres)
0– 25	7,411
25– 50	9,501
50– 75	13,492
75–100	41,226
100–125	24,704
125–150	32,875
150–175	76,012
175–200	83,234
200–225	90,645
225–250	43,517
250–275	45,607
275–300	61,570
300–325	73,624
325–350	45,567
TOTAL	648,988



EXPLANATION

• Well used for control

——200—— Line showing approximate pumping lift, in feet.

Interval is 25 feet

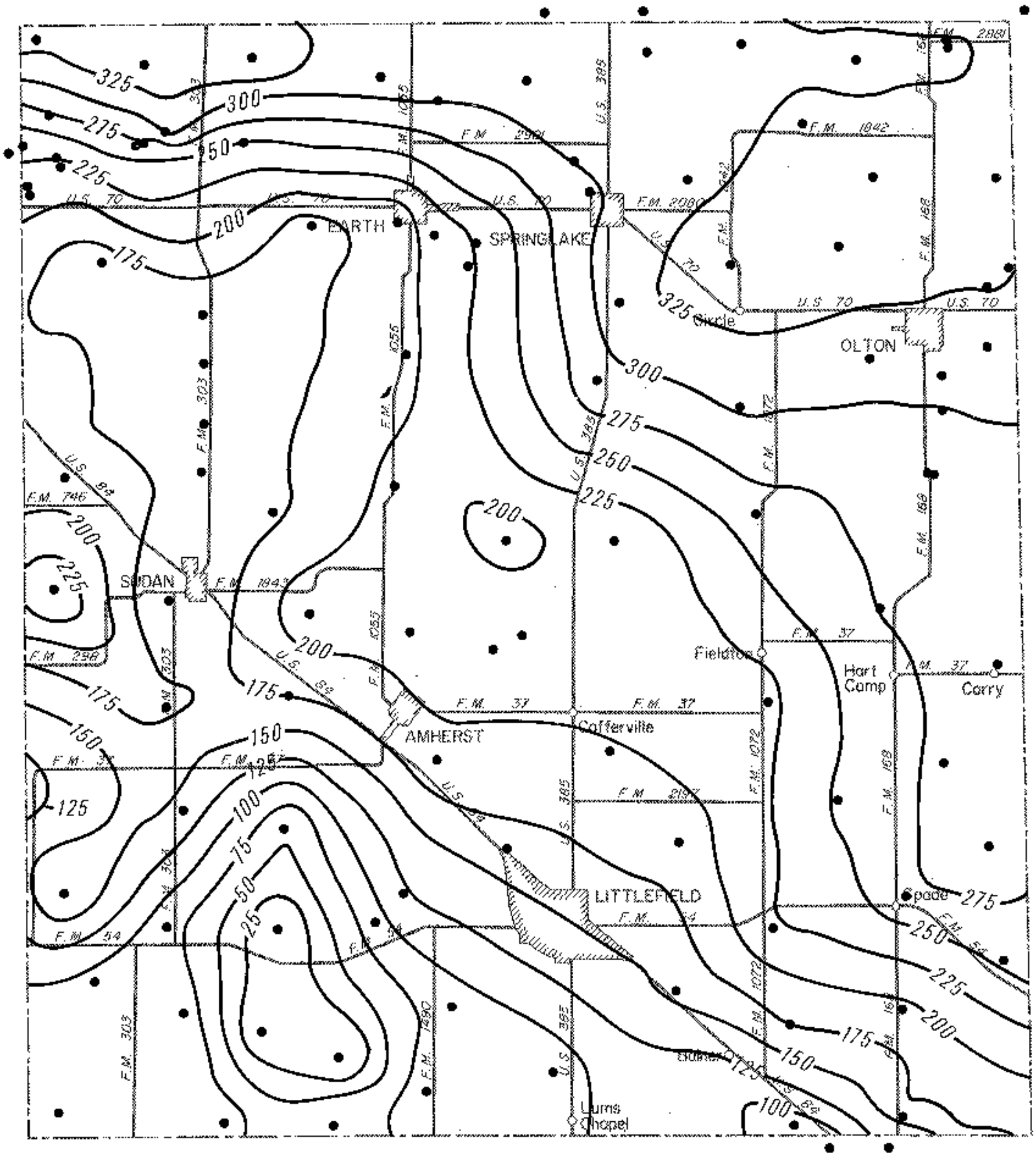
0 5 10 Miles

N

2010
Projected Pumping Lifts

Surface Area Corresponding to Mapped Pumping-Lift Intervals

MAPPED PUMPING-LIFT INTERVAL (feet)	SURFACE AREA (acres)
0– 25	7,411
25– 50	9,501
50– 75	13,492
75–100	41,226
100–125	24,704
125–150	32,875
150–175	76,012
175–200	82,664
200–225	87,034
225–250	42,567
250–275	42,377
275–300	51,878
300–325	82,575
325–350	53,724
350–375	945
TOTAL	648,988



EXPLANATION

•
Well used for control

——200——
Line showing approximate pumping lift, in feet.

Interval is 25 feet

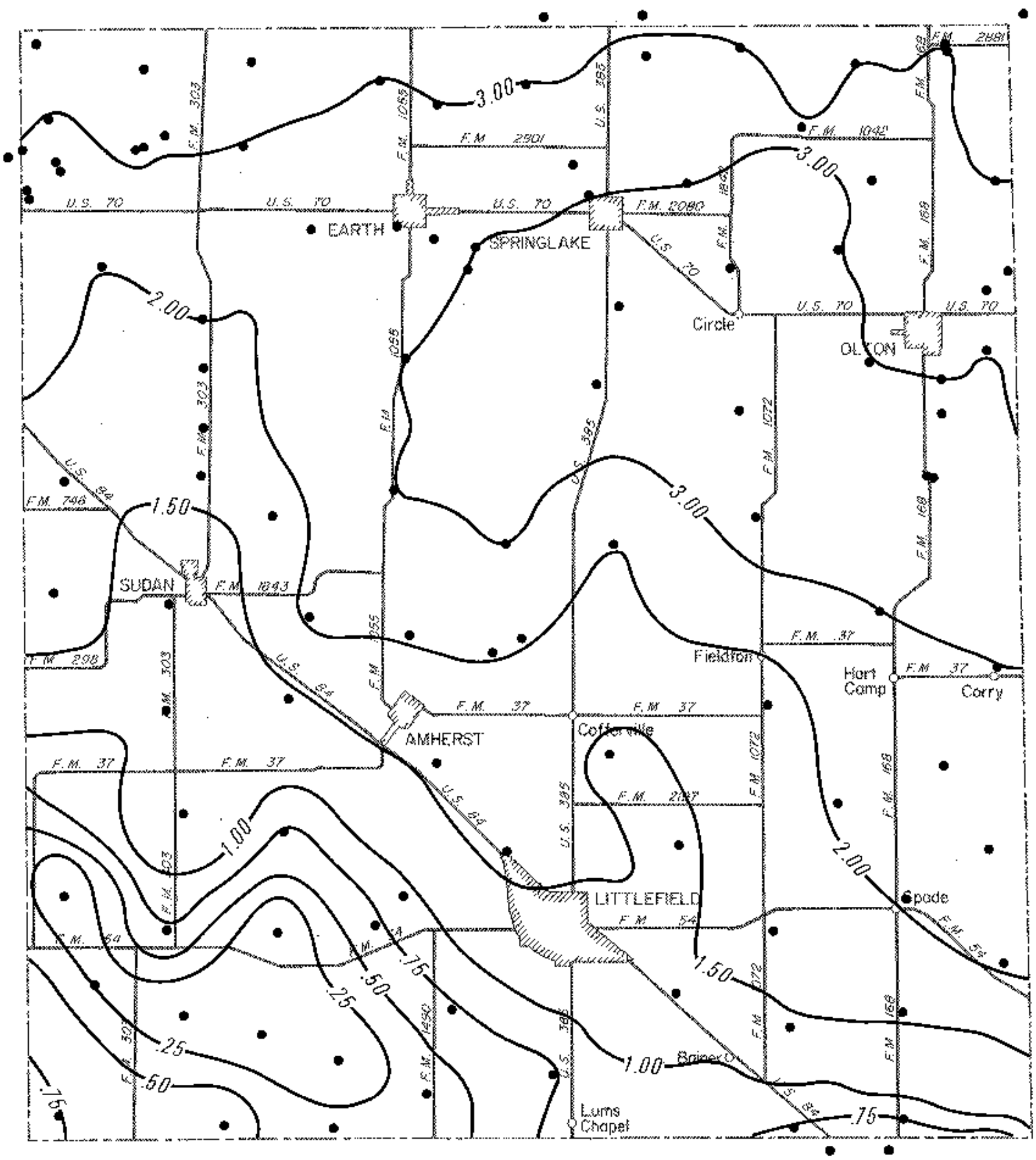
0 5 10 Miles

2020
Projected Pumping Lifts

PUMPAGE FROM THE OGALLALA AQUIFER

Pumpage Corresponding to Mapped Decline-Rate Intervals

MAPPED DECLINE-RATE INTERVAL (feet)	SURFACE AREA (acres)	STORAGE CAPACITY OF DEWATERED SECTION (acre-feet)	ESTIMATED PUMPAGE RATE, INCLUDING NATURAL RECHARGE AND IRRIGATION RECIRCULATION (acre-feet per year)
0.00–0.25	18,555	338	2,261
.25– .50	24,405	1,342	4,051
.50– .75	28,523	2,689	6,079
.75–1.00	32,866	4,386	8,550
1.00–1.50	87,110	16,700	28,751
1.50–2.00	117,974	30,520	48,422
2.00–3.00	193,373	75,400	109,817
3.00–4.00	153,431	74,564	104,820
TOTAL	656,238	205,941	312,751



EXPLANATION

• Well used for control

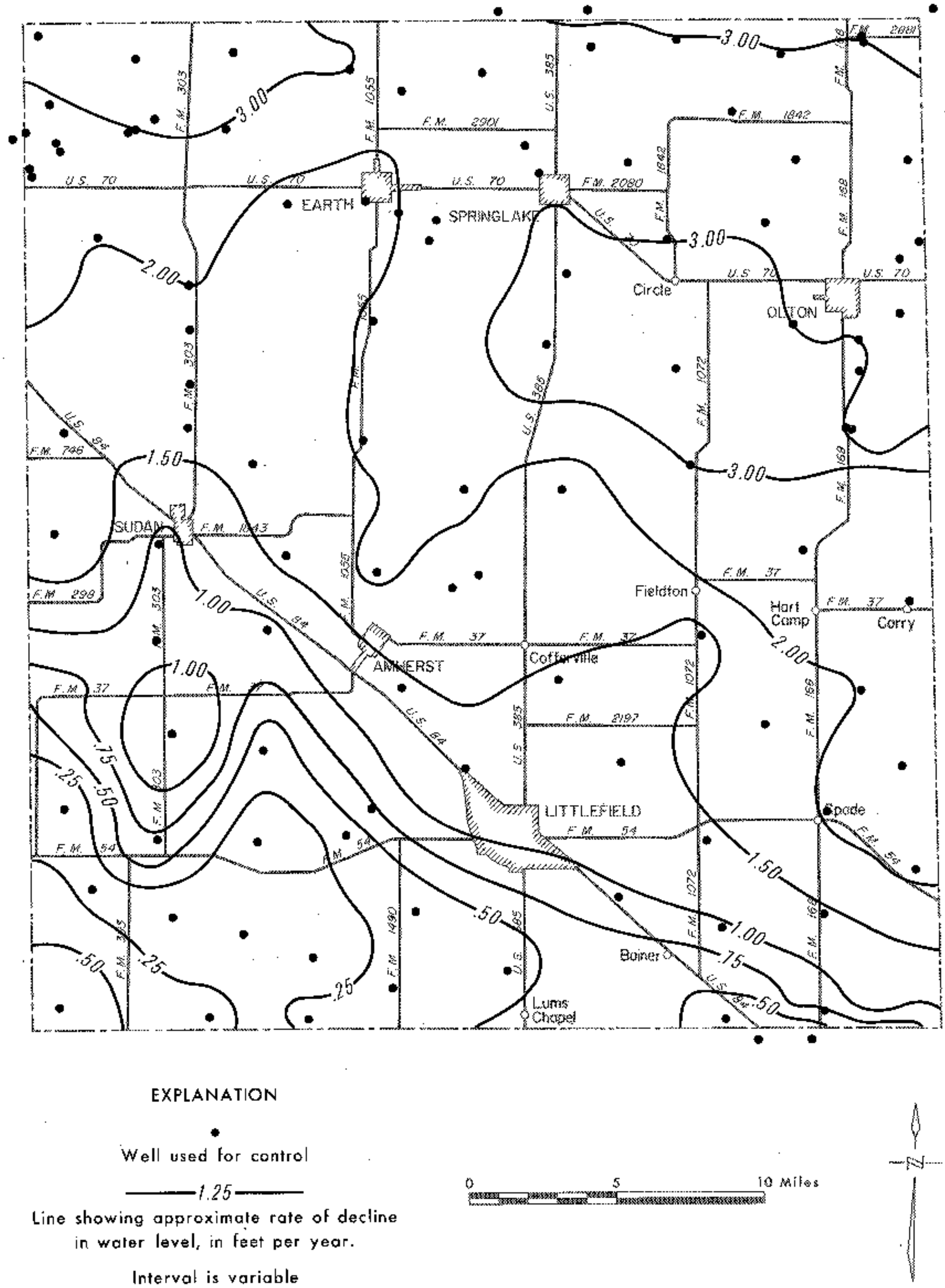
——— 1.25 ———
Line showing approximate rate of decline in water level, in feet per year.

Interval is variable

1974
Estimated Rates of Water-Level Decline

Pumpage Corresponding to Mapped Decline-Rate Intervals

MAPPED DECLINE-RATE INTERVAL (feet)	SURFACE AREA (acres)	STORAGE CAPACITY OF DEWATERED SECTION (acre-feet)	ESTIMATED PUMPAGE RATE, INCLUDING NATURAL RECHARGE AND IRRIGATION RECIRCULATION (acre-feet per year)
0.25–0.50	63,463	3,702	10,789
.50– .75	38,104	3,563	8,087
.75–1.00	40,818	5,374	10,531
1.00–1.50	92,522	17,713	30,508
1.50–2.00	124,051	32,546	51,461
2.00–3.00	208,358	75,514	111,452
3.00–4.00	79,224	38,576	54,214
TOTAL	646,542	176,991	277,042

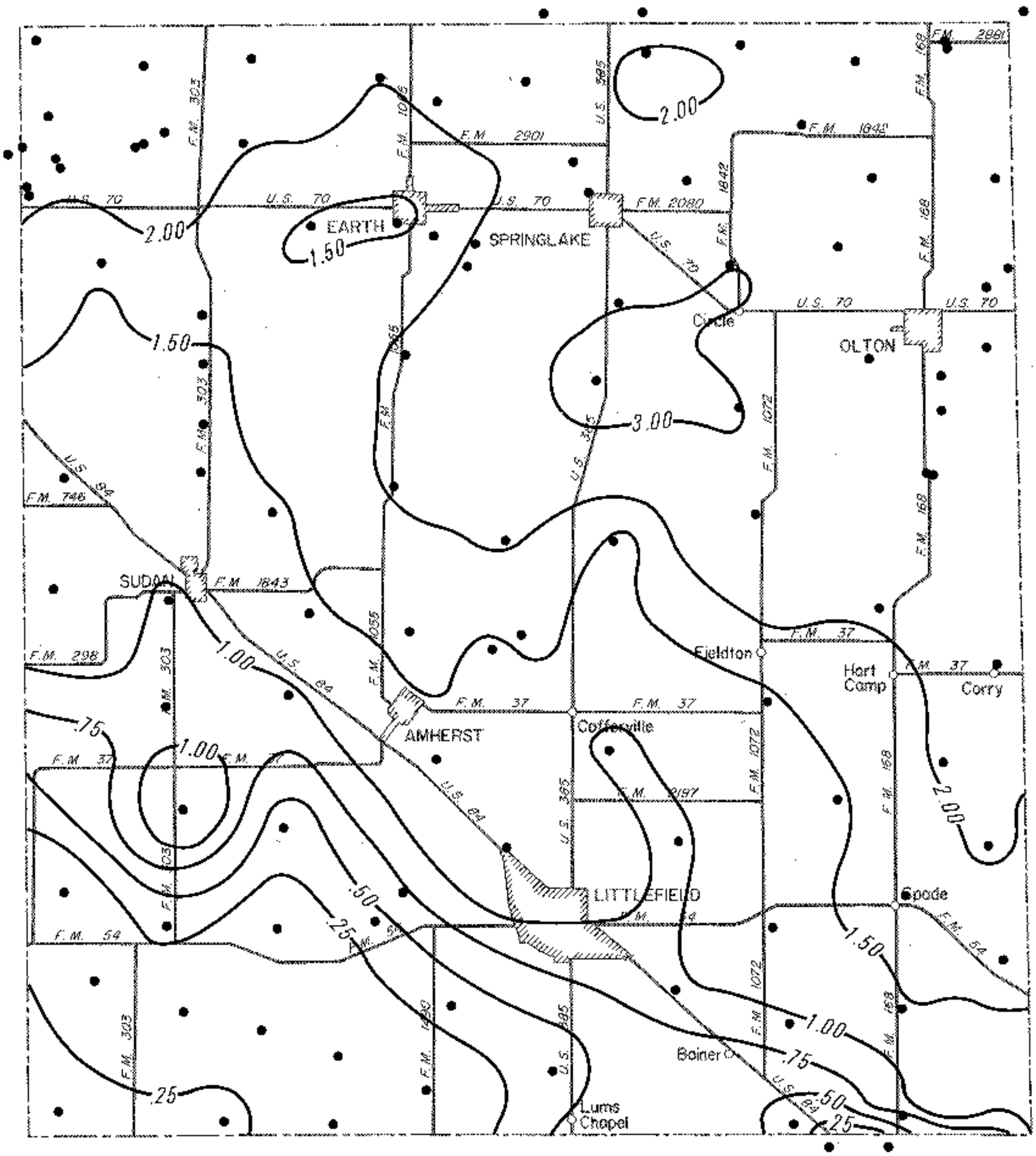


1980

Projected Rates of Water-Level Decline

Pumpage Corresponding to Mapped Decline-Rate Intervals

MAPPED DECLINE-RATE INTERVAL (feet)	SURFACE AREA (acres)	STORAGE CAPACITY OF DEWATERED SECTION (acre-feet)	ESTIMATED PUMPAGE RATE, INCLUDING NATURAL RECHARGE AND IRRIGATION RECIRCULATION (acre-feet per year)
0.25–0.50	74,597	4,195	12,494
.50– .75	34,351	3,214	7,292
.75–1.00	58,522	7,824	15,241
1.00–1.50	119,482	22,844	39,361
1.50–2.00	125,626	32,634	51,724
2.00–3.00	220,689	77,265	114,787
3.00–4.00	13,274	6,173	8,735
TOTAL	646,542	154,150	249,634



EXPLANATION

•
Well used for control

———1.25———
Line showing approximate rate of decline in water level, in feet per year.

Interval is variable

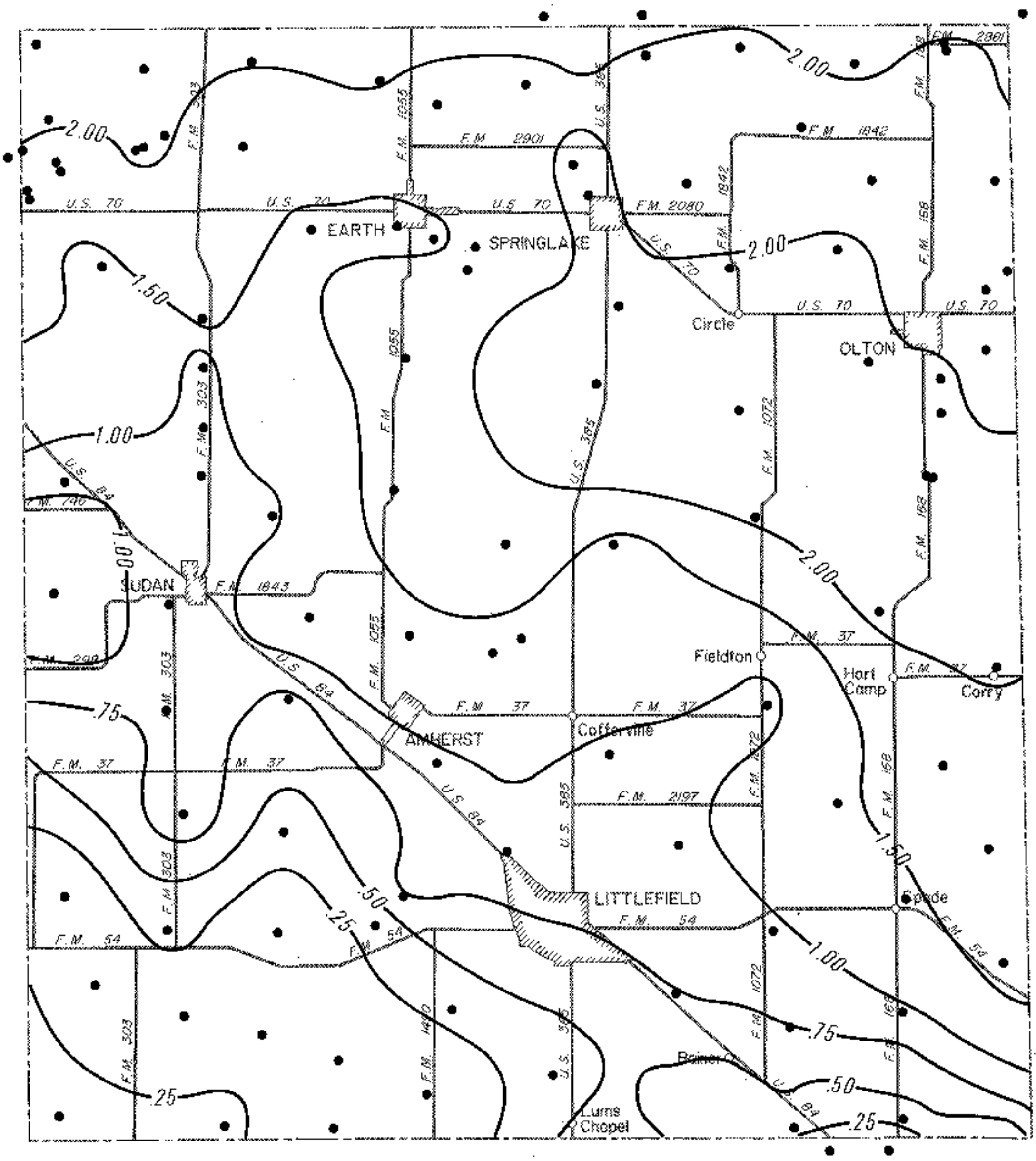
0 5 10 Miles

N

1990
Projected Rates of Water-Level Decline

Pumpage Corresponding to Mapped Decline-Rate Intervals

MAPPED DECLINE-RATE INTERVAL (feet)	SURFACE AREA (acres)	STORAGE CAPACITY OF DEWATERED SECTION (acre-feet)	ESTIMATED PUMPAGE RATE, INCLUDING NATURAL RECHARGE AND IRRIGATION RECIRCULATION (acre-feet per year)
0.25–0.50	83,141	4,697	13,951
.50– .75	55,635	5,233	11,843
.75–1.00	109,635	14,227	28,036
1.00–1.50	115,344	21,930	37,851
1.50–2.00	189,425	48,703	77,386
2.00–3.00	92,982	32,139	47,865
3.00–4.00	380	174	247
TOTAL	646,542	127,105	217,179



EXPLANATION

• Well used for control

——— 1.25 ——— Line showing approximate rate of decline in water level, in feet per year.

Interval is variable

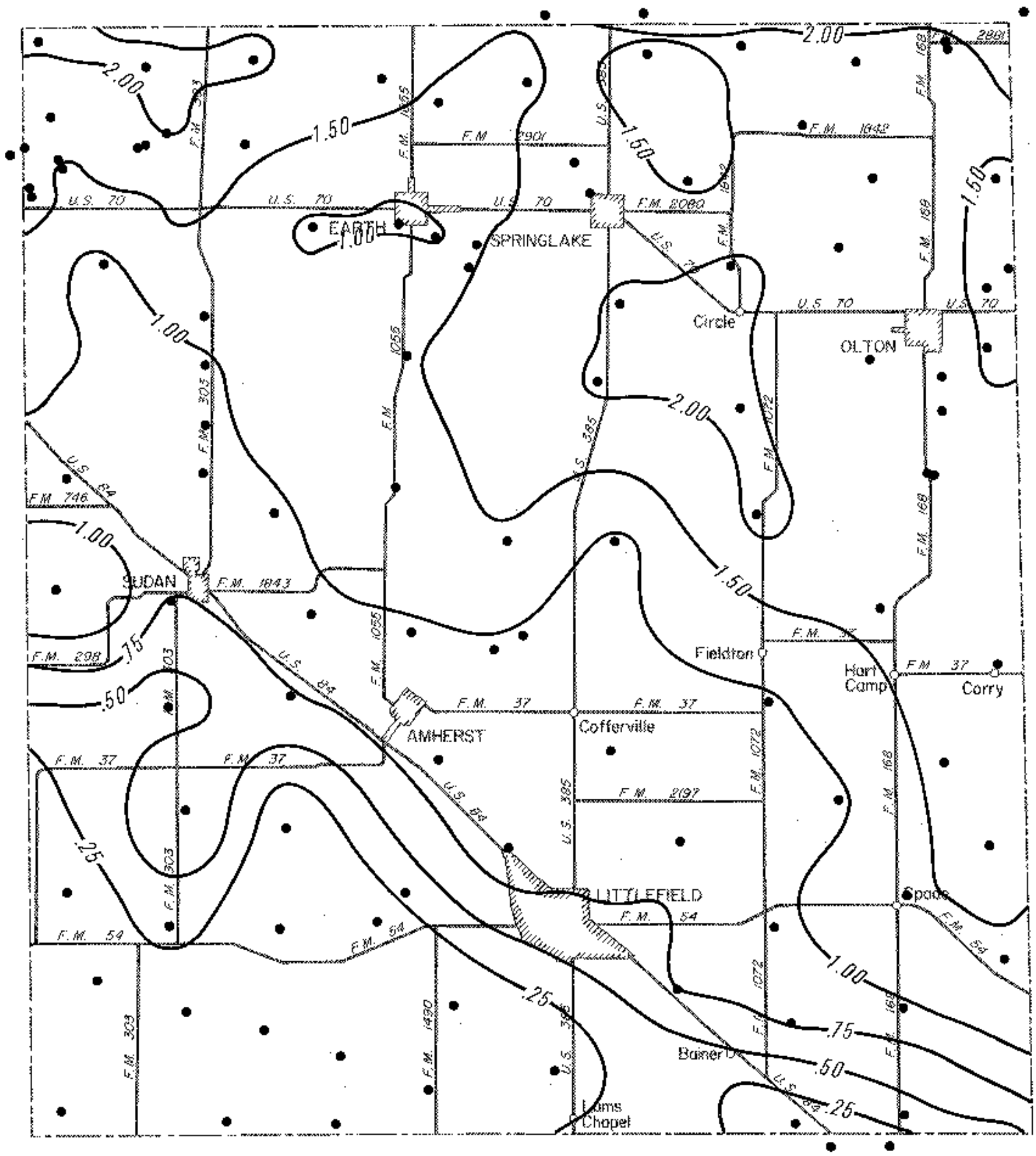
0 5 10 Miles

2000

Projected Rates of Water-Level Decline

Pumpage Corresponding to Mapped Decline-Rate Intervals

MAPPED DECLINE-RATE INTERVAL (feet)	SURFACE AREA (acres)	STORAGE CAPACITY OF DEWATERED SECTION (acre-feet)	ESTIMATED PUMPAGE RATE, INCLUDING NATURAL RECHARGE AND IRRIGATION RECIRCULATION (acre-feet per year)
0.25–0.50	103,819	6,006	17,589
.50– .75	78,664	7,627	17,019
.75–1.00	121,787	15,682	30,997
1.00–1.50	177,661	34,871	59,611
1.50–2.00	146,707	37,641	59,840
2.00–3.00	17,903	5,619	8,534
TOTAL	646,542	107,447	193,590



EXPLANATION

•
Well used for control

——1.25——
Line showing approximate rate of decline in water level, in feet per year.

Interval is variable

0 5 10 Miles

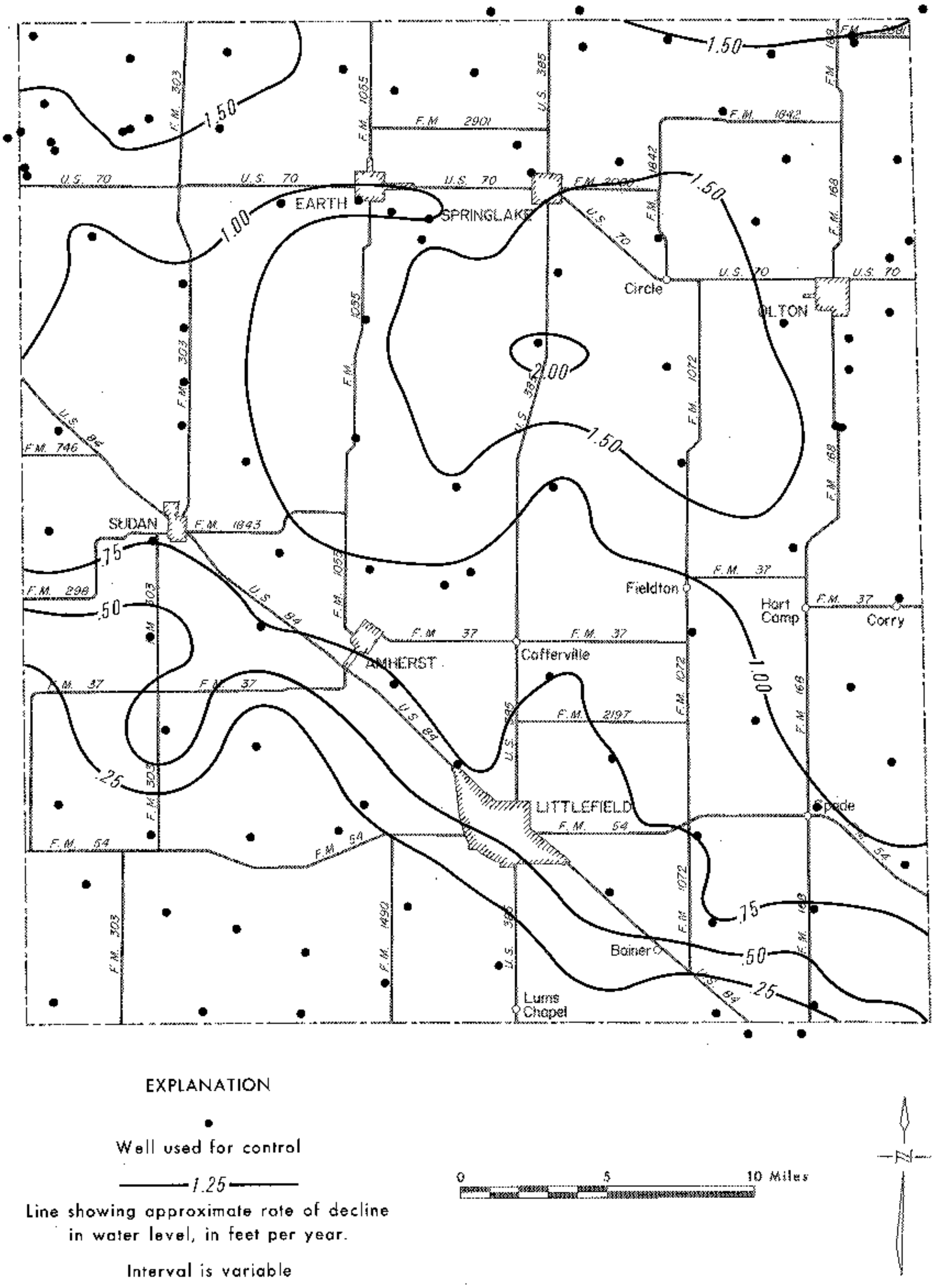
N

2010
Projected Rates of Water-Level Decline

2020

Pumpage Corresponding to Mapped Decline-Rate Intervals

MAPPED DECLINE-RATE INTERVAL (feet)	SURFACE AREA (acres)	STORAGE CAPACITY OF DEWATERED SECTION (acre-feet)	ESTIMATED PUMPAGE RATE, INCLUDING NATURAL RECHARGE AND IRRIGATION RECIRCULATION (acre-feet per year)
0.25–0.50	126,238	7,327	21,416
.50– .75	91,948	9,042	20,046
.75–1.00	174,132	22,209	44,064
1.00–1.50	193,167	37,189	63,944
1.50–2.00	61,056	14,496	23,501
TOTAL	646,542	90,264	172,971



2020
Projected Rates of Water-Level Decline

ACKNOWLEDGEMENTS

Special appreciation is expressed to the Lamb County landowners and water users for allowing their wells to be measured by Board and Water District personnel. This study could not have been accomplished without their cooperation and the records obtained from their wells.

Special thanks are also expressed to the staff of the High Plains Underground Water Conservation District No. 1, Mr. Frank A. Rayner, general manager, for providing records and consultation during the study.

Additionally, appreciation is expressed for consultation provided by numerous individuals: Dr. Donald Reddell, associate professor of Engineering, Texas A&M University; Leon New, irrigation specialist, Texas Agriculture Extension Service, Lubbock, Texas; Shelby Newman, superintendent, Texas Agricultural Experiment Station, Stephenville, Texas; Dr. C. C. Reeves, Jr., associate professor of Geosciences, Texas Tech University; and Dr. James Osborn, chairman of the Department of Agricultural Economics, Texas Tech University.

STAFF INVOLVEMENT

This report was prepared principally in the Texas Water Development Board's Ground Water Data and Protection Division, Mr. Fred L. Osborne, Jr., director. Numerous staff members of this Division assisted the authors in assembling and evaluating data and information. The Board's Information Systems and Services Division, Mr. David L. Ferguson, director, provided automated data processing and computational services, and prepared the manuscript copy of tabular and graphical displays.

SELECTED REFERENCES

Alexander, W. H., Jr., 1961, Geology and ground-water resources of the Northern High Plains of Texas, progress report no. 1: Texas Board Water Engineers Bull. 6109, 47 p.

Alexander, W. H., Jr., Broadhurst, W. L., and White, W. N., 1943, Progress report on ground water in the High Plains in Texas: Texas Board Water Engineers duplicated rept., 22 p.

Baker, C. L., 1915, Geology and underground waters of the northern Llano Estacado: Univ. Texas Bull. 57, 225 p.

Baker, E. T., Jr., Long, A. T., Jr., Reeves, R. D., and Wood, L. A., 1963, Reconnaissance investigation of the ground-water resources of the Red River, Sulphur River, and Cypress Creek basins, Texas: Texas Water Comm. Bull. 6306, 137 p.

Barnes, J. R., and others, 1949, Geology and ground water in the irrigated region of the Southern High Plains of Texas, progress report no. 7: Texas Board Water Engineers duplicated rept., 51 p.

Bell, A. E., and Sechrist, A. W., 1970, Playas-Southern High Plains of Texas: Playa Lake Symposium, ICASALS, Texas Tech Univ., Lubbock, Texas, Oct. 1970, Proc., p. 35-39.

Brand, J. P., 1953, Cretaceous of Llano Estacado of Texas: Univ. Texas, Bur. Econ. Geology Rept. of Inv. 20, 59 p.

Broadhurst, W. L., Sundstrom, R. W., and Weaver, D. E., 1949, Public water supplies in western Texas: Texas Board Water Engineers duplicated rept., 277 p.

______1951, Public water supplies in western Texas: U.S. Geol. Survey Water-Supply Paper 1106, 168 p.

Cronin, J. G., 1961, A summary of the occurrence and development of ground water in the Southern High Plains of Texas: Texas Board Water Engineers Bull. 6107, 110 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.

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, 163 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.

Evans, G. L., and Meade, G. E., 1945, Quaternary of the Texas High Plains *in* Contributions to geology, 1944: Univ. Texas Pub. 4401, p. 485-507.

Fenneman, N. M., 1931, Physiography of the western United States: New York, McGraw-Hill Book Co., 534 p.

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, 79 p.

Frye, J. C., 1970, The Ogallala Formation—a review: Ogallala Aquifer Symposium, Texas Tech Univ., Lubbock, Texas, 1970, Proc., p. 5-14.

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, Bur. Econ. Geology Rept. of Inv. 32, 62 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, 120 p.

Gillett, P. T., and Janca, I. G., 1965, Inventory of Texas irrigation, 1958 and 1964: Texas Water Comm. Bull. 6515, 317 p.

Gould, C. N., 1906, The geology and water resources of the eastern portion of the Panhandle of Texas: U.S. Geol. Survey Water-Supply Paper 154, 64 p.

______1907, The geology and water resources of the western portion of the Panhandle of Texas: U.S. Geol. Survey Water-Supply Paper 191, 70 p.

Grubb, H. W., 1966, Importance of irrigation water to the economy of the Texas High Plains: Texas Water Devel. Board Rept. 11, 53 p.

Haragan, D. R., 1970, An investigation of clouds and precipitation for the Texas High Plains: Texas Water Devel. Board Rept. 111, 125 p.

Havens, J. S., 1966, Recharge studies on the High Plains in Northern Lea County, New Mexico: U.S. Geol. Survey Water-Supply Paper 1819-F, 52 p.

Hughes, W. F., and Harman, W. L., 1969, Project economic life of water resources, Subdivision no. 1, High Plains underground water reservoir: Texas A&M Univ. Tech. Mon. 6, 82 p.

Lang, J. W., and Twichell, Trigg, 1945, Water resources of the Lubbock district, Texas: Texas Board Water Engineers duplicated rept., 168 p.

Leggat, E. R., 1952, Geology and ground-water resources of Lynn County, Texas: Texas Board Water Engineers Bull. 5207, 76 p.

_____1954a, Summary of ground-water development in the Southern High Plains, Texas: Texas Board Water Engineers Bull. 5402, 21 p.

_____1954b, Ground-water development in the Southern High Plains of Texas, 1953: Texas Board Water Engineers Bull. 5410, 7 p.

_____1957, Geology and ground-water resources of Lamb County, Texas: Texas Board Water Engineers Bull. 5704, 187 p.

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

Luckey, R. R., and Hofstra, W. E., 1974, Digital model of the Ogallala aquifer of the northern part of the Northern High Plains of Colorado: Colorado Water Conservation Board, Colorado Water Resources Circ. No. 24, 22 p.

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, progress report no. 2: Texas Water Comm. Bull. 6402, 30 p.

Moulder, E. A., and Frazor, D. R., 1957, Artificial-recharge experiments at McDonald well field, Amarillo, Texas: Texas Board Water Engineers Bull. 5701, 34 p.

Myers, B. N., 1969, Compilation of results of aquifer tests in Texas: Texas Water Devel. Board Rept. 98, 537 p.

New, Leon, 1968, High Plains irrigation survey: Texas A&M Univ. Ext. Service duplicated rept., 14 p.

_____1969, High Plains irrigation survey: Texas A&M Univ. Ext. Service duplicated rept., 14 p.

_____1970, High Plains irrigation survey: Texas A&M Univ. Ext. Service duplicated rept., 10 p.

_____1971, High Plains irrigation survey: Texas A&M Univ. Ext. Service duplicated rept., 16 p.

_____1972, High Plains irrigation survey: Texas A&M Univ. Ext. Service duplicated rept., 18 p.

_____1973, High Plains irrigation survey: Texas A&M Univ. Ext. Service duplicated rept., 16 p.

_____1974, High Plains irrigation survey: Texas A&M Univ. Ext. Service duplicated rept., 18 p.

North Plains Ground Water Conservation District No. 2, 1966, Geology and ground-water resources of the North Plains Ground Water Conservation District No. 2: North Plains Ground Water Conservation District No. 2, progress rept. no. 2, 49 p.

_____1970, Geology and ground-water resources of the North Plains Ground Water Conservation District: North Plains Ground Water Conservation District No. 2, progress rept. no. 3, 35 p.

_____1973, Geology and ground-water resources of Lipscomb County, Texas: North Plains Ground Water Conservation District No. 2, 31 p.

Osborn, J. E., Harris, T. R., and Owens, T. R., 1974, Impact of ground water and petroleum on the economy of the Texas High Plains: Texas Tech Univ., Dept. Agr. Econ., 87 p.

Rayner, F. A., 1965, The ground-water supplies of the Southern High Plains of Texas: Proc. 3rd West Texas Water Conf., Texas Tech Coll., p. 20-42.

_____1973, Taking a new look at the demise of the Ogallala aquifer: Testimony presented to West Texas Citizens Advisory Council on Water Resources public hearing, Lubbock, Texas, Oct. 3, 1973, 16 p.

Rettman, P. L., and Leggat, E. R., 1966, Ground-water resources of Gaines County, Texas: Texas Water Devel. Board Rept. 15, 186 p.

Schwiesow, W. F., 1965, Playa lake use and modification in the High Plains, *in* Studies of playa lakes in the High Plains of Texas: Texas Water Devel. Board Rept. 10, p. 1-8.

Sherrill, D. W., 1958, High Plains irrigation survey: Texas A&M Coll. Ext. Service duplicated rept., 10 p.

_____1959, High Plains irrigation survey: Texas A&M Coll. Ext. Service duplicated rept., 10 p.

Smith, J. T., 1973, Ground-water resources of Motley and northeastern Floyd Counties, Texas: Texas Water Devel. Board Rept. 165, 8 p.

Swann, T., 1974, Texas High Plains facts: Lubbock, Water, Inc., 10 p.

Texas Board Water Engineers, 1960, Reconnaissance investigation of the ground-water resources of the Canadian River basin, Texas: Texas Board Water Engineers Bull. 6016, 33 p.

Texas Water Development Board, 1971, Inventories of irrigation in Texas, 1958, 1964, and 1969: Texas Water Devel. Board Rept. 127, 232 p.

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

Thurmond, R. V., 1951, High Plains irrigation survey: Texas A&M Coll. Ext. Service duplicated rept., 4 p.

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.

Wyatt, A. W., 1968, Progress report no. 1, A general discussion accompanied by hydrological maps pertaining to the ground-water resources in the South Plains Underground Water Conservation District No. 4: South Plains Underground Water Conservation District No. 4, 24 p.

_____1975, TWDB High Plains study shows 340 million acre-feet of water in 45-county area, *in* Water for Texas: Texas Water Devel. Board pub., V. 5, no. 1 and 2, p. 20-22.

Wyatt, A. W., and others, 1970, Water-level data from observation wells in the Southern High Plains of Texas, 1965-70: 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.