NUMERICAL SIMULATION OF THE HIGH PLAINS REGIONAL AQUIFER, NORTHWESTERN OKLAHOMA

By John S. Havens and Scott C. Christenson

U.S. GEOLOGICAL SURVEY
WATER-RESOURCES INVESTIGATIONS REPORT 83-4269

Oklahoma City, Oklahoma

1984

UNITED STATES DEPARTMENT OF THE INTERIOR
WILLIAM P. CLARK, Secretary

GEOLOGICAL SURVEY
Dallas L. Peck, Director

For additional information write to:

James H. Irwin, District Chief
U.S. Geological Survey
Water Resources Division
Room 621, Old Post Office Building
215 Dean A. McGee Avenue
Oklahoma City, Oklahoma 73102

Telephone: (405) 231-4256

Copies of this report can be purchased from:

Open-File Services Section
Western Distribution Branch
U.S. Geological Survey
Box 25425, Federal Center
Lakewood, Colorado 80225

Telephone: (303) 234-5888

CONTENTS

ILLUSTRATIONS

[Plates are in pocket]

TABLES

CONVERSION FACTORS

For readers who prefer to use metric units, conversion factors for terms used in this report are listed below:

Multiply	By	To obtain
acre-foot (acre-ft)	1,233	cubic meter
foot (ft)	0.3048	meter
foot per second (ft/s)	0.3048	meter per second
foot per day (ft/d)	0.3048	meter per day
foot squared per day (ft^2/s)	0.0929	meter squared per day
cubic foot per second (ft^2/s)	0.02832	cubic meter per second
foot per mile (ft/mi)	0.1894	meter per kilometer
gallon per minute (gal/min)	0.06308	liter per second
inch (in.)	25.4	millimeter
inch per year (in./yr)	25.4	millimeter per year
mile (mi)	1.609	kilometer
square mile (mi^2)	2.590	square kilometer

Temperature in degrees Fahrenheit (°F) can be converted to degrees Celsius (°C) as follows:

$$°F = 1.8(°C) + 32°$$

National Geodetic Vertical Datum of 1929 (NGVD of 1929): A geodetic datum derived from a general adjustment of the first-order level nets of both the United States and Canada, called NGVD of 1929, is referred to as sea level in this report.

NUMERICAL SIMULATION
OF THE HIGH PLAINS REGIONAL AQUIFER,
NORTHWESTERN OKLAHOMA

By

John S. Havens and Scott C. Christenson

ABSTRACT

In 1978 the U.S. Geological Survey began a 5-year study of the High Plains regional aquifer system to provide hydrologic information for evaluating the effects of long-term development of the aquifer and to develop a capability for predicting aquifer response to alternative changes in ground-water management. By use of a digital model, this report presents a quantitative description of the High Plains aquifer in Oklahoma.

The High Plains aquifer consists predominantly of the Tertiary Ogallala Formation and overlying Quaternary alluvium and terrace deposits which are hydraulically connected to the High Plains aquifer. Much of the aquifer is underlain by formations of Permian through Cretaceous age, which generally have very small hydraulic conductivities. In some areas parts of underlying Triassic, Jurassic, or Cretaceous rocks are hydraulically connected with the aquifer. The High Plains aquifer is a water-table aquifer in which water moves generally to the east-southeast. Before the beginning of extensive irrigation in the 1960's, the aquifer was essentially in dynamic equilibrium with recharge from precipitation balanced by natural discharge from the aquifer. Ground-water discharge appeared in streams leaving the area or was returned to the atmosphere through evapotranspiration.

Accurate records of irrigation pumpage are not available from the High Plains. In order to estimate irrigation pumpage, published records of crop distribution were used and a consumptive use was assigned to each principal irrigated crop. This method gave an estimated irrigation demand. Pumpage was taken as a percentage of the total irrigation demand. Irrigation has decreased ground-water discharge from the High Plains aquifer. Ground-water discharge was estimated as approximately 118 cubic feet per second in 1980.

A finite-difference digital model was used to simulate flow in the High Plains aquifer. The recharge was adjusted so that 1980 ground-water discharge was 118 cubic feet per second, the estimated ground-water discharge for 1980. Recharge in the eastern half of the modeled area was 0.45 inch per year; one-half this value was used in the western half of the modeled area. Hydraulic conductivity was divided into three zones: 19.3 feet per day in the eastern zone; 16.2 feet per day in the central zone; and 8.28 feet per day in the western zone. A specific yield of 14.7 percent was used in the model. Using all these parameters, the model was calibrated so that the mean difference between predevelopment modeled and measured heads was -0.044 foot.

Following the calibration procedure, the model was used to predict the volumes of water in storage and distribution of saturated thickness in 1993 and 2020 using the 1980 pumping rates. The calculated quantity of water in storage in the aquifer in 1941 (predevelopment) was approximately 135.2 million acre-feet; in 1980, approximately 121.9 million acre-feet; in 1993, approximately 112.7 million acre-feet; and in 2020, approximately 96.2 million acre-feet.

The High Plains aquifer in Oklahoma will continue to be an important source of water past the year 2000. As withdrawals continue from the aquifer at the present rate, the water table will continue to decline and when the water table drops below the streambed in any part of the area, ground-water discharge to streams will cease in that area. Based on the calculated volumes of water in storage, the volume of water remaining in storage as compared to the predevelopment volume is as follows: 90 percent in 1980, 83 percent in 1993, and 71 percent in 2020.

INTRODUCTION

Purpose and Scope

In 1978, the U.S. Geological Survey began a 5-year study of the High Plains regional aquifer system (fig. 1) to provide hydrologic information to evaluate the effects of long-term development of the aquifer and to develop a capability for predicting aquifer response to alternative changes in ground-water management (Weeks, 1978). This report presents an abbreviated description of the High Plains aquifer in the State of Oklahoma and describes a digital model analysis of the aquifer whereby projections of change of water in storage and distribution of saturated thickness with time were made.

Data Sources and Model Type

Water-level data from approximately 1,600 wells were used for drawing the predevelopment water-table map (Havens, 1982c). About 670 water-level measurements were used for constructing the 1980 water-table map (Havens, 1982b) and about 1,300 well logs were used in drawing the aquifer-base map (Havens, 1982a). Low-flow measurements were taken from published and unpublished data in the files of the U.S. Geological Survey. Water-use data were obtained from published data stored on a data base maintained by the U.S. Geological Survey (Heimes and Luckey, 1982). A two-dimensional finite-difference model (Trescott, Pinder, and Larson, 1976) was used to describe the aquifer and to predict the effects of future ground-water withdrawals.

Other data used in preparing this report came from published and unpublished data in the files of the U.S. Geological Survey, from the files of the Oklahoma Water Resources Board, and from field inventory of wells in 1980 by the Oklahoma Water Resources Board under contract to the U.S. Geological Survey.

Previous Studies

Extensive studies of the three Panhandle counties--Cimarron, Texas, and Beaver--were made in the late 1930's and early 1940's (Schoff, 1939, 1943; Marine and Schoff, 1962). With the exception of Woodward County (Wood and Stacey, 1965) few studies have been made of the eastern segment of the High Plains area in Oklahoma.

Increasing use of water from the High Plains aquifer for irrigation, municipal, industrial, and domestic purposes in the Panhandle led to new studies in the 1960's and 1970's. Hydrologic atlases (Wood and Hart, 1976; Sapik and Goemaat, 1973; Morton and Goemaat, 1973) of the Panhandle area were supplemented by hydrologic reconnaissance atlases of the Woodward and Clinton quadrangles (Morton, 1980; Carr and Bergman, 1976). Additional studies of the entire Panhandle area include reports by Hart, Hoffman, and Goemaat (1976) and Morton (1973). Irwin and Morton (1969) reported briefly on the possible mingling of brine from lower formations with fresh water from the High Plains aquifer in the Panhandle.

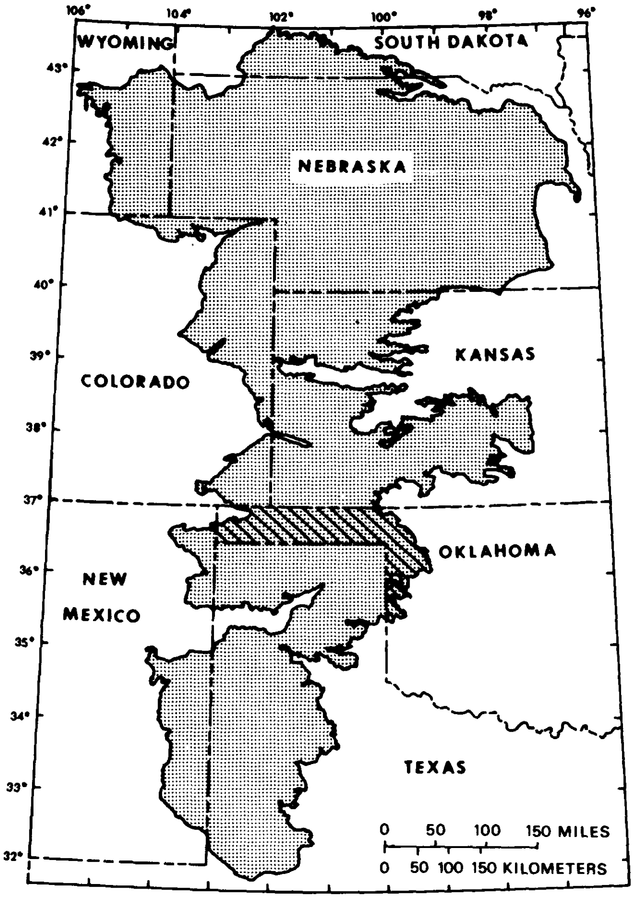
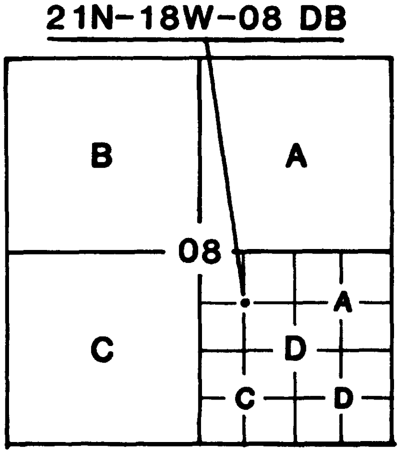


Figure 1.--Location of the High Plains regional aquifer (shaded) and the area of this report (hachured).

Five preliminary open-file map reports showing aquifer base, predevelopment and 1980 water tables, 1980 saturated thickness, and predevelopment to 1980 water-level change (Havens, 1982a, 1982c, 1982b, 1982d, 1983) have been issued as a part of the present study.

Explanation of the Site-Numbering System

The standard legal method of describing a location of data-collection sites by fractional section, section, township and range is replaced in this report by the method illustrated in the diagram below. By the legal method, the location of the site indicated by the dot would be described as NW 1/4 SE 1/4 sec. 8, T.21 N., R.18 W. The method used in this report changes the order and indicates quarter subdivisions of the section by letters. By this method, the location of the site is given as 21N-18W-08 DB.



Physiography and Drainage

Much of the 7,000 mi^2 study area in Oklahoma is part of the High Plains section of the Great Plains physiographic province; the eastern part of the area lies in the Osage Plains section of the Central Lowlands province (Fenneman, 1930). The altitude of the study area ranges from about 4,800 ft in the west to 1,950 ft in the east. The general slope of the land surface is about 15 ft/mi. The High Plains is generally a flat, featureless plain with little relief; local relief is generally less than 50 ft.

Most of the area is drained principally by the North Canadian-Beaver River; the Cimarron, South Canadian, and Washita Rivers drain smaller parts of the area. Wolf Creek drains to the North Canadian River with occasional periods of no flow. Major reservoirs in the area are Optima Lake on the Beaver River about 20 mi east of Guymon and Fort Supply Reservoir on Wolf Creek, about 12 mi northwest of Woodward.

Precipitation

Precipitation increases from west to east in Oklahoma. In the modeled area, the 30-year normal precipitation for 1941-70 ranged from about 16 in. in Cimarron County on the west to about 24 in. in Woodward County on the east and about 25 in. in Roger Mills County to the southeast.

GEOLOGY

The geologic units in the High Plains of Oklahoma are summarized in table 1.

Table 1.--Generalized chart of geologic units in the High Plains of Oklahoma

System	Stratigraphic unit	
Quaternary	Alluvium	
	Terrace deposits	
Tertiary	Ogallala Formation	
Cretaceous	Colorado Group	Greenhorn Limestone Graneros Shale
	Dakota Sandstone	
	Purgatoire Formation	Kiowa Shale Member Cheyenne Sandstone Member
Jurassic	Morrison Formation	
	Exeter Formation	
Triassic	Dockum Group	
Permian	Undifferentiated red beds	

Permian System

Rocks of Permian age.--Rocks of Permian age underlie the entire study area. These rocks crop out along Palo Duro Creek in Texas County and along the Beaver and Cimarron Rivers in Beaver, Harper, Ellis, and Woodward Counties. Undifferentiated Permian red beds are exposed along the eastern edge of the High Plains where the Ogallala Formation has been removed by erosion.

Undifferentiated Permian red beds form the base of the Ogallala Formation in much of Texas County, in all of Beaver County, and in all of the eastern segment of the study area.

In general, the Permian red beds at the base of the Ogallala have very low hydraulic conductivity and yield less than 10 gal/min of water to wells (Hart, Hofman, and Goemaat, 1976). Most water wells in the High Plains area do not penetrate the red beds to any appreciable depth.

The red beds consist mostly of reddish-brown sandstone, siltstone, shale, and sandy shales. Thin dolomite and limestone beds, halite, and gypsum are present within the red bed sequence. Permian rocks thicken to the east and southeast and generally exceed 1,000 ft throughout the area (Hart, Hoffman, and Goemaat, 1976).

Triassic System

Dockum Group.--The Dockum Group of Triassic age crops out in northwestern Cimarron County and is present in the subsurface in Cimarron County. The Dockum is present in the subsurface of west-central Texas County where it also crops out in a few small areas. It is completely eroded in the area east of Guymon.

The upper unit of the Dockum consists of varicolored shales, shaly sandstones, and siltstones. Most of the lower unit consists of pink to red sandstone, slightly micaeous and shaly, with minor amounts of varicolored shales and siltstones. The upper shaly unit is as much as 450 ft thick; the sandstones in the lower unit average about 100 ft (Hart, Hoffman, and Goemaat, 1976).

Wells in the Dockum yield 10 to 50 gal/min of water to stock and domestic wells. Water in the Triassic is probably in hydraulic continuity with the High Plains aquifer, particularly in Texas County where the upper shaly beds have been removed by erosion.

Jurassic System

Rocks of Jurassic age.--The Exeter Sandstone, the basal member of the Jurassic in the Panhandle area, consists of as much as 35 ft of white to pink sandstone. The sand grains are fine to medium, subrounded to rounded, and well sorted. The Exeter thins eastward from Cimarron County. Wells in the Exeter reportedly yield as much as 20 gal/min (Hart, Hoffman, and Goemaat, 1976).

The Morrison Formation overlies the Exeter. From its subcrop limit near the central part of Cimarron County, the Morrison thickens westward to about 325 ft. it consists mostly of pale green and red shale and siltstone, interbedded with lenses of very fine to coarse sandstone (Morton, 1973). Yields from wells in the Morrison are reportedly less than 20 gal/min (Hart, Hoffman, and Goemaat, 1976).

Cretaceous System

Purgatoire Formation.--The Purgatoire Formation consists of a lower Cheyenne Sandstone Member and an upper Kiowa Shale Member. Maximum thickness of the Cheyenne is about 125 ft of fine- to medium-grained, white to buff sandstone; locally the lower part of this member is conglomeratic. The Kiowa consists of as much as 65 ft of dark grey to black shale, grading upward to sandy shales and thin-bedded sandstones.

The Purgatoire is present in the subsurface in the western one-third of Cimarron County; it crops out only in northwestern Cimarron County. Erosion has truncated the Purgatoire to the east where it is overlain by the Ogallala Formation.

Wells in the Cheyenne may yield as much as 500 gal/min of water. The Kiowa is not known to yield water to wells (Hart, Hoffman, and Goemaat, 1976).

Dakota Sandstone.--The Dakota Sandstone, overlying the Purgatoire, is present in the subsurface throughout most of the western one-third of Cimarron County. Outcrops are present in northwestern Cimarron County and along major streams in southwestern Cimarron County. The Dakota reaches a thickness of 200 ft in the west, thinning to zero thickness, because of truncation, along an irregular northeast-southwest line generally 6 mi west of Boise City, Oklahoma.

The Dakota is composed of fine to medium sand and may contain a thin grey shale unit locally. Wells finished in the Dakota may yield a maximum of 150 gal/min. For increased yields, many wells are finished in the Dakota and other water-bearing zones penetrated while drilling the well.

Where overlain by relatively impervious shale or clay, water in the Dakota is under artesian pressure. Water-table conditions are present where the Dakota is overlain by sandy facies of the High Plains aquifer (Hart, Hoffman, and Goemaat, 1976).

Colorado Group.--The Colorado Group is composed of the Graneros Shale and Greenhorn Limestone and ranges in thickness from zero to a maximum of 200 ft. Lithology of the group consists of alternating beds of shale, marl, limestone, and bentonite (Morton, 1973; Hart, Hoffman, and Goemaat, 1976). The Colorado Group does not crop out in the study area; subcrops are present in the western one-third of Cimarron County.

No wells are known to obtain water from the Colorado Group in the study area.

Tertiary and Quaternary Systems

The Tertiary and Quaternary Systems are combined in this report. Most of the units represented by these systems are lithologically similar and form a continuous hydraulic unit. The Ogallala Formation of Tertiary age and alluvium and terrace materials of Quaternary age comprise the main body of the High Plains aquifer as used in this report.

Ogallala Formation.--The Ogallala Formation was deposited upon an erosional surface of Cretaceous and older rocks by eastward-flowing streams. Material forming the Ogallala was derived from the ancestral Rocky Mountains and sedimentary rocks near the mountains. Parts of the Ogallala were derived from removal and reworking of previously deposited sediments in the depositional area. Because the Ogallala was deposited on an irregular erosional surface, its thickness changes rapidly within a short distance, and ranges from zero to about 650 ft. In Oklahoma sinkholes produced by salt dissolution in the underlying Permian sediments have been filled with thick deposits. The Ogallala thins along major stream valleys and drainageways.

The Ogallala consists of interbedded sand, siltstone, clay, gravel, thin limestones, and caliche. The proportion of various lithologic materials changes rapidly from place to place, but poorly sorted sand and gravel generally predominate. The rocks are poorly to moderately well cemented by calcium carbonate. Near the surface, beds of caliche are common and may form a well-indurated caprock. Rocks of the Ogallala are generally light tan or buff to light grey, but locally may be shades of red, pink, yellow, black, or white.

Originally deposited over a larger area, the Ogallala is now bounded on all sides by erosional escarpments. Several outliers in northern Woods County mark the known eastern extent of the Ogallala in Oklahoma. Locally, the Ogallala has been removed by stream erosion within the boundaries of the High Plains. The upper surface of the formation in Oklahoma is an erosion surface and a complete Ogallala section is not present in the State.

Well yields from the Ogallala range from a few gallons per minute where the aquifer is thin or has a low hydraulic conductivity to as much as 2,000 gal/min in thick, highly conductive sections.

Alluvium and terrace deposits.--Alluvium and terrace deposits overlying the Ogallala are composed of poorly sorted grey to brown sand, gravel, clay, and silt. The thickness of these deposits seldom exceeds 100 ft. Along the Beaver-North Canadian River the Quaternary deposits may be as much as 8 mi wide; width of Quaternary deposits elsewhere is generally less than 1 mi.

Wells finished in the alluvium and terrace deposits may yield as much as 750 gal/min.

HYDROLOGY

Occurrence and Movement of Ground Water

The High Plains aquifer consists of the Tertiary Ogallala Formation and Quaternary alluvium and terrace deposits which are in hydraulic continuity. In some areas of bedrock highs, parts of the underlying Triassic, Jurassic, or Cretaceous rocks are hydraulically connected with the Ogallala Formation and are included with the High Plains aquifer.

The High Plains aquifer is a water-table aquifer except in local areas where lenses of clay may cause limited areas of the aquifer to exhibit artesian characteristics. Water in the High Plains aquifer moves generally to the east-southeast; the slope of the water table is about 14 ft/mi. The altitude of the water table ranges from about 4,600 ft above mean sea level in Cimarron County to about 2,000 ft in Woodward County (Havens, 1982b, 1982c). Discharge to streams along major stream valleys causes local variations in the water table.

Before the beginning of extensive pumping for irrigation in the 1960's the High Plains aquifer was essentially in dynamic equilibrium with recharge from precipitation balanced by discharge from the aquifer. Discharge appeared in streams leaving the area or was returned to the atmosphere as evapotranspiration. However, with the advent of artificial discharge in the form of irrigation pumpage in the 1960's and with no increase in recharge, the water table in the High Plains aquifer began to decline. The result is a reduction in ground-water discharge and a reduction in saturated thickness.

Water-level contours of the predevelopment water table (Havens, 1982c) were based on about 1,600 water-level measurements made from 1937 through 1940 in the Oklahoma Panhandle and from the 1950's through the 1970's in the remainder of the study area. The eastern part of the study area was not developed extensively until the 1970's. The 1980 water-table contours (Havens, 1982b) were based on about 670 measurements made in January, February, and March 1980. Comparison of these two sets of measurements shows a decline of more than 100 ft southeast of Guymon and a decline of 50 ft or more northwest, southwest, and northeast of Guymon. Other declines of more than 100 ft are present in southwestern Woodward County and in northwestern and south-central Ellis County. Areas of decline correspond with areas of greatest irrigation development. Water-level rises are present in Cimarron County, east of Boise City, and in Texas County, northeast of Guymon (Havens, 1983).

Recharge to and Discharge from the Aquifer

Recharge to the High Plains aquifer comes from precipitation on the land surface and is dependent on the quantity, intensity, and distribution of precipitation. As precipitation increases to the east in Oklahoma, recharge can be expected to increase from west to east. Only a small percentage of the total precipitation falling on the land surface reaches the underlying aquifer as recharge.

Discharge from the High Plains aquifer consists of ground-water discharge plus evapotranspiration plus pumpage. Evapotranspiration and irrigation pumpage are at a minimum during the winter months while plants are dormant and few crops are being irrigated. Discharge measurements made during the winter months will therefore give, as closely as possible, ground-water discharge from the aquifer.

Discharge measurements for the period 1970-79 are given in table 2. Stream-flow records for several stations were of sufficient length for statistical analysis by standard surface-water techniques. For these stations, 7-day low-flow values during January and February with a 2-year recurrence interval were used as an indication of ground-water discharge. Other values appearing in this table are measurements or the average of several measurements taken during the winter months, December-March. During these months, the effects of transpiration are at a minumum and there will be periods when there is no overland runoff, thus most flow in the stream will represent ground-water discharge from the aquifer. The value of 118 ft^3/sec for the period 1970-79 is considered representative of the 1980 ground-water discharge.

Table 2.--Discharge of streams draining the High Plains regional aquifer, northwestern Oklahoma.

(Remarks: 1, January-February 7-day low-flow value, 2-year recurrence interval, 1970-79;
2, January-February 7-day low-flow value, 2-year recurrence interval, 1971-79;
3, Seven-day low-flow value, 2-year recurrence interval, *from* Huntzinger, 1978;
4, *from* Huntzinger, 1978;
5, *from* Davis, Christenson, and Blumer, 1981
Reference numbers refer to locations shown on figure 2.)

Reference number	Station name and location	Discharge, ft^3/s	Remarks
1	North Canadian River at Woodward, OK	17.3	1
2	Indian Creek at 22N-19W-21 DD	4.95	5; average of 3 values, Dec-Mar, 1978-79
3	Persimmon Creek at 21N-18W-08 DB	6.50	5; average of 3 values, Dec-Mar, 1978-79
4	Bent Creek at 20N-17W-22 AC	4.43	5; average of 3 values, Dec-Mar, 1978-79
5	Canadian River near Canadian, TX	22.3	1
6	Commission Creek near Grand, OK	.58	3
7	Turkey Creek near Carmargo, OK	2.26	4; average of 11 values, Dec-Mar, 1965-73
8	Cimarron River near Forgan, OK	40.3	2
9	Crooked Creek near Nye, KS	8.90	1
10	North Fork Red River near Texola, OK	1.80	4; average of 4 values, Jan-Mar, 1952-53
11	Sweetwater Creek near Texola, OK	1.48	3
12	Starvation Creek near Prentice, OK	1.33	4; average of 10 values, Dec-Mar, 1965-73
13	Washita River near Cheyenne, OK	5.53	Average of Jan-Feb 1979 mean
		117.78	

As accurate records of irrigation pumpage are not available from the High Plains, another method of estimating irrigation pumpage was used in this study. Reasonably complete records of crop distribution are published by the U.S. Department of Commerce as a Census of Agriculture. Heimes and Luckey (1982) assigned a consumptive use to each principal irrigated crop and estimated the irrigation demand for the High Plains. In the High Plains in northwestern Oklahoma, pumpage used in this study was calculated as a percentage of the total crop demand as determined by Heimes and Luckey. The estimated 1941-80 pumpage is given in table 3.

Table 3.--Estimated irrigation pumpage in the High Plains aquifer in parts of Colorado, Kansas, New Mexico, Oklahoma, and Texas, 1941-80.

Pumping period	Pumpage (million ac-ft/yr)
1941-45	0.06
1946-50	0.17
1951-55	0.28
1956-60	0.85
1961-65	1.52
1966-70	2.65
1971-75	3.21
1976-80	3.47

DIGITAL SIMULATION MODEL

Application to the High Plains Aquifer

A digital model was used to simulate flow in the High Plains aquifer. The digital model was used to verify estimates of the aquifer's characteristics (such as hydraulic conductivity) and estimated components of the water budget (such as rates of recharge) and to predict the aquifer's response to pumpage. Such response is shown as hydraulic head and saturated thickness at future times.

The High Plains aquifer in Oklahoma was simulated using a finite-difference model developed by Trescott, Pinder, and Larson (1976). The finite-difference model replaces the differential flow equations with approximating difference equations. The continuous region for which a solution is desired is replaced by an array of discrete points, or nodes. The resulting system of algebraic equations are solved at each node. The system of equations generated by this method is generally so large that a digital computer is used to obtain a solution.

In order to have a problem of manageable size, models must be much less complex than the systems they simulate. Assumptions and simplifications are made when a model is constructed. These assumptions limit the accuracy of answers obtained from the model. A list of major assumptions necessary to simulate the High Plains aquifer is shown below:

1. Flow of water in the aquifer is consistent with Darcy's law.
2. The aquifer is isotropic in the horizontal direction with respect to hydraulic conductivity, the volume of water that will move in unit time under unit hydraulic gradient thorough a unit area measured at right angles to the direction of flow (Lohman and others, 1972).
3. The vertical flow component in the aquifer is negligible in comparison with the horizontal flow component.
4. The density of water in the aquifer is constant in time and space.
5. Recharge to the aquifer is constant with time.

The High Plains aquifer was subdivided into a finite-difference grid having 28 rows and 52 columns (plate 1). Nodes are located at the centers of the grid blocks and are 5 mi apart.

Several types of boundary conditions were used in the model. As a computational necessity, the area is surrounded by a no-flow boundary. Where the aquifer terminates against the relatively impermeable Permian red beds, a no-flow boundary was used to approximate actual conditions. To the north, where the High Plains aquifer continues into Kansas, the model was extended until the no-flow boundary had minimal effect on the the High Plains aquifer in Oklahoma.

The major streams in the area that discharge ground water from the High Plains aquifer were treated as partially-penetrating streams with leaky streambeds. An area-vector weighting method was used to proportion the streambed leakage at a node to the amount of stream area within the grid block. A value of .86 ft/d was used for vertical hydraulic conductivity of the streambed.

Along the southern edge of the model, the Canadian River is used as the boundary. The High Plains aquifer is quite thin along the Canadian River, so very little water in the Ogallala moves south under the river. At some locations, the Canadian River is outside of the model grid. Rather than extend the model grid to include all of the river, leakage nodes were placed in a model node near the edge and the modeled thickness of the confining layer was equal to the distance from the node to the river. The vertical hydraulic conductivity at these nodes was adjusted to approximate the horizontal hydraulic conductivity of the section between the river and the nodes. These are shown on plate 1 as "grid block with head-dependent boundary condition."

Originally, the modeled area of the High Plains aquifer extended farther west into New Mexico (plate 1). Early in the modeling process this area was the cause of problems. As the model iteratively closed in on a solution, nodes in this area would became dry as model-computed heads fluctuated and dropped out of the simulation. As much of this area is very thinly saturated, the volume of water in storage and the volume of flow were not significant when compared to the High Plains aquifer in Oklahoma. Therefore, the area covered by columns 1 through 9 was deleted from the model. However, the model grid, as shown in plate 1, was not reformed to eliminate these nodes.

Model Calibration

Most ground-water models are calibrated in two phases. First, conditions prior to development are simulated. This phase is generally referred to as a steady-state simulation, even though aquifers are probably never at a true steady-state (equilibrium) condition. Next, the model is calibrated to some future time when heads have been significantly lowered by pumping. This phase is referred to as the transient calibration, as it calibrates the time-dependent variables (principally storage) in the model.

Steady-state calibration of a ground-water model consists of adjusting the coefficients in the finite-difference flow equations to match calculated head distribution and flow rates to observed head distribution and flow rates in the aquifer. The coefficients in the flow equations correspond to aquifer parameters. Some of the parameters, such as the altitude of the aquifer base, can be measured and are therefore not adjusted. Other parameters, such as hydraulic conductivity and recharge, are difficult to measure and thus may be adjusted within a reasonable range for the aquifer.

The model aquifer parameters are adjusted until several different criteria are met. The rate at which water enters and leaves the model must closely agree with flow rates that are observed in the field (a table of model flow rates is usually called a mass balance). A flow rate that is commonly used during model calibration is stream flow. (In fact, these streamflow data are generally the only flow data available for most aquifers). For this study, heads were compared using the average difference between computed heads and measured heads and the sum of the absolute values of the differences between computed heads and measured heads. The average difference between model computed heads and measured heads should be minimized. However, since differences in head can be both positive and negative, it is possible to have a very small average difference in heads while having large differences at individual nodes. Therefore, the mean of the absolute values of the difference between measured and observed heads at the individual nodes should also be minimized during calibration.

Historic head data for the High Plains aquifer in Oklahoma are available to the late 1930's. At that time pumpage was insignificant, and head data for that period are considered representative of steady-state conditions. However, flow data, in the form of stream-flow records, are unavailable for many of the area streams for this early period. The year 1980 was chosen as the target date for the transient calibration period. Good head and stream-flow data are available for 1980, while at the time of the study, data were not available for years after 1980.

Because measured stream flows were not available for the late 1930's, it was necessary to adopt a somewhat different calibration strategy than that used in most model studies. The model was calibrated to steady-state conditions for heads only, essentially ignoring the mass balance. The model was then stressed using the known pumping history from 1941 to 1980, and the modeled streamflows were compared to measured streamflows in 1980. A new steady-state calibration was then undertaken, with the knowledge of which direction the mass balance needed to be adjusted in order to match the 1980 streamflows. This iterative process was undertaken several times until the model adequately matched the 1941 head data and the 1980 head and streamflows.

The earliest versions of the steady-state model used uniform values for recharge and hydraulic conductivity. However, uniform values produced unacceptable errors in large parts of the model. The calculated water-level surface was higher than the observed water-level surface in the western part of the model. Because precipitation is lower in the western parts of the study area, recharge was lowered in the west to half the value used in the eastern section of the model. The dividing line between recharge zones was between columns 29 and 30. Hydraulic conductivity was also divided into zones, with 3 zones ultimately being used. Columns 24 through 51 were assigned the largest initial value, columns 16 through 23 were reduced to 84 percent of that initial value, and columns 1 through 15 were reduced to 43 percent of the initial value. The absolute values of these numbers probably do not accurately represent the variations in recharge and hydraulic conductivity in the aquifer. Rather, the decrease in recharge and hydraulic conductivity to the west are probably general trends, which are included in the model.

As aquifer parameters were adjusted to produce a match between computed and observed data, values for hydraulic conductivity and recharge for the different zones were gradually fixed. For the steady-state model, recharge in the eastern half of the model was .45 in./yr. For the western half of the model the recharge is one-half this value. Hydraulic conductivity in the eastern zone was 19.3 ft/d. For the central hydraulic conductivity zone, the value was 84 percent of the eastern zone, or 16.2 ft/d, and hydraulic conductivity in the western zone was 43 percent of the eastern zone, or 8.28 ft/d. These values may be somewhat lower than published values. Published values generally reflect hydraulic conductivity of irrigation wells which tend to be drilled in areas of assured production. Overall values will be lower. These parameter values resulted in a mean difference between computed and measured heads of -0.044 ft in the 356 nodes that were in the Oklahoma portion of the model, and the mean of the absolute value of the differences was 50.1 ft.

The calibrated steady-state model was tested to determine what effect the artificial no-flow boundary along its northern edge had on heads in the Oklahoma part of the model. A row of constant-head nodes was placed along the first row of active nodes (in plate 1, row 2 was assigned constant head). As a no-flow node has the effect of allowing no water to enter or leave the model and a constant-head node has the effect of allowing any amount of water to enter or leave the model, the difference between the two different boundary conditions gives an indication of the effect of the boundary condition on the model. Substitution of the constant-head boundary produced no effect on the mean of the difference or the sum of the absolute values between computed and measured heads in the Oklahoma section of the model.

The model-calculated predevelopment-1941 water levels and the measured predevelopment water levels (Havens, 1982c) are shown in plate 2.

The mass balance for the steady-state simulation is:

Change in storage	0.0 ft /sec
Recharge from precititation	552.2 ft /sec
Pumpage	0.0 ft /sec
Ground-water discharge to stream	-551.8 ft /sec
Total	0.4 ft /sec

The total is a measure of the round-off error in the computer's calculations.

The leakage to streams of -118.2 ft^3/sec is considered representative of ground-water discharge from the High Plains aquifer in the study area. It is very close to the total estimate of 117.8 ft^3/sec given in table 2.

Model Projections of Saturated Thickness and Volume of Water in Storage

After the model was calibrated, it was used as a predictive tool. Using the aquifer parameters determined during the calibration process the future volumes of water in storage and distribution of saturated thickness were calculated. Oklahoma ground-water law uses 1993 as a target date for administration. This year has therefore been used as a date for predicting ground-water distribution and volumes.

A simulation was made from 1980 to 1993 using the 1980 pumping rate. As the future development of the aquifer depends on many factors, such as fuel costs and farm prices, no attempts were made to predict future withdrawal rates. The model moved forward in time in one-year time steps. The calculated 1993 potentiometric surface is shown in plate 5 and the resulting distribution of saturated thickness is shown in plate 6. The 1993 mass balance is :

Change in storage	4147.3 ft^3/sec
Recharge from precipitation	552.2 ft^3/sec
Pumping	-4638.4 ft^3/sec
Ground-water discharge to stream	-64.7 ft^3/sec
Total	-3.6 ft^3/sec

The model pumping rate at the end of the 1993 is less than in 1980, even though the 1980 pumping rate was used. This is because as the saturated thickness in a node decreased to less than 15 feet, the pumpage in that node was set to zero. Fifteen feet is usually the minimum saturated thickness needed to complete an irrigation well in the High Plains aquifer (Morton, 1980).

A similar projection was made to 2020, again beginning with the 1980 pumping rates and one-year time steps. The resulting potentiometric surface for 2020 is shown in plate 7 and the distribution of saturated thickness is shown in plate 8. The 2020 mass balance is shown below:

Change in storage	3239.5 ft^3/sec
Recharge from precipitation	552.2 ft^3/sec
Pumpage	-3876.3 ft^3/sec
Ground-water recharge from stream	81.6 ft^3/sec
Total	3.0 ft^3/sec

The steady-state values for recharge and hydraulic conductivity were used in the transient simulation from 1941 (predevelopment) to 1980. A transient simulation calibrates the model to the volume of water that has been removed by pumping over a period of time. This volume is equal to the difference in the altitude of the steady-state potentiometric surface and the altitude of the potentiometric surface at the end of the simulation (1980 in this case), multiplied by the area of the model and the specific yield of the aquifer. Specific yield is the amount of water a water-table aquifer will yield per unit volume. In order to calibrate the transient model, either the specific yield or the volume of water that has been withdrawn by pumping must be known. Morton (1980) used a specific yield of 15 percent for most of Texas County. Estimates made from drillers' logs indicate that most specific yields range from 10 to 20 percent in the High Plains in Oklahoma. For this investigation, it was decided that a specific yield value of 15 percent was representative of the aquifer. Pumpage was distributed in the model based on irrigation demand and was adjusted to match the volume of water withdrawn, based on the difference between the measured 1941 and 1980 potentiometric surfaces and the estimated specific yield.

The transient model was assigned 8 five-year pumping periods, with one-year time steps. Pumping was considered to be constant for each five-year pumping period (table 3). At the end of the transient simulation period, the mean difference between computed and measured head was calculated, and the computed ground-water discharge was compared to the measured discharge. At the end of the transient simulation process, it was found that using a specific yield of 14.7 percent instead of 15 percent gave a closer agreement between computed and measured heads and discharges. It is important to emphasize that while a specific yield of 14.7 percent shows better agreement in the calibration criteria, this is not necessarily a better estimate of aquifer parameters, since there is at least a 10 percent error in the estimate of specific yield. The specific yield was adjusted only to get the closest possible agreement between the 1980 computed heads and ground-water discharge. The 1980 computed heads and discharge were the starting point for all simulations beyond 1980.

A uniform specific yield of 14.7 percent gave a mean difference between computed and measured heads of -0.011 ft and a mean of the absolute values of the differences of 48.0 ft. As in the case of hydraulic conductivity, this specific yield figure represents an over-all average, rather than the average for successfully completed wells. The model-calculated water levels and the observed water levels for 1980 (Havens, 1982b) are both shown in plate 3. The mass balance at the end of the simulation, representing 1980, is:

Change in storage	4355.7 ft^3/sec
Recharge from precipitation	552.2 ft^3/sec
Pumpage	-4793.3 ft^3/sec
Ground-water discharge to stream	-118.2 ft^3/sec
Total	-3.6 ft^3/sec

The calculated and observed (Havens, 1982d) saturated thickness for 1980 are shown on plate 4; the calculated thickness was determined by the model as the difference between the bedrock (Havens, 1982a) and the calculated 1980 potentiometric surface.

In this simulation, pumpage has decreased significantly since 1980 as saturate thickness at many nodes decreased to less than 15 feet. The calculated irrigation pumpage, 1980-2020, is shown in figure 2. Leakage of ground water through streambeds changes sign, indicating that streams switch from gaining streams to losing streams in the study area. The model assumes that sufficient water is always available to supply the losing streams.

Calculated volumes of water in storage in the Oklahoma portion of the High Plains aquifer are shown below:

Year	Volume	Percentage of original volume remaining in storage
	(million acre-ft)	
1941	135.2	100
1980	121.9	90
1993	112.7	83
2020	96.19	71

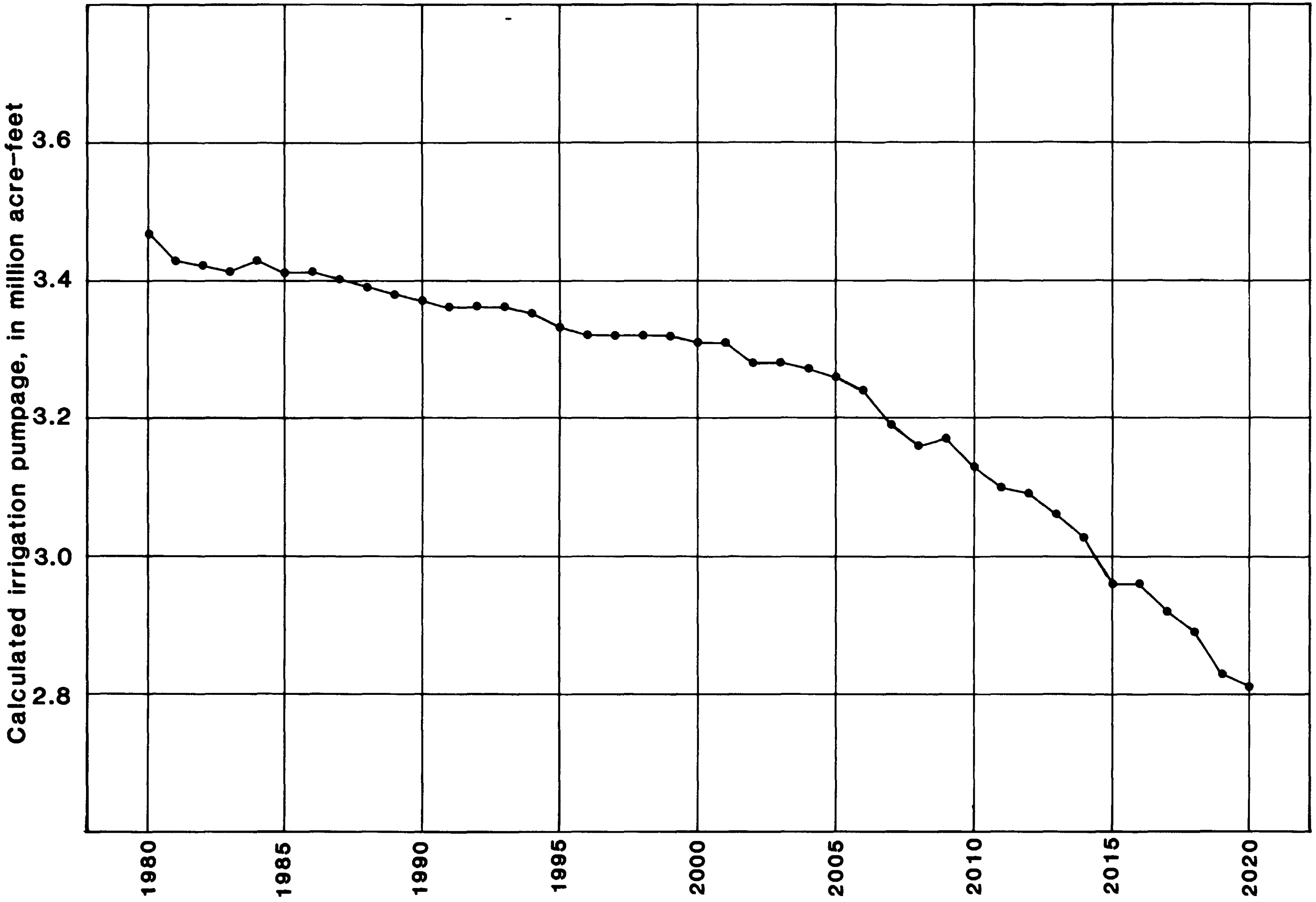


Figure 2.--Calculated irrigation pumpage in the High Plains aquifer in parts of Colorado, Kansas, New Mexico, Oklahoma, and Texas, 1980-2020.

CONCLUSIONS

The High Plains aquifer in Oklahoma will continue to be an important source of water past the year 2000. Lowering of the water table at this rate of pumpage will reduce the saturated thickness of the aquifer. As a general rule, when the saturated thickness is less than 15 ft, ground water cannot be produced in sufficient quantities for irrigation and use of ground water for other than domestic and livestock supplies becomes uneconomical and will be curtailed. Withdrawal of these areas of thin saturation from ground-water production will effectively reduce the draft upon the aquifer.

As withdrawal of water from the aquifer continues, the water table will continue to decline and as the water table declines, ground-water discharge will decrease and, in some areas, will ultimately cease. Streams will then flow only when precipitation is sufficient to cause runoff.

Based on the calculated volumes of water remaining in storage, approximately 71 percent of the water in storage in 1941 will still be in storage in the year 2020.

SELECTED REFERENCES

Bingham, R. H., 1969, Ground-water levels in observation wells in Oklahoma, 1967-68: U.S. Geological Survey Open-File Report, 92 p.

Carr, J. E., and Bergman, D. L., 1976, Reconnaissance of the water resources of the Clinton quadrangle, west-central Oklahoma: Oklahoma Geological Survey Hydrologic Atlas 5, scale 1:250,000, 4 sheets.

Davis, R. E., Christenson, S. C., and Blumer, S. P., 1980, Hydrologic data for the alluvium and terrace aquifer of the Beaver-North Canadian River from the Panhandle to Canton Lake, northwestern Oklahoma: U.S. Geological Survey Open-File Report 80-159, 77 p.

Feder, G. L., and Krothe, N. C., 1981, Results of a reconnaissance water-quality sampling program of the Ogallala aquifer in Colorado, Kansas, Nebraska, Oklahoma, South Dakota, and Texas: U.S. Geological Survey Water-Resources Investigations 81-65, 7 p.

Fenneman, N. M., 1930, Physical divisions of the United States: U.S. Geological Survey map (1946 edition).

Goemaat, R. L., 1976, Ground-water levels in observation wells in Oklahoma, 1971-74: U.S. Geological Survey Open-File Report 76-664, 142 p.

________1977a, Ground-water levels in observation wells in Oklahoma, 1975: U.S. Geological Survey Open-File Report 77-238, 35 p.

________1977b, Selected water-level records for western Oklahoma, 1950-75: U.S. Geological Survey Open-File Report 77-73, 94 p.

________1977c, Selected water-level records for western Oklahoma, 1975-76: U.S. Geological Survey Open-File Report 77-239, 50 p.

Goemaat, R. L., and Spiser, D. E., 1978, Selected water-level records for Oklahoma, 1975-77: U.S. Geological Survey Open-File Report 78-721, 58 p.

________1979, Selected water-level records for Oklahoma, 1976-78: U.S. Geological Survey Open-File Report 79-1580, 48 p.

Gutentag, E. D., and Weeks, J. B., 1980, Water table in the High Plains aquifer in 1978 in parts of Colorado, Kansas, Nebraska, New Mexico, Oklahoma, South Dakota, and Wyoming: U.S. Geological Survey Open-File Report 80-50, 1 sheet, scale 1:2,500,000.

Hart, D. L., Jr., 1963, Ground-water levels in observation wells in Oklahoma, 1956-60: U.S. Geological Survey Open-File Report, 196 p.

________1967, Ground-wter levels in observation wells in Oklahoma, 1965-66: U.S. Geological Survey Open-File Report, 61 p.

Hart, D. L., Jr., and others, 1971, Records of water-level measurements in wells in the Oklahoma Panhandle, 1966-70: U.S. Geological Survey Open-File Report, 66 p.

Hart, D. L., Jr., Hoffman, G. L., and Goemaat, R. L., 1972, Records of water-level measurements in the Oklahoma Panhandle, 1971-72: U.S. Geological Survey Open-File Report, 39 p.

________1976, Geohydrology of the Oklahoma Panhandle, Beaver, Cimarron, and Texas Counties: U.S. Geological Survey Water-Resources Investigations 25-75, 62 p.

Havens, John S., 1982a, Generalized altitude and configuration of the base of the High Plains regional aquifer, northwestern Oklahoma: U.S. Geological Survey Water-Resources Investigations Open-File Report 81-1117, scale 1:250,000, 2 sheets.

Havens, John S, continued

______1982b, Altitude and configuration of the 1980 water table in the High Plains regional aquifer, northwestern Oklahoma: U.S. Geological Survey Water-Resources Investigations Open-File Report 82-100, scale 1:250,000, 2 sheets.

______1982c, Altitude and configuration of the predevelopment water table in the High Plains regional aquifer, northwestern Oklahoma: U.S. Geological Survey Water-Resources Investigations Open-File Report 82-275, scale 1:250,000, 2 sheets.

______1982d, Saturated thickness of the High Plains regional aquifer in 1980, northwestern Oklahoma: U.S. Geological Survey Water-Resources Investigtions Open-File Report 82-760, scale 1:250,000, 2 sheets.

______1983, Water-level changes in the High Plains regional aquifer, northwestern Oklahoma, predevelopment to 1980: U.S. Geological Survey Water-Resources Investigtions Report 83-4073, scale 1:500,000, 1 sheet.

Heimes, F. J., and Luckey, R. R., 1982, Method for estimating historical irrigation requirements from ground water in the High Plains in parts of Colorado, Kansas, Nebraska, New Mexico, Oklahoma, South Dakota, Texas, and Wyoming: U.S. Geological Survey Water-Resources Investigations 82-40, 64 p.

Hershey, L. A., and Hampton, E. R., 1974, Geohydrology of Baca and southern Prowers Counties, southeastern Colorado: U.S. Geological Survey Water-Resources Investigations Open-File Report 16-74, 1 sheet.

Hoffman, G. L., and Hart, D. L., Jr., 1973, Records of selected water wells and test holes in the Oklahoma Panhandle: U.S. Geological Survey Open-File Report, 59 p.

Huntzinger, T. L., 1978, Low-flow characteristics of Oklahoma streams: U.S. Geological Survey Open-File Report 78-166, 93 p.

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

Knowles, T., Nordstrom, P., and Klemt, W. B., 1982, Evaluating the ground-water resources of the High Plains of Texas, final report; Volume 2, Basic data for northern third of region: Texas Department of Water Resources LP-173, 451 p.

Krothe, N. C., and Oliver, J. W., 1982, Sulfur isotopic composition and water chemistry in water from the High Plains aquifer, Oklahoma Panhandle and southwestern Kansas: U.S. Geological Survey Water-Resources Investigations 82-12, 27 p.

Krothe, N. C., Oliver, J. W., and Weeks, J. B., 1982, Dissolved solids and sodium in water from the High Plains aquifer in parts of Colorado, Kansas, Nebraska, New Mexico, Oklahoma, South Dakota, Texas, and Wyoming: U.S. Geological Survey Hydrologic Investigations Atlas HA-658, scale 1:2,500,000, 2 sheets.

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

Luckey, R. R., Gutentag, E. D., and Weeks, J. B., 1981, Water-level and saturated-thickness changes, predevelopment to 1980, in the High Plains aquifer in parts of Colordo, Kansas, Nebraska, New Mexico, Oklahoma, South Dakota, Texas, and Wyoming: U.S. Geological Survey Hydrologic Investigations Atlas HA-652, scale 1:2,500,000, 2 sheets.

Marine, I. W., 1963, Correlation of water-level fluctuations with climatic cycles in the Oklahoma Panhandle: U.S. Geological Survey Water-Supply Paper 1669-K, 10 p.

Marine, I. W., and Schoff, S. L., 1962, Ground-water resources of Beaver County, Oklahoma: Oklahoma Geological Survey Bulletin 97, 74 p.

McLaughlin, T. G., 1946, Geology and ground-water resources of Grant, Haskell, and Stevens Counties, Kansas: State Geological Survey of Kansas Bulletin 61, 217 p.

Mize, L. D., 1975, Statistical summaries of streamflow records, Oklahoma, through 1974: U.S. Geological Survey Open-File Report, 399 p.

Moore, R. L., 1972, Ground-water levels in observation wells in Oklahoma, 1969-70: U.S. Geological Survey Open-File Report, 85 p.

Morton, R. B., 1973, Preliminary investigations of the hydrogeology of the Middle Permian to Tertiary rocks of the Oklahoma Panhandle: U.S. Geological Survey Miscellaneous Geologic Investigations Map I-738, scale approximately 1:250,000, 2 sheets.

_______1980, 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, 34 p.

Morton, R. B., and Goemaat, R. L., 1972, Reconnaissance of the water resources of Beaver County, Oklahoma: U.S. Geological Survey Hydrologic Investigations Atlas HA-450, scale 1:125,000, 3 sheets.

Pabst, M. E., and Stulken, L. E., 1981, Altitude and configuration of the water table in the High Plains aquifer of Kansas, 1980: U.S. Geological Survey Water-Resources Investigations Open-File Report 81-1004, scale 1:500,000 (in press).

Sapik, D. B., and Goemaat, R. L., 1972, Reconnaissance of the ground-water resources of Cimarron County, Oklahoma: U.S. Geological Survey Hydrologic Investigations Atlas HA-373, scale 1:125,000, 3 sheets.

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

______1943, Geology and ground-water resources of Cimarron County, Oklahoma, with a section on Mesozoic stratigraphy by J. W. Stovall: Oklahoma Geological Survey Bulletin 64, 317 p.

Scott, G. R., 1968, Geologic and structure contour map of the La Junta quadrangle, Colorado and Kansas: U.S. Geological Survey Miscellaneous Geologic Investigations I-560, 1 sheet, scale 1:250,000.

Stulken, L. E., and Pabst, M. E., 1981, Altitude and configuration of the water table in the High Plains aquifer of Kansas, pre-1950: U.S. Geological Survey Water-Resources Investigations Open-File Report 81-117, scale 1:500,000 (in press).

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

University of Texas at Austin, 1969, Geologic Atlas of Texas, Amarillo sheet: Bureau of Economic Geology, University of Texas at Austin, scale 1:250,000, 1 sheet.

_______1970, Geologic Atlas of Texas, Perryton sheet: Bureau of Economic Geology, University of Texas at Austin, 1 sheet, scale 1:250,000.

Watts, K. R., and Stulken, L. E., 1981, Generalized configuration of the base of the High Plains regional aquifer in Kansas: U.S. Geological Survey Water-Resources Investigations Open-File Report 81-344, scale 1:500,000 (in press).

Weeks, J. B., 1978, Plan of study for the High Plains regional aquifer systems analysis in parts of Colorado, Kansas, New Mexico, Oklahoma, South Dakota, Texas, and Wyoming: U.S. Geological Survey Water-Resources Investigations 78-70, 28 p.

Weeks, J. B., and Gutentag, E. D., 1981, Bedrock geology, altitude of base, and 1980 saturated thickness of the High Plains aquifer in parts of Colorado, Kansas, Nebraska, New Mexico, Oklahoma, South Dakota, Texas, and Wyoming: U.S. Geological Survey Hydrologic Investigations Atlas HA-648, 2 sheets.

Wood, P. R., 1965, Ground-water levels in observations wells in Oklahoma, 1963-64: U.S. Geological Survey Open-File Report, 82 p.

Wood, P. R., and Hart D. L., Jr., 1967, Availability of ground water in Texas County, Oklahoma: U.S. Geological Survey Hydrologic Investigations Atlas HA-250, scale 1:125,000, 3 sheets.

Wood, P. R., and Moeller, M. D., 1964, Ground-water levels in observation wells in Oklahoma, 1961-62: U.S. Geological Survey Open-File Report, 119 p.

Wood, P. R., and Stacy, B. L., 1965, Geology and ground-water resources of Woodward County, Oklahoma: Oklahoma Water Resources Board Bulletin 21, 114 p.