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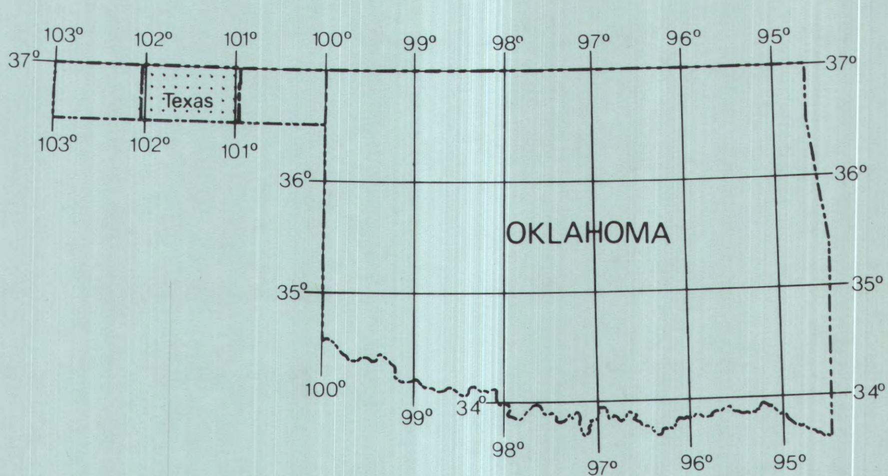
DIGITAL-MODEL PROJECTION OF SATURATED THICKNESS AND RECOVERABLE WATER IN THE OGALLALA AQUIFER, TEXAS COUNTY, OKLAHOMA

U. S. GEOLOGICAL SURVEY

Open File Report 79-565



n cooperation with the

MA WATER RESOURCES BOARD

Morton—DIGITAL-MODEL STUDY OF THE OGALLALA AQUIFER, TEXAS COUNTY, OKLAHOMA—Geological Survey Open-File Report 79-565

U.S. DEPARTMENT OF THE INTERIOR
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DEPARTMENT OF THE INTERIOR
GEOLOGICAL SURVEY

DIGITAL-MODEL PROJECTION OF SATURATED THICKNESS AND RECOVERABLE WATER IN THE OGALLALA AQUIFER, TEXAS COUNTY, OKLAHOMA

By Robert B. Morton

Open File Report 79-565

Prepared in cooperation with the
OKLAHOMA WATER RESOURCES BOARD

Oklahoma City, Oklahoma
January, 1980

UNITED STATES DEPARTMENT OF THE INTERIOR
CECIL D. ANRUS, Secretary

GEOLOGICAL SURVEY
H. W. Menard, Director

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ILLUSTRATIONS

Plates in pocket:

SELECTED FACTORS FOR CONVERTING INCH-POUND UNITS TO INTERNATIONAL SYSTEM (SI) UNITS

Inch-Pound units used in this report may be converted to SI (metric) units by the following conversion factors:

Inch-Pound	Multiply by	Metric
in. (inch)	25.40	mm (millimeter)
in./yr (inch per year)	.0000008054	mm/s (millimeter per second)
ft (foot)	.3048	m (meter)
mi (mile)	1.609	km (kilometer)
mi^2 (square mile)	2.590	km^2 (square kilometer)
acre	.004047	km^2 (square kilometer)
acre-ft (acre-foot)	1,233	m^3 (cubic meter)
(acre-ft/acre)/yr(acre-foot per acre per year)	4.98995	(m^3/km^2)/yr (cubic meter per square kilometer per year)
ft/mi (foot per mile)	.1894	m/km (meter per kilometer)
ft^2/s (square foot per second)	.09290	m^2/s(square meter per second)
ft^3/s (cubic foot per second)	.02832	m^3/s (cubic meter per second)
ft/d (foot per day)	.000003528	m/s (meter per second)
gal/min (gallon per minute)	.06309	l/s (liter per second)
(gal/min)/ft (gallon per minute per foot)	.207	(l/s)/m (liter per second per meter)

Glossary of Technical Terms

(The following definitions are from Lohman and others, 1972, Lohman, 1972, and Gary and others, 1972, except the boundary definitions which are the author's)

Aquifer.--An aquifer is a formation, group of formations, or part of a formation that contains sufficient saturated permeable material to yield significant quantities of water to wells and springs.

Boundary, hydrologic.--Surfaces bounding a three-dimensional body of ground-water and characterized by any of several physical conditions which have a limiting effect on the flow of water in the aquifer. Two physical boundary conditions are as follows:

1. Constant head, h(L). A condition in which the head, as subsequently defined in the glossary, is a constant value.
2. Constant flux, (L^3). A condition in which the input or withdrawal of water at a point, on a line or through a specified surface area, is a constant amount which may be a finite value, or zero in the case of an impermeable (no-flow) condition.

Conductivity, hydraulic, $K(LT^{-1})$.--If a porous medium is isotropic and the fluid is homogeneous, the hydraulic conductivity of the medium is the volume of water at the existing kinematic viscosity that will move in unit time under a unit hydraulic gradient through a unit area measured at right angles to the direction of flow.

Ground water, confined.--Confined ground water is under pressure significantly greater than atmospheric, and its upper limit is the bottom of a bed of distinctly lower hydraulic conductivity than that of the material in which the confined water occurs.

Ground water, unconfined.--Unconfined ground water is water in an aquifer that has a water table.

Hydraulic gradient (dimensionless).--The hydraulic gradient is the change in static head per unit of distance in a given direction. If not specified, the direction generally is understood to be that of the maximum rate of decrease in head.

Head, static, h(L).--The static head is the height above a standard datum of the surface of a column of water (or other liquid) that can be supported by the static pressure at a given point.

Homogeneity.--Homogeneity is synonymous with uniformity. A material is homogeneous if its hydrologic properties are identical everywhere. Although no known aquifer is homogeneous in detail, models based upon the assumption of homogeneity have been shown empirically to be valuable tools for predicting the approximate relationship between discharge and potential in many aquifers.

Isotropy.--Isotropy is that condition in which all significant properties are independent of direction. Although no aquifers are isotropic in detail, models based upon the assumption of isotropy have been shown to be valuable tools for predicting the approximate relationship between discharge and potential in many aquifers.

Phreatophyte.--A plant that obtains its water supply from the zone of saturation or through the capillary fringe and is characterized by a deep root system.

Potentiometric surface.--The potentiometric surface is a surface which represents the static head. As related to an aquifer, it is defined by the levels to which water will rise in tightly cased wells. The water table is a particular potentiometric surface.

Return flow.--Irrigation water not consumed by evapotranspiration but returned to its source or to another body of ground or surface water.

Specific capacity (L^2T^{-1}).--The specific capacity of a well is the rate of discharge of water from the well divided by the drawdown of water level within the well.

Specific yield, S_y (dimensionless).--The specific yield of a rock or soil is the ratio of (1) the volume of water which the rock or soil, after being saturated, will yield by gravity to (2) the volume of the rock or soil. The definition implies that gravity drainage is complete.

Steady-state flow.--In steady-state flow, as of ground water through permeable material, there is no change in head with time.

Storage coefficient, S (dimensionless).--The storage coefficient is the volume of water an aquifer releases from or takes into storage per unit surface area of the aquifer per unit change in head.

Stream, gaining.--A gaining stream is a stream or reach of a stream whose flow is being increased by inflow of ground water.

Transmissivity, T (L^2T^{-1}).--Transmissivity is the rate at which water of the prevailing kinematic viscosity is transmitted through a unit width of the aquifer under a unit hydraulic gradient.

Water table.--The water table is that surface in an unconfined water body at which the pressure is atmospheric. It is defined by the levels at which water stands in wells that penetrate the water body just far enough to hold standing water. In wells which penetrate to greater depths, the water level will stand above or below the water table if an upward or downward component of ground-water flow exists.

Digital-Model Prediction of Saturated Thickness and Recoverable Water in the Ogallala Aquifer, Texas County, Oklahoma

Abstract

A digital model was used to provide a quantitative description of the Ogallala aquifer in Texas County, Oklahoma, and to predict saturated thickness and water in storage from the aquifer at specified future times. The Ogallala aquifer, which consists of unconsolidated sand, gravel, and clay, is the principal source of ground water in Texas County. Saturated thickness ranged from 0 feet to over 600 feet. The estimated value used for specific yield in most of the areas was 0.15 but 0.05 was used in some places. Hydraulic conductivity ranged from 0 to more than 200 feet per day, and recharge ranged from 0.2 to 2.2 inches per year.

Irrigation pumpage was estimated using crop acreage and estimate of irrigation requirements. For projection simulations with large stress, a reasonable maximum stress using a minimum of 4 wells per square mile and 1972 pumping rate per well, if saturated thickness was more than 38 feet, was used.

Four types of boundaries were used in the model. They are:

1. A zero-flux (impermeable) boundary on the perimeter of the modeled area.
2. A constant-head boundary for a reach of the Cimarron River.
3. A boundary which is a constant-head boundary initially but converts to an impermeable boundary (depending on the potentiometric gradient at the boundary) for a reach of Beaver River, Palo Duro Creek, and south of Palo Duro Creek.
4. A boundary which is a partially penetrating stream with leaky-stream bed for parts of Beaver River and Coldwater Creek.

The base period for calibration was 1966. The model was calibrated by a simulation from 1966 to 1968 in which pumpage was modified until the 1968 calculated heads matched closely the 1968 observed heads. The model was verified by a simulation from 1966 to 1972, using the 1966 to 1972 pumpage stress, in order to determine the degree of conformity between 1972 calculated heads and 1972 observed heads. The agreement was acceptable.

A total of 6 projection tests were made, each with a simulation period beginning in 1972. Test 1 was a simulation to 1973, made at the request of the Oklahoma Water Resources Board in order to provide data for use in the application of Oklahoma's ground-water law, to determine 1973 saturated thickness using 1972 well distribution and pumping rates. Based on test 1, calculations show that water in storage in the aquifer was approximately 39.70 million acre-feet. Test 2 was a projection to 1993 using the 1972 stress and well distribution to determine saturated thickness. The test showed that approximately 32.60 million acre-feet of water will be in storage at the end of 1993. Test 3 assumed a reasonable maximum stress using a minimum of 4 wells per square mile and 1972 pumpage rate per well and a projection was made to 1993 to determine saturated thickness. Approximately 14.75 million acre-feet of water in storage was projected for the aquifer after this amount of stress. Test 4 was a continuation of test 3 to the year 2013. The test indicated the remaining saturated thickness would include approximately 10.50 million acre-feet of water in storage. Test 5 was a continuation of the test 3 stress to the year 2050. The projection to 2050 showed 35 percent of the 1973 irrigated acreage overlying the Ogallala aquifer will have a saturated thickness of 15 feet or less and approximately 7.85 million acre-feet, or 20 percent, of water in storage in 1972 will remain in the aquifer.

Test 6 was made at the request of the Oklahoma Water Resources Board in order to provide data for use in the application of Oklahoma's ground-water law. A simulation was made to 1993 to determine the pumpage necessary to reduce the saturated thickness to 15 feet, or less, for one-half the acreage overlying the saturated part of the Ogallala aquifer in 1973, with the assumption that the initial pumping rate is equal for all of the approximately 1,255,600 acres having more than 15 feet of saturated thickness on July 1, 1973, and that on the same date each irrigator having more than 15 ft of saturated thickness is entitled to an equal proportionate share per acre of the ground water in that part of the Ogallala aquifer within Texas County. The initial pumping rate was 5 acre-feet/acre/year. The average pumping rate for 20 years, the minimum life of the "basin", was 1.67 acre-feet/acre/year. The lower average pumping rate was the result of decreased transmissivity as the saturated thickness was reduced. Approximately 3.20 million acre-feet of water in storage was projected for the aquifer at the end of 1993 under these conditions.

SUMMARY OF INFORMATION REQUIRED TO MEET OKLAHOMA GROUND-WATER LAW

In order to provide equitable distribution of the State's ground water, the Oklahoma legislature passed certain laws on water and water rights which became effective July 1, 1973, and which are administered by the Oklahoma Water Resources Board. As required by law (82 Oklahoma Statutes Supp. 1973, paragraph 1020.1 et seq.), determination of the maximum annual yield of each ground water basin for a minimum 20-year life must be based upon the following:

1. The total land area overlying the basin or subbasin.
2. The amount of water in storage in the basin or subbasin.
3. The rate of natural recharge to the basin or subbasin and total discharge from the basin or subbasin.
4. Transmissibility of the basin or subbasin.
5. The possiblity of pollution of the basin or subbasin from natural sources.

According to determinations made by the Oklahoma Water Resources Board, the total amount of ground water established under prior rights is 353,075 acre-ft per year and the total amount of land covered by prior rights is 214,974 acres.

Based upon the report by Hart, Hoffman, and Goemaat (1976) and this study, the following determinations were made:

1. The total land area overlying the basin is 1,255,600 acres. Ground-water basin by Oklahoma law means a distinct underground body of water overlain by contiguous land and having substantially the same geological and hydrological characteristics and yield capacities. As used in this report, "basin" refers to that part of the Ogallala aquifer in Texas County that has a saturated thickness of more than 15 ft as of July 1, 1973.
2. The amount of water in storage in the "basin" was approximately 39.70 million acre-ft as of July 1, 1973.

3. The rate of natural recharge to the "basin" ranged from 0.2 to 2.2 in./yr and averaged .44 in./yr. Total discharge at the end of test 6 made for the period July 1, 1973, to July 1, 1993, was 42,037,643 acre-ft (from the cumulative mass balance) or 2,101,732 acre-ft per year which is the maximum annual yield stated by Oklahoma Statutes 1973, paragraph 1020.5 for the 20-year minimum life of the aquifer. The equal proportionate share of water from storage and natural recharge to each acre of land overlying the basin is, therefore, 1.67 acre-ft/acre/year. The determination of 1.67 acre-ft/acre/year was based on computer simulation of all prior appropriative and subsequent allocated pumping for twenty years (July 1, 1973 to July 1, 1993). Return flow of irrigation water, which is estimated at 20 percent of applied water, is treated in the model as a deduction from pumpage. If the estimated 20 percent return flow is added to the value of 1.67 acre-ft/acre/year, the total equal proportionate share from storage, recharge, and return flow is 2.09 acre-ft/acre/year. If return flow is estimated at 25 percent, the total equal proportionate share is 2.23 acre-ft/acre/year; if a value of 30 percent is used the total equal proportionate share is 2.39 acre-ft/acre/year.
4. The 1973 transmissivity of the "basin" ranged from less than 0.1 to 1.1 ft^2/s.
5. The digital model used in this study was not designed to model mass transport in a ground-water flow system; therefore, the possibility of pollution of the "basin" from natural sources cannot be determined from the model results. However, excessive local pumpage for irrigation may lower the head sufficiently in the Ogallala aquifer to induce upward migration of water high in dissolved solids from Permian-age rocks below and adjacent to the Ogallala aquifer. Pollution caused in this manner probably would be of limited extent.

INTRODUCTION

Background

Beginning in the mid-1960's, the use of water from the Ogallala aquifer for irrigation in Texas County, Oklahoma (figure 1) increased sharply. Ground-water withdrawal rates in several large areas exceed the recharge rate as shown by water-table declines in wells. The water table during the period 1966 to 1972 has declined at the rate of 1 to 7 ft/yr in the Guymon area and in an area in northwestern Texas County (Hart and others, 1976).

Purpose and Scope

This study was undertaken in cooperation with the Oklahoma Water Resources Board, because of water-table declines and the need by ground-water managers to know the ground-water reserves in the Ogallala aquifer. The report provides a quantitative description of the Ogallala aquifer, and projects saturated thickness and the amount of water in storage in the aquifer at specified future times under assumed rates and distribution of ground-water withdrawal. The study is focused on Texas County; however, the effects of pumping for irrigation outside the county are taken into account. Thus, the modeled area includes approximately 60 mi on all sides of Texas County.

Location and General Description of Texas County

Texas County is the middle county of the three counties comprising the Oklahoma Panhandle in the northwestern part of the state. It extends 60 miles east to west, about 34.5 mi north to south, and covers about 2,062 mi^2. Texas County is part of the High Plains section of the Great Plains physiographic province. About three-fourths of the county consists of comparatively flat and undissected upland plains and about one-fourth flood plains and "breaks". The upland plain slopes southeastward from an altitude of about 3,700 ft in the northwest corner of the county to about 2,750 ft north of Beaver River along the east central boundary. The estimated average slope is 18 ft/mi southeastward.

The Beaver River and seven principal tributaries drain the county. The Beaver River downstream from Guymon is a gaining stream during most of the year. Coldwater and Palo Duro Creeks, tributaries in the south-eastern part of the county, are gaining streams most of the year in the lower reaches before joining Beaver River. The valleys of the main streams range from 1 to 4 mi in width, and from about 100 to 200 ft below the uplands.

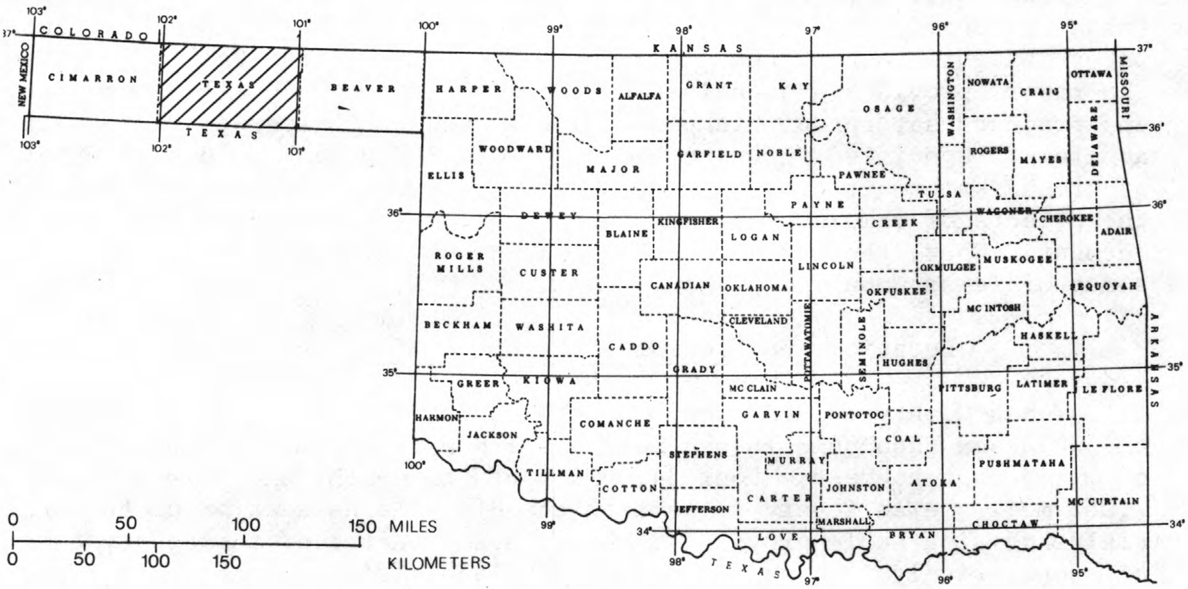

Figure 1.– Index map of Oklahoma showing the location of Texas County.

Except where cultivated, the upland areas support a suite of native grasses. Trees are scarce; however, a few cottonwoods, salt cedars, or other phreatophytes occur, especially along stream courses. Historically the two principal crops grown are sorghum and small grain, mostly wheat. However, in recent years with the increase of feed lots, corn acreage has equaled or exceeded either of the other two crops.

The average annual temperature is about 56°F (13.3°C) and the average annual precipitation in the county is about 17.5 in. Most of the precipitation occurs as rain during severe thunderstorms from May to August.

Previous Studies

Several studies have been made of the geology and ground-water resources of Texas County. Stuart L. Schoff (1939) was the first to report on Texas County and later was followed by Wood and Hart (1967) who published a reconnaissance-type atlas of water availability and water quality. Subsequent studies have included the other two Panhandle counties. Two of the later studies reported on hydrologic and geologic data in formations older than the Ogallala Formation, and are by Irwin and Morton (1969), and by Morton (1973). The latest is a quantitative study of the Ogallala Formation by Hart, Hoffman, and Goemaat (1976).

Additional reports covering the geology and ground-water resources of the Oklahoma Panhandle and adjoining areas are listed in the selected references.

Acknowledgments

The personnel at several of the state and county offices were most helpful in providing data used in preparing this report; included are the Oklahoma Water Resources Board, Texas County Tax Assessor, Panhandle State College, Oklahoma State University, and Texas County Extension Director.

The writer gratefully acknowledges the technical assistance given by J.S. Downey and J.E. Reed.

GEOLOGY

The geology and hydrology of Texas County and adjacent areas have been described in varying detail in earlier reports to which the reader is referred for more comprehensive information (see section on Previous Studies). The Ogallala Formation of late Tertiary age is the major aquifer and extends over most of the county. It unconformably overlies the bedrock which includes rocks of Permian, Triassic, and Jurassic age. Limited exposures of bedrock occur along a few streams in the west-central and southeastern parts of the county. Unconsolidated deposits, consisting mostly of the Ogallala Formation, range in thickness from 0 ft at the bedrock outcrops to more than 700 ft in the northeastern part of the county near the Kansas line. As used in this report, the term Ogallala aquifer includes the Ogallala Formation and, where present, sedimentary rocks younger than the Tertiary (Irwin and Morton, 1969).

The Ogallala Formation consists of interbedded sand, siltstone, clay, gravel, thin limestone, and caliche. The proportions of the different rock types composing the Ogallala Formation change rapidly from place to place but sand and gravel generally predominate. Most of the gravel usually occurs near the aquifer base. Rocks of the Ogallala Formation generally are light tan, buff, or almost white, but locally may show pastel shades of almost any color. In the northeastern part of the county, the middle part of the Ogallala has changed to predominately a clay facies having an irregular pattern and a maximum thickness of more than 300 ft. The clay area coincides generally with the area of maximum thickness of the Ogallala Formation.

The maximum width of the Quaternary alluvium along Beaver River is approximately a mile and the alluvium probably does not exceed 100 ft in thickness.

A bedrock high occurs in the west-central part of Texas County (Morton, 1973); consequently, the water table is in rocks of Triassic age below the Ogallala aquifer over the crest of the high.

Deep, hardland soils cover much of Texas County but locally deep, loamy or sandy soils occur especially in the northeast part of the county (Meinders and others, 1961). The topography generally is flat to very gently rolling and poorly dissected except for the "breaks" along the Beaver River and its principal tributaries.

POLLUTION FROM NATURAL SOURCES

In order to provide data for use in application of Oklahoma's ground-water law (82 Oklahoma Statutes Supp. 1973) the Oklahoma Water Resources Board requested that this report include an appraisal of pollution from natural sources. The digital model used in this study and described beginning on page 9, does not provide for the modeling of mass transport in a ground-water flow system; therefore, variations in the chemical quality of water from the Ogallala aquifer in time or space is not a part of this study.

Water in the Ogallala aquifer is generally uniform in quality, is acceptable for most local uses, and generally is rated good for irrigation. However, a local sharp increase in the dissolved mineral content of the water in the Ogallala aquifer occurs in extreme eastern and southeastern Texas County (Irwin and Morton, 1969; Hart, Hoffman, and Goemaat, 1976). Large withdrawal for irrigation locally, especially in areas of low transmissivity, may lower the head sufficiently in the Ogallala aquifer to induce upward migration of water high in dissolved solids, especially sodium chloride, from Permian rocks below and adjacent to the Ogallala aquifer.

HYDROLOGY

Hydraulic Conductivity and Specific Yield

Hydraulic conductivity values for Texas County used at the start of the model study were calculated by Hart, Hoffman, and Goemaat (1976) from transmissivity (figure 2) determined from aquifer tests and saturated thickness. Saturated thickness, ranging from 0 ft to more than 600 ft, was determined by subtracting bedrock altitide from water-table altitude. Hydraulic conductivity was calculated by dividing transmissivity by the saturated thickness. As shown in figure 3, hydraulic conductivity values used in this study range generally from 0 to more than 200 ft/d. The range of hydraulic conductivity values used outside the county is about the same as that for Texas County.

The estimated value for specific yield (figure 4) in most of the Texas County area is 0.15 (Moulder and Frazier, 1957; Cronin, 1964; Boettcher, 1966; Jones and Schneider, 1970); however, where geologic information indicates significant amounts of clay, shale, or siltstone in the aquifer, values as low as 0.05 were used for specific yield. The foregoing statements apply generally to specific yield in the areas surrounding Texas County; however, values as low as 0.01 were used in parts of Morton County, Kansas, and 0.005 was used in the extreme south-eastern part of Baca County, Colorado, and the extreme northeastern part of Cimarron County, Oklahoma.

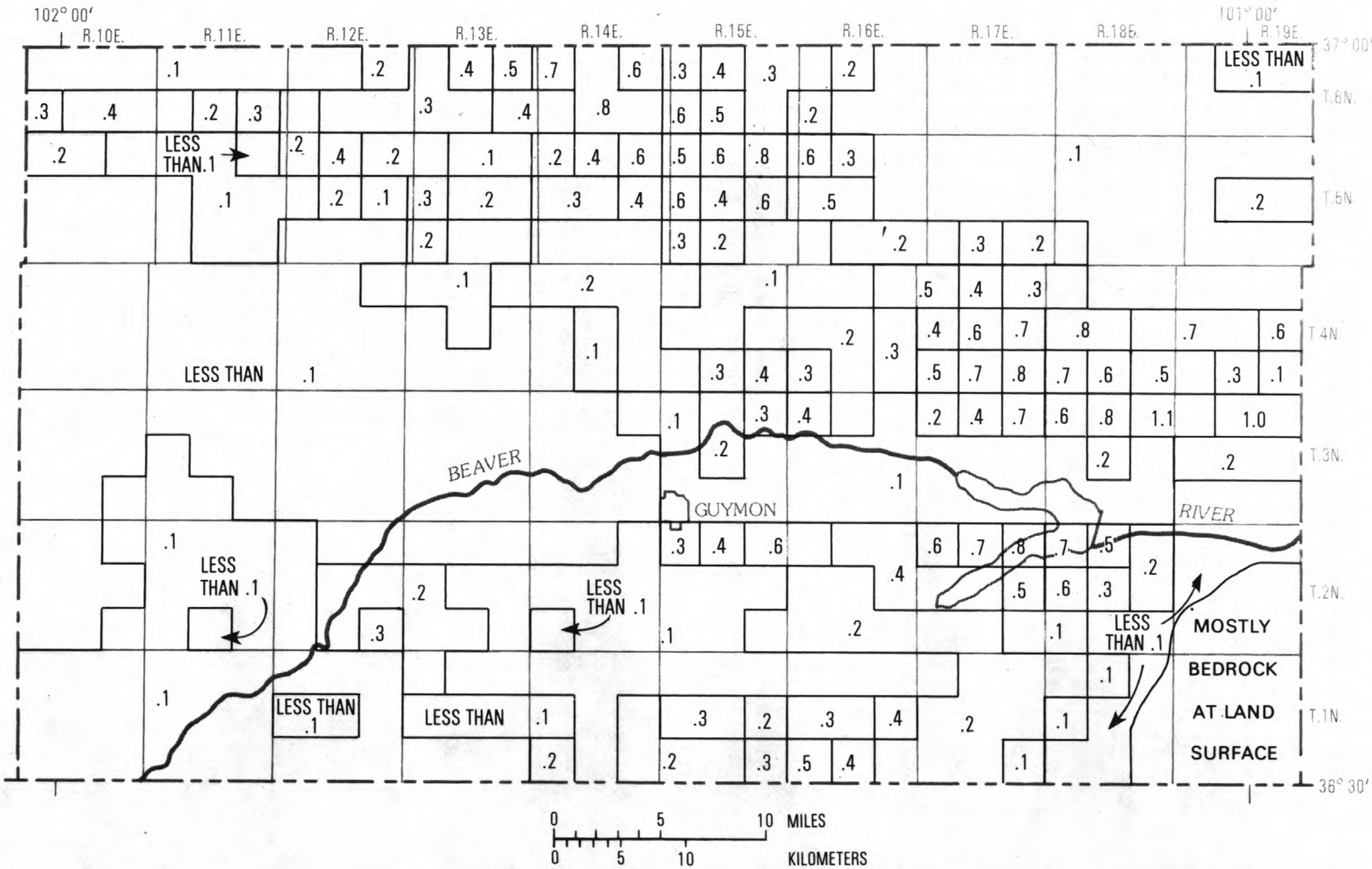

Figure 2.– Transmissivity, 1973, in square feet per second, Ogallala Aquifer, Texas County, Oklahoma.

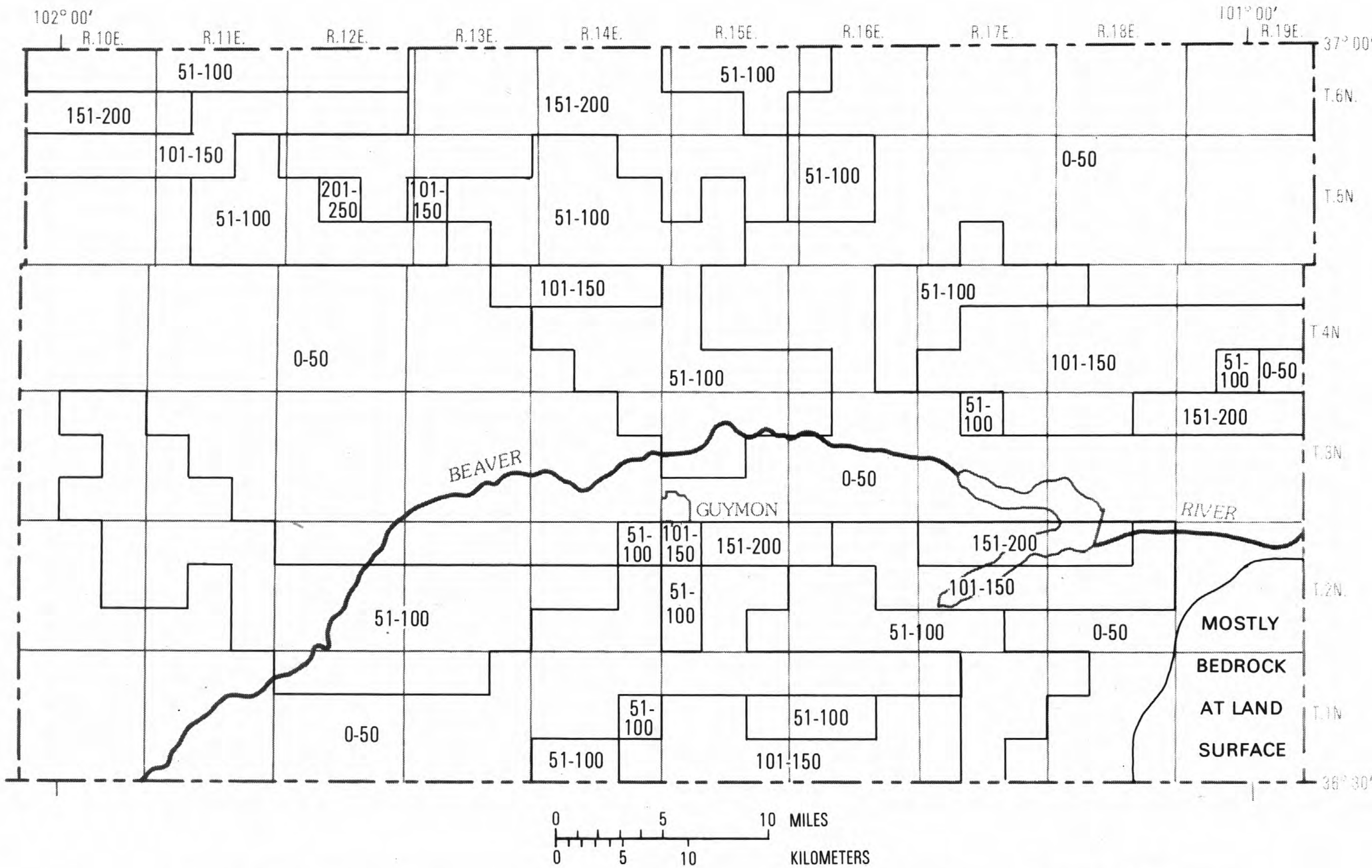

Figure 3.–Hydraulic conductivity, in feet per day, Ogallala Aquifer, Texas County, Oklahoma.

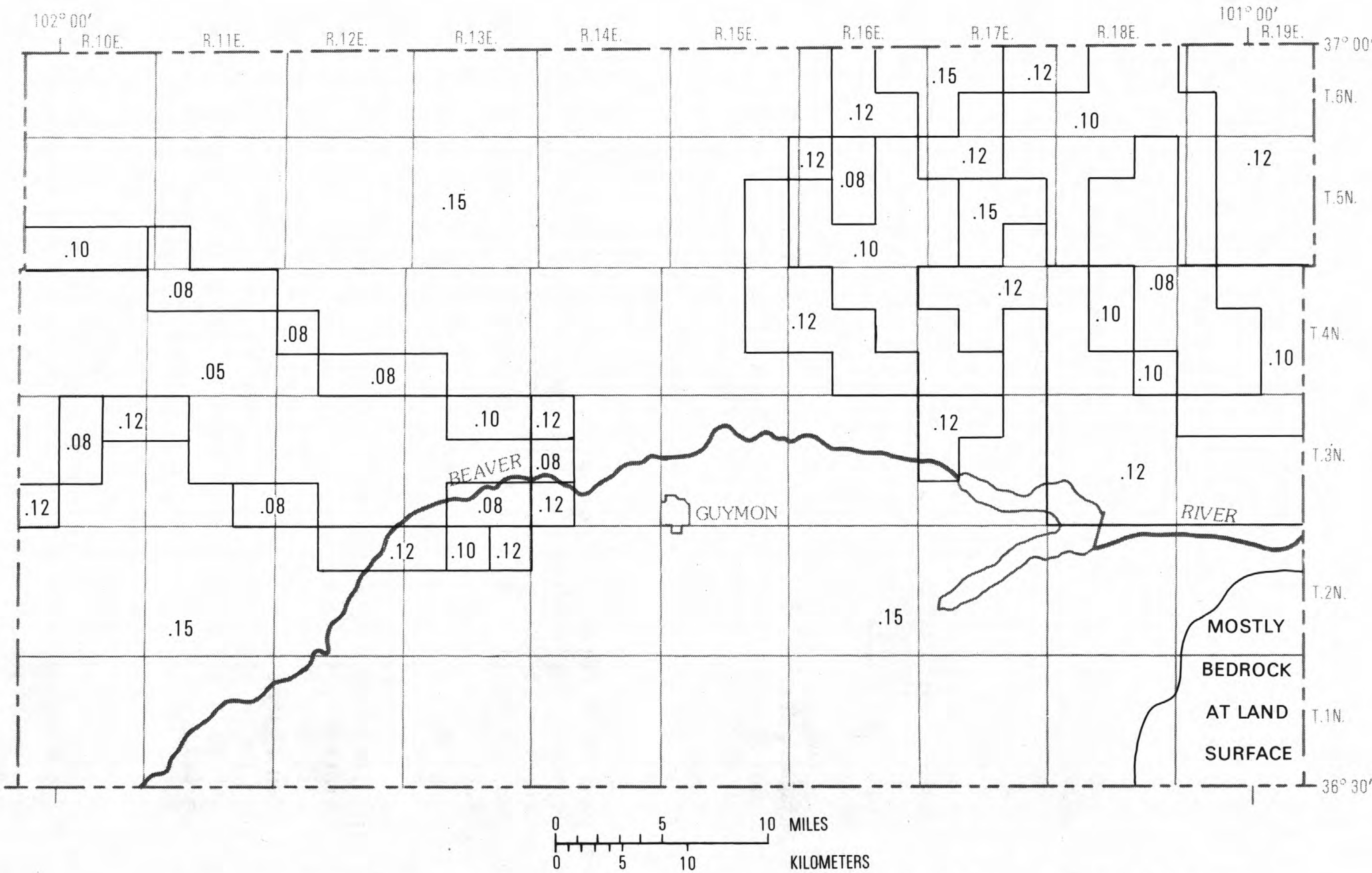

Figure 4.– Estimated specific yield, dimentionless, Ogallala Aquifer, Texas County, Oklahoma.

Ground-Water Flow System

Recharge to the Ogallala aquifer, as shown in figure 5, is very low, mostly because of the small amount of precipitation. The average annual recharge probably is less than 1 in. in Texas County (Schoff, S.L., 1939). However, recharge in the county is variable and the recharge values used for Texas County were based, in part, on soil types as previously described in the section on geology. Recharge is greatest in areas of sandy or loamy soils and least in areas of hardland soils. Thus relative recharge rates are based on soil permeability. Recharge values used were determined during steady-state simulation more fully described in the section on assumptions and calibration of the model. An estimated 20 percent of irrigation water becomes recharge as return flow. Recharge values used in Texas County range from 0.2 to 2.2 in/yr but do not include return flow. Recharge values outside the county were in about the same range as those for Texas County.

Water in the Ogallala aquifer generally is unconfined, but may be confined locally depending on the geology. Generally, the hydraulic gradient is to the east-southeast at about 14 ft/mi, whereas locally, the gradient is toward Coldwater and Palo Duro Creeks and Beaver River where they become gaining streams. Coldwater Creek becomes a gaining stream in the northeast quarter of township 2 north, range 17 east. Palo Duro Creek becomes a gaining stream about 20 mi south of the Oklahoma-Texas line in Hansford County, Texas. Beaver River becomes a gaining stream at about the longitude of Guymon, Oklahoma. Discharge measurements made at a point just below the confluence of Beaver River and Coldwater Creek in March 1966, showed a base flow of 26.3 ft^3/s.

Discharge in the form of transpiration probably is insignificant because the depth to water ranges from a few feet along the principal streams to more than 250 ft in the northeastern part of the county, and the area of shallow water table along the principal streams is small.

Hart and others (1976) have shown that from 1938 to 1976 the water table in the Ogallala aquifer has declined considerably, because of pumpage, south and southwest of Guymon, Oklahoma. Maximum water-table decline in this area is more than 60 ft. Another area showing significant decline during the same period is in the northwestern part of the county where the water table, in several places, has dropped a maximum of over 40 ft as the result of irrigation pumpage. Where pumping stress on the aquifer has been absent or minimal, a water-table rise has occurred and in places, such as in the northeast part of the county, water-table rises of over 20 ft are recorded. The hydrographs in figure 6 show a decline in the water table in two wells and a rise in the water table in a third well.

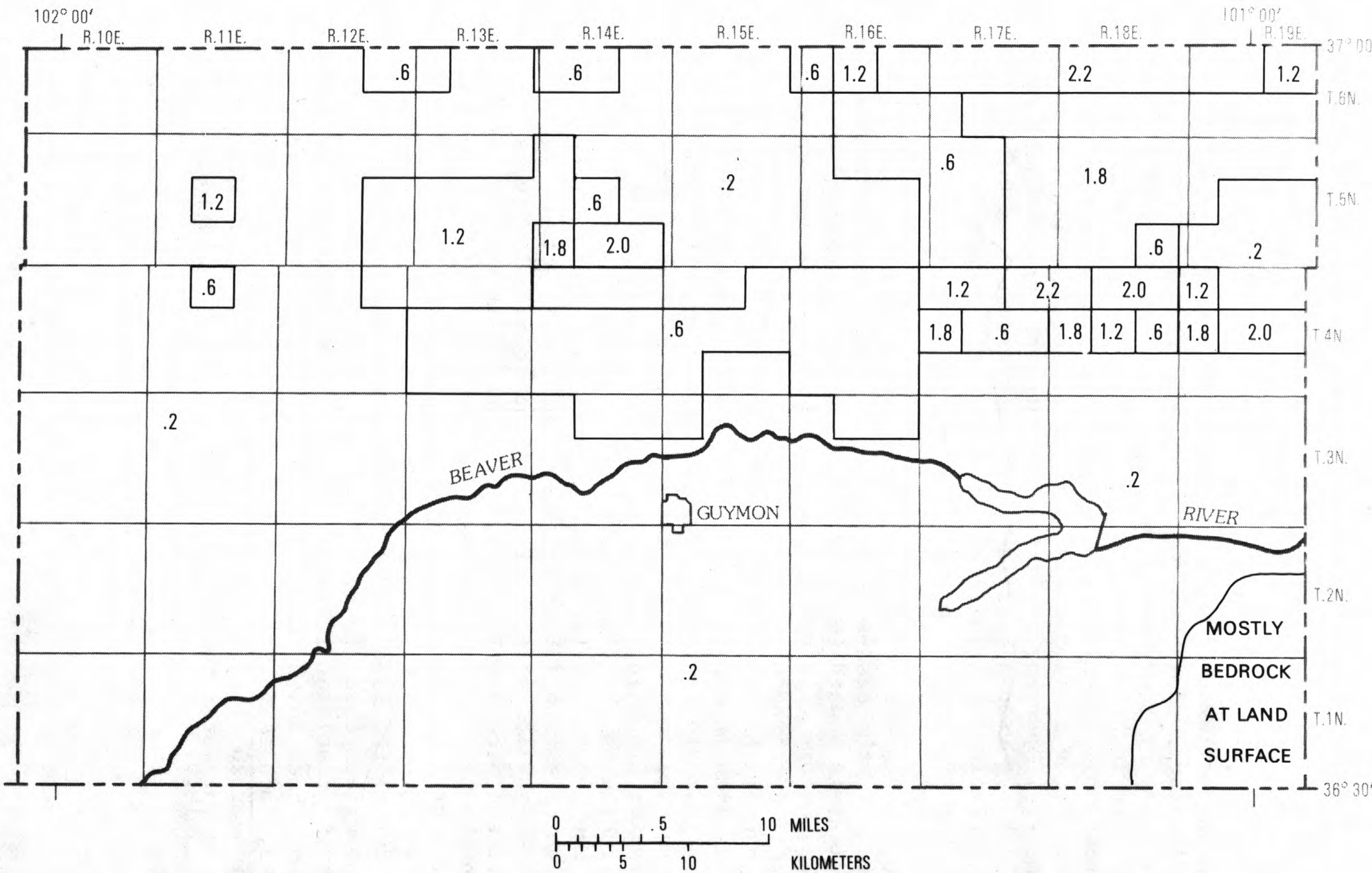

Figure 5.– Average recharge, in inches per year, to the Ogallala Aquifer, Texas County, Oklahoma.

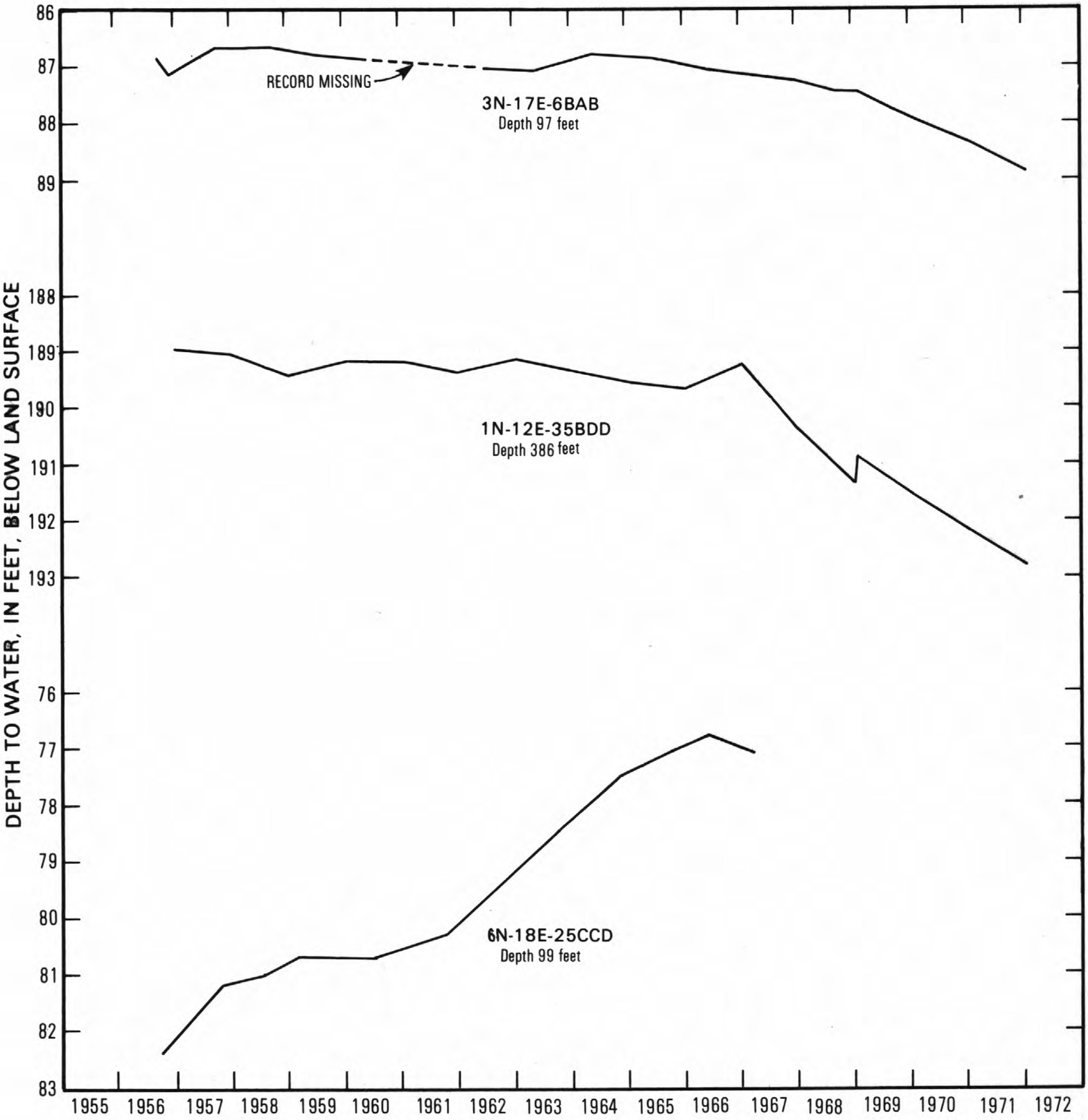

Figure 6.–Hydrographs of selected wells in the Ogallala Aquifer, Texas County, Oklahoma.

Irrigation Pumpage

Accurate records of irrigation pumpage are not available for Texas County. Consequently pumpage was estimated using crop acreage and estimate of irrigation requirements. Water need and the number of acres planted per crop each year were determined. From these data a net pumping discharge for the county was calculated. The discharge per well was determined by dividing total withdrawal for Texas County per year, minus estimated 20 percent for return flow, by the total number of large capacity wells pumped per year. The distribution of known large capacity wells is shown on plate 1. Figure 7 shows the approximate range of discharge in thousands of acre-ft per 4 mi^2 in Texas County at the end of 1972.

The amount of pumpage in the modeled areas of Kansas and the Texas Panhandle was about the same as that in Texas County; however, pumpage in Beaver County, Oklahoma, from 1965 to 1972 was about 11 percent of that in Texas County, and Cimarron County was about 41 percent (Hart, Hoffman, and Goemaat, 1976). Pumpage in Baca County, Colorado, probably was the same or slightly less than that in Cimarron County, Oklahoma.

For projection simulations with large pumping stress in Texas County a maximum stress of 1 well per 160 acres, was considered reasonable. Figure 8 shows the approximate range of discharge in ten thousands of acre-ft per 4 mi^2 per yr with a minimum of 4 wells per mi^2 pumping at 1972 rates. One 4 mi^2 area, with 19 wells in Texas County in 1972, exceeded the assumed minimum.

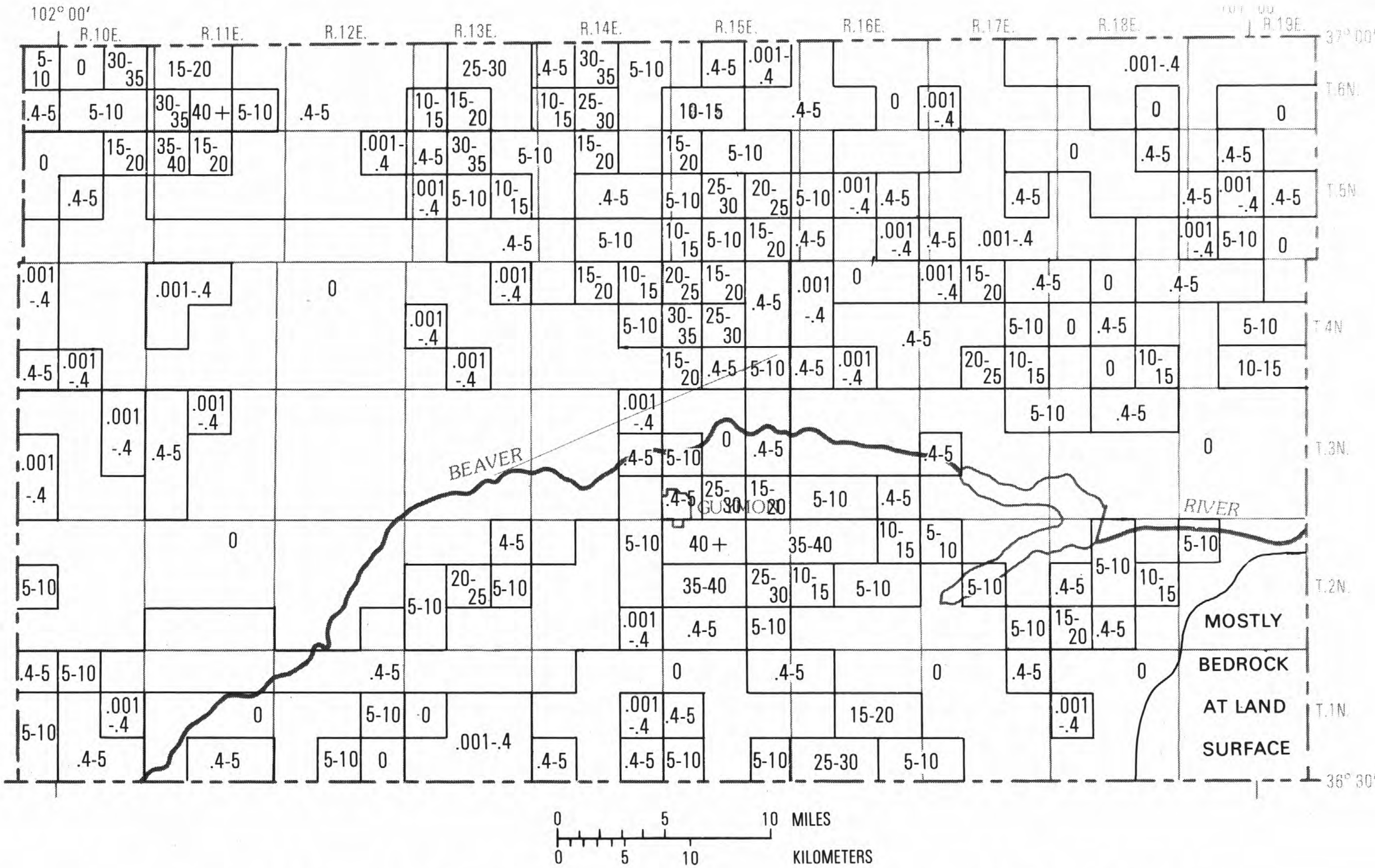

Figure 7.– Pumpage, 1972, in thousands of acre-feet per 4 square miles, Texas County, Oklahoma.

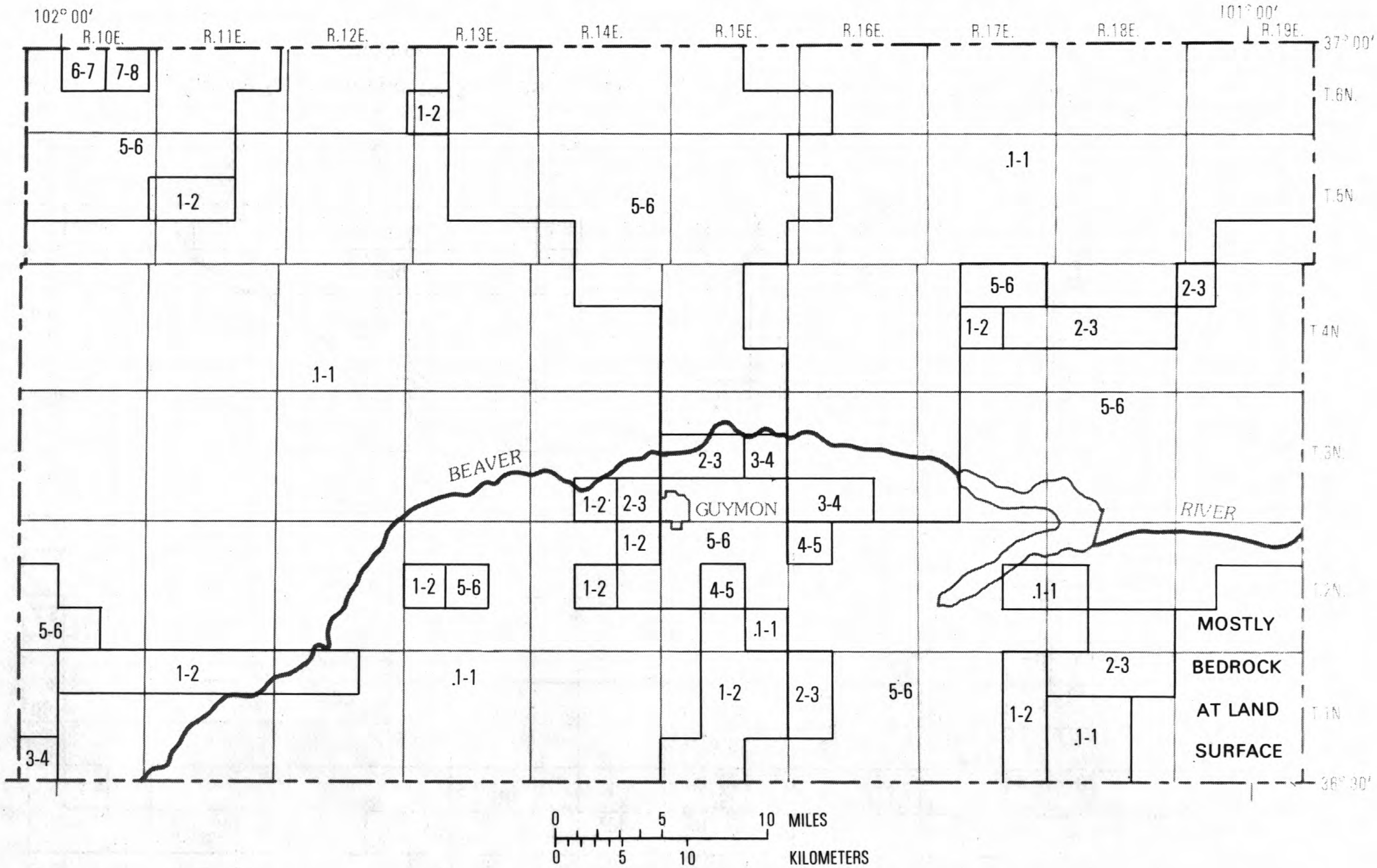

Figure 8.– Pumpage, in ten thousands of acre-feet per 4 square miles per year, based on a minimum of 4 wells per square mile pumping at 1972 pumping rates, Texas County, Oklahoma.

DESCRIPTION OF THE DIGITAL MODEL

Theory

Head changes that occur in the Ogallala aquifer with applied stress may be calculated by solution of the following partial differential equation for nonsteady flow in a nonhomogeneous porous medium (Luckey and Hofstra, 1973).

$$\frac{\partial}{\partial x}\left(T_{(x,y)}\frac{\partial h}{\partial x}\right) + \frac{\partial}{\partial y}\left(T_{(x,y)}\frac{\partial h}{\partial y}\right) = S_{(x,y)}\frac{\partial h}{\partial t} + W_{(x,y,t)}$$

where:

h = the hydraulic head (L);

$S_{(x,y)}$ = the storage coefficient (dimensionless);

t = time (T);

$T_{(x,y)}$ = the transmissivity (L^2T^{-1});

$W_{(x,y,t)}$ = the recharge or pumpage per unit area (LT^{-1});

x and y are the coordinate directions.

The equation may be approximated by a finite difference equation by applying Taylor's theorem (Pinder and Bredehoeft, 1968). The finite difference equation is solved at each node of a rectangular grid on a digital computer. For this study the flow equation was solved on a digital computer using the strongly implicit technique in the program developed by Trescott, Pinder and Larson (1976) and modified for this study as described in the section on principal modifications. The following physical conditions are assumed in the equation.

1. The Ogallala aquifer is an extensive ground-water body and is an elastic, nonhomogeneous, porous media.
2. At any given point within the aquifer, flow is two dimensional and the vertical flow component is very small in comparison to the horizontal component.
3. The aquifer is isotropic in the horizontal direction with respect to hydraulic conductivity.
4. Density of the water is constant in time and space.
5. Flow in the aquifer obeys Darcy's law.

The modeled area was divided into a large number of rectangular cells (nodes) with constant cell dimensions of 2 mi on a side in the Texas County study area. Beyond the Texas County line, the grid was expanded outward in each of the four directions. The ratio of the dimension of an added node in any of the four directions to the same dimension of an adjacent node was no greater than 1.5. The resulting finite difference grid consisted of 31 rows and 44 columns. Each cell was then assigned an appropriate value for altitude of initial head, hydraulic conductivity, altitude of base of aquifer, specific yield, storage coefficient, recharge, and discharge. Boundary conditions were entered at the appropriate nodes.

Model Boundaries

The boundaries used in the model and their locations are shown on plate 2. The head values used for constant-head boundaries were taken from the 1972 calculated potentiometric surface map. Considerable irrigation-well pumpage occurs for many miles on all sides of Texas County and affects the heads within the county. Therefore, the position of the no-flow boundary around the modeled area was determined by expanding the finite difference grid until the position of the boundary had a negligible effect on the water table within Texas County. The influence within the county of the no-flow boundary was checked by a simulation using a constant-head boundary, and the head differences in Texas County resulting from the two simulations were negligible.

Stream erosion has breached the Ogallala aquifer and bedrock is exposed at the land surface along the lower reaches of Palo Duro Creek and that part of the Beaver River east of the Texas-Beaver County line. These reaches are a physical boundary and are gaining reaches of the streams because of spring discharge from the Ogallala aquifer. The lower reaches of Palo Duro Creek and Beaver River east of the Texas-Beaver County line are modeled as a boundary that is a constant-head boundary initially, but converts to a no-flow boundary if the gradient toward the stream decreases to zero or reverses.

The south half of Beaver County, Oklahoma, and all or parts of Hansford, Ochiltree, and Lipscomb Counties, Texas, are separated hydrologically from the study area because Palo Duro Creek and Beaver River east of the Texas-Beaver County line have eroded the Ogallala aquifer and exposed the bedrock in most places. The boundary along Palo Duro Creek has been projected southward along the Hutchinson-Roberts County line where it operates as a constant-head boundary. Model runs indicate that this boundary has a negligible effect on the heads in Texas County.

The Cimarron River becomes a gaining stream approximately 16 mi north of Liberal, Kansas, in the northwestern part of Seward County. A constant-head boundary is used in the model along the course of the river from the point north of Liberal.

Rocks of Permian age underlying the Ogallala aquifer form a relatively impervious barrier to the flow of water and are considered a no-flow boundary. However, rocks of Triassic age are pervious and yield water to wells at the rate of several hundred gallons per minute. The water table, at the start of projection simulation, is in rocks of Triassic age below the Ogallala in the area of the bedrock high in the west-central part of Texas County. Consequently, as the water table declines in the area of the bedrock high, rocks of Triassic age will contribute water to the Ogallala. Therefore, a no-flow boundary was not modeled for this area.

The Beaver River, beginning at the approximate longitude of Guymon, is a gaining stream most of the year and is treated in the model as partially penetrating with a leaky-stream bed from about Guymon to the juncture with the changing boundary near the Texas-Beaver County line. Heads for 1966 were used for the reach treated as a leaky-stream bed. The area of the stream bed was less than the area of the leaky-stream bed nodes by a ratio of 1 to 10. The vertical conductivity of the confining bed was estimated at 18 ft/d. Therefore, the amount of leakage was reduced at the same ratio by using a confining bed thickness of 180 ft.

Assumptions and Calibration of the Model

The digital model used in this study is based on the following assumptions:

1. The geologic materials underlying the aquifer form a relatively impervious barrier to the flow of water except in the area where pervious rocks of Triassic age underly and are connected hydrologically with the Ogallala aquifer in the west-central part of Texas County.
2. Streams in the area are in hydraulic connection with the ground-water system downstream from the point at which they become gaining streams.
3. Recharge is constant with time.
4. Wells pumping at the beginning of the predictive phase will continue to pump at the initial rate until saturated thickness becomes less than 38 ft at which time the pumping rate progressively declines and ceases altogether when saturated thickness reaches 15 ft as described in the section on principal modifications.
5. Stress on the aquifer will not change significantly from that used in the model provided that farming practices, crop demand, and government farm policies do not deviate significantly.

The study was modeled in two phases. Phase I was a steady-state simulation of the 1966 head distribution in the Ogallala. By changing values within reasonable limits for the various input parameters such as recharge, hydraulic conductivity, the thickness of the confining bed, and the hydraulic conductivity of the confining bed, the simulation was accomplished within the accuracy of the input data available. The simulated head over most of the aquifer was within several feet of the 1966 measured head. Base flow was used in the simulation of 1966 head distribution; simulated base flow compared closely with observed flow.

Phase II initially consisted of a series of non-steady-state simulations using the data refined under phase I with the addition of estimated pumping stress for the years 1966 to 1968. Pumpage was modified until the 1968 calculated heads matched closely the 1968 observed heads as shown by comparing plates 3 and 4, respectively. Estimated pumpage was increased about 30 percent during calibration. This increase is commensurate with the degree of accuracy of the original pumping data. The final part of phase II was a non-steady-state simulation in which the aquifer was pumped from 1966 to 1972, using the 1966 to 1972 pumpage stress, in order to determine how well 1972 calculated heads agreed with 1972 observed heads. A comparison of plates 5 and 6, respectively, shows the degree of conformity. The agreement is relatively good for 1968 and 1972; therefore, the conclusion was made that the model was calibrated and verified.

Sensitivity Analysis

The digital model used in this study is similar to the models used in the Missouri River Basin Commission (1975) level B study of Stream-Aquifer Hydrology in the Platte River Basin of Nebraska. Rocks in the two study areas are Tertiary and Quaternary in age and consist generally of interbedded deposits of gravel, sand, shale and clay. Hydrologic characteristics such as specific yield, recharge, transmissivity, boundary conditions, and pumping stress also are similar in the areas. Because of the similarity of the two studies, the sensitivity analyses made by the Missouri River Basin Commission are reproduced here as figures 9, 10, and 11 showing the sensitivity of predicted water-table change to transmissivity, specific yield, and net withdrawal, respectively. According to E.G. Lappala, author of the Missouri River Basin Commission Study, (oral communication, 1978) the water-table changes shown represent an area of approximately 20 mi^2. The analyses give reasonable upper and lower limits on the accuracy of the predictive simulations. The functions are given in dimensionless form and can be used to indicate the change in predicted water-table decline that would result if the aquifer parameters were in error. For example, in figure 9, an error of +20 percent in transmissivity will cause about -5 percent error in the predicted water-table decline. By contrast, in figure 11, an error of +20 percent in net withdrawal will cause an approximate +20 percent error in the predicted water-table decline.

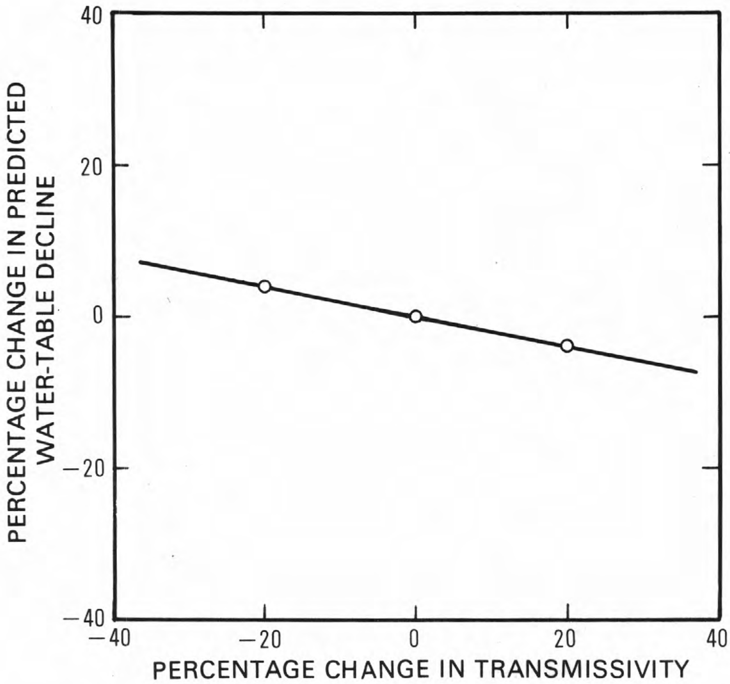

Figure 9.–Sensitivity of water-table change to transmissivity Elkhorn Subbasin, Nebraska.

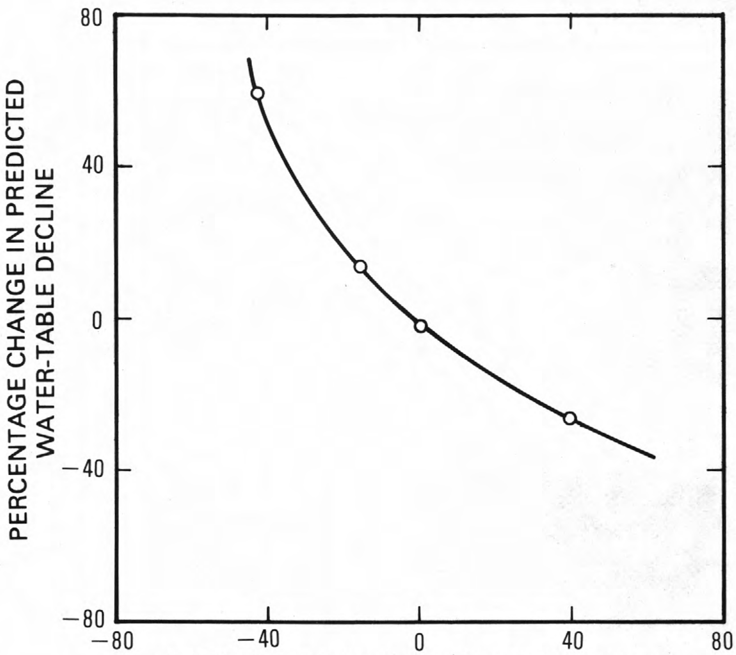

Figure 10.–Sensitivity of water-table change to specific yield, Elkhorn Subbasin, Nebraska.

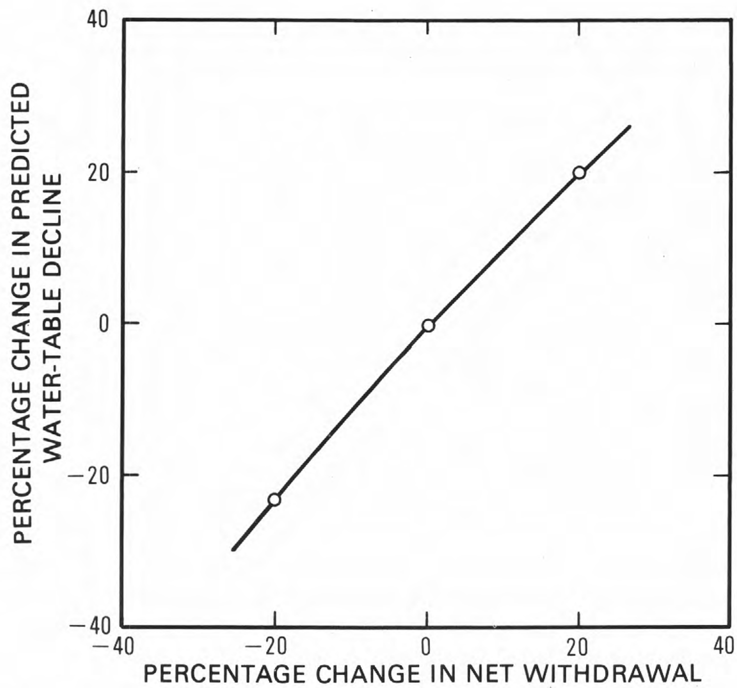

Figure 11.–Sensitivity of water–table change to net withdrawal, Elkhorn Subbasin, Nebraska.

Principal Modifications

The basic computer program was modified so that the boundary, as shown on plate 2, in the southeastern part of the area changes from a constant-head to a no-flow boundary depending on the potentiometric gradient near the boundary. When the gradient is toward the boundary the program simulates the boundary as constant head. When sufficient stress is applied to the system to cause the gradient to flatten or reverse direction the program changes this boundary to a no-flow condition.

The basic computer program also was modified to decrease pumpage depending on saturated thickness. According to James Howell, agronomist in the county agent's office of Texas County (oral communication, 1978), the minimum well yield required for a pivot-sprinkler system irrigating a 130-acre circle is approximately 650 gal/min. Hart, Hoffman, and Goemaat (1976) indicate that a minimum of about 250 gal/min are required for other forms of irrigation, and that the average specific capacity of wells in Texas County is 17 (gal/min)/ft of drawdown. Based on the ratio of the above minimum well yield limits to the specific capacity, the computer program used in this study maintains constant pumpage at a node until the saturated thickness decreases to 38 ft. From this value to a minimum saturated thickness of 15 ft, at which point pumping ceases, the pumping rate is reduced according to the following equation:

$$Q_n = Q_o \frac{(b-b_m)}{(b_c-b_m)}$$

where:

Q_n = discharge for next time step, L^3/T;

Q_o = discharge for current time step, L^3/T;

b = current saturated thickness, L;

b_m = saturated thickness below which pumpage fails, L;

b_c = saturated thickness below which pumpage declines, L.

In this study, 38 ft was used for b_c and 15 feet was used for b_m. The percentage decrease in pumpage for saturated thicknesses between 38 and 15 ft is shown graphically in figure 12. Thus, at a saturated thickness of about 26 ft, the pumpage is decreased about 50 percent. The slope of the line is based on the above data (b_c=38 ft, b_m=15 ft); different data would result in a different slope.

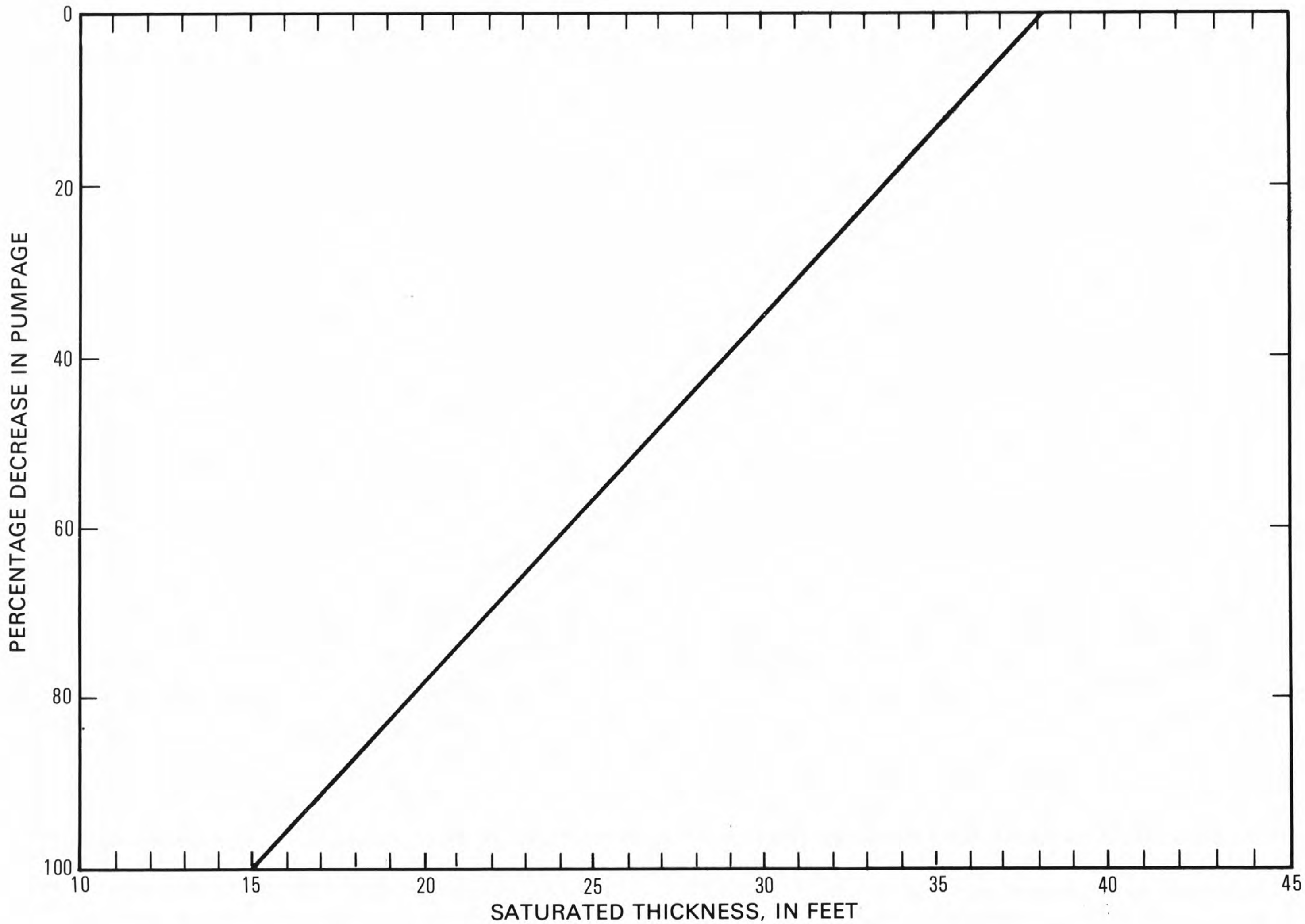

Figure 12.–Percentage decrease in pumpage as saturated thickness decreases. Based on data used in this study.

PROJECTIONS OF STRESS APPLIED TO THE AQUIFER

Predictive simulations were made for the purpose of determining saturated thickness and the amount of ground water stored in the aquifer at the end of given simulation periods. The amount of water in storage is the product of the specific yield, area of the aquifer, and the average saturated thickness. In the following tests, the beginning date for projection is 1972, and the values for head were taken from the 1972 water-table map. The 1966 water-table map was used to determine heads for leaky-stream nodes.

Test 1.--The initial projection to 1973, using 1972 well distribution and pumping rates per 4 mi^2, was made at the request of the Oklahoma Water Resources Board in order to provide data for use in the application of Oklahoma's ground-water law (82 Oklahoma Statutes Supp. 1973, paragraph 1020.1 et seq.). Calculated saturated thickness for 1973 is shown on plate 7. Approximately 39.70 million acre-ft of water will be in storage at the end of 1973.

Test 2.--A projection to 1993 was made, using the 1972 stress to the aquifer, to determine saturated thickness and the amount of water in storage. The results show that approximately 32.60 million acre-ft of water will be in storage at the end of 1993. Calculated saturated thickness is shown on plate 8.

Test 3.--A reasonable maximum stress, assuming a minimum of 4 wells per mi^2 and pumping at 1972 pumping rate per well, was applied to the aquifer and a simulation made to 1993. The saturated thickness resulting from this stress is shown on plate 9. Approximately 14.75 million acre-ft of water will be in storage in 1993.

Test 4.--The stress applied to the aquifer under test 3 was continued to the year 2013. The saturated thickness at the end of this simulation is shown on plate 10. About 10.50 million acre-ft of water will be in storage at the end of 2013.

Test 5.--A simulation was made to 2050 using Test 3 stress conditions and the resulting saturated thickness is shown on plate 11. By 2050 approximately 35 percent of the 1973 irrigated acreage overlying the Ogallala aquifer will have a saturated thickness of 15 ft or less and therefore, can no longer be irrigated under the assumptions made in this study. At the end of 2050 approximately 7.85 million acre-ft, or 20 percent, of water will remain in storage in the aquifer.

Test 6.--In order to provide data for use in the application of Oklahoma's ground-water law (82 Oklahoma Statutes Supp. 1973, paragraph 1020.1 et seq.), the Oklahoma Water Resources Board requested that a projection be made to 1993 to determine the pumpage necessary to reduce the saturated thickness to 15 ft or less, for one-half the acreage overlying the saturated part of the Ogallala aquifer in 1973, with the following assumptions. (1). The initial pumping rate is equal for all of the approximately 1,255,600 acres having more than 15 ft of saturated thickness on July 1, 1973. (2). Beginning on July 1, 1973, each irrigator having more than 15 ft of saturated thickness is entitled to an equal proportionate share per acre of the ground water in that part of the Ogallala aquifer within Texas County. In order to meet the foregoing requirements as closely as possible, a no-flow boundary was assigned to the nodes just outside Texas County. The initial net annual pumping rate per 2560-acre node necessary to meet the foregoing constraints was 12,800 acre-ft, or 5 acre-ft/acre/yr. The average net pumping rates in cumulative 5-year increments from 1973 to 1993 for the 1,255,600 acres are shown below:

Years	Average net pumping rate (acre-ft/acre/yr)
5	3.78
10	2.95
15	2.14
20	1.67

Pumping ceased when the saturated thickness was reduced to 15 ft. The decrease in the average pumping rate from 5 acre-ft/acre/yr to 1.67 acre-ft/acre/yr from 1973 to 1993 is caused by pumping which lowers transmissivity by reason of reduced saturated thickness. Progressive reduction of transmissivity is accompanied by lower well yield. The areal distribution of the saturated thickness resulting from this stress, as shown on plate 12, is meaningful only in the administering of the Oklahoma ground-water law, and is not intended to represent the application of the hydrologic principles used elsewhere in this report.

The cumulative mass balance at the end of test 6 is shown below:

Sources	Acre-feet
Storage	36,967,239
Recharge	913,024
Constant Head	559,721
Leakage	3,604,539
Total Sources	42,044,523
Discharges	
Constant Head	6,757
Quantity Pumped	42,028,520
Leakage	2,366
Total Discharge	42,037,643
Discharge - Sources	-6,880
Per Cent Difference	-0.02

Based on the results of test 6, approximately 3.20 million acre-ft of water will be in storage at the end of 1993.

Summary of tests.--

Summarized below are the approximate volumetric data resulting from each of the 6 tests. The amount of water in storage at the beginning of 1972 was 40.5 million acre-ft. The percentage of water withdrawn from storage for test 1 refers to 1972, whereas the remaining percentages refer to the amount of water in storage in 1973, or 39.70 million acre-ft.

TEXAS COUNTY					MODELED AREA
Test no.	Stress period	Amount of water in storage (millions of acre-ft)	Amount of water withdrawn from storage in the aquifer (millions of acre-ft)	(percent)	Cumulative net pumpage (millions of acre-ft)
1	1972-1973	39.70	0.80	2	4.25
2	1972-1993	32.60	7.10	18	43.00
3	1972-1993	14.75	24.95	63	86.30
4	1972-2013	10.50	29.20	74	134.00
5	1972-2050	7.85	31.85	80	187.65
6	1972-1993	3.20	37.30	94	42.00 1/

1/ Texas County only

CONCLUSIONS

Any projection necessarily must assume certain facts which influence the projection results. For the first five tests made in this study two sets of yearly-pumping stress were assumed. For tests 1 and 2, the 1972 well distribution and 1972 pumping rate per 4 mi^2 were assumed; for tests 3, 4, and 5, a reasonable maximum well density of 4 wells per mi^2 and 1972 pumpage rate per well were assumed. Future irrigation-well pumping in Texas County will stress the aquifer an amount probably between the limits of the two assumptions. The Ogallala aquifer will yield water to irrigation wells considerably beyond 2050 in 65% of the area overlying the saturated part of the Ogallala aquifer in 1973, at an assumed well density of 4 wells per mi^2 and the 1972 pumping rate per well. However, plate 11 and figure 12 provide data which show that well yield will be less than the original yield in approximately half of the area mentioned, because about half the area has a saturated thickness of 38 ft or less. The water remaining in 2050 is 20 percent of the water available in 1973.

With the constraints imposed in Test 6 to meet the requirements of the Oklahoma ground-water law, test results show approximately one-half the acreage is underlain by 15 ft or less of saturated thickness by 1993, but 94 percent of water in storage has been removed. Therefore, as shown by plate 12, most of the remaining saturated thickness is less than 35 ft.

FUTURE USE OF THE GROUND-WATER MODEL

The quantitative data for the Ogallala aquifer presented in this report is but a small part of the information available by application of the model either in its present form or with further modification. For any projected time, data such as head distribution, rate of head change, transmissivity, saturated thickness, rate of change in saturated thickness, amount of water in storage, pumping lifts, and other data can be generated. For maximum effectiveness, all input data should be updated continuously as such information becomes available. As time progresses, detailed studies of smaller areas may be necessary.

SELECTED REFERENCES

Boettcher, A.J., 1966, Ground-water development of the High Plains of Colorado: U.S. Geol. Survey Water-Supply Paper 1819-I, 22 p.

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

Gary, Margaret, McAfee, Robert Jr., and Wolf, C.L., 1972, Glossary of geology: American Geol. Institute, 805 p.

Hart, D.L., Hoffman, G.L., and Goemaat, R.L., 1976, Geohydrology of the Oklahoma Panhandle, Beaver, Cimarron, and Texas Counties: U.S. Geol. Survey Water-Resources Inv. 76-25, 62 p.

Irwin, J.H., and Morton, R.B., 1969, Hydrogeologic information on the Glorieta Sandstone and the Ogallala Formation in the Oklahoma Panhandle and adjoining areas as related to underground waste disposal: U.S. Geol. Survey Circ. 630, 26 p.

Jones, O.R., and Schneider, A.D., 1970, Comparison of methods for determining the specific yield of the Ogallala, in the Ogallala aquifer, a symposium: Lubbock, Texas Tech. Univ., Spec. Rept. No. 39, p. 118-130.

Lohman, S.W., 1972, Ground-water hydraulics: U.S. Geol. Survey Prof. Paper 708, 70 p.

Lohman, S.W., and others, 1972, Definitions of selected ground-water terms - revisions and conceptual refinements: U.S. Geol. Survey Water-Supply Paper 1988, 21 p.

Luckey, R.R., and Hofstra, W.E., 1973, Digital model of the hydrologic system, Northern High Plains of Colorado: Colorado Water Resources Circ. 19, 25 p.

Meinders, H.C., Mitchell, Maurice, Grover, E.S., and Frie, J.W., 1961, Soil survey of Texas County, Oklahoma: U.S. Dept. of Agriculture Soil Survey Rept. No. 6, Series 1958, 60 p.

Missouri River Basin Commission, 1975, Stream-Aquifer Hydrology, Level B. Study, Platte River Basin, Nebraska: Missouri River Basin Commission, 67 p.

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

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

Pinder, G.F., and Bredehoeft, J.D., 1968, Application of the digital computer for aquifer evaluation: Water Resources Research, V. 4, No. 5, p. 1069-1093.

Schoff, S.L., 1939, Geology and ground-water resources of Texas County, Oklahoma: Oklahoma Geol. Survey Bull. 59, 248 p.

Trescott, P.C., Pinder, G.F., and Larson, S.P., 1976, Finite-difference model for aquifer simulation in two dimensions with results of numerical experiments: Techniques of Water-Resources Inv. of the U.S. Geol. Survey, Book 7, Chap. C1, 116 p.

Wood, P.R., and Hart, D.L., 1967, Availability of Ground Water in Texas County, Oklahoma: U.S. Geol. Survey Hydrol. Atlas HA-250.