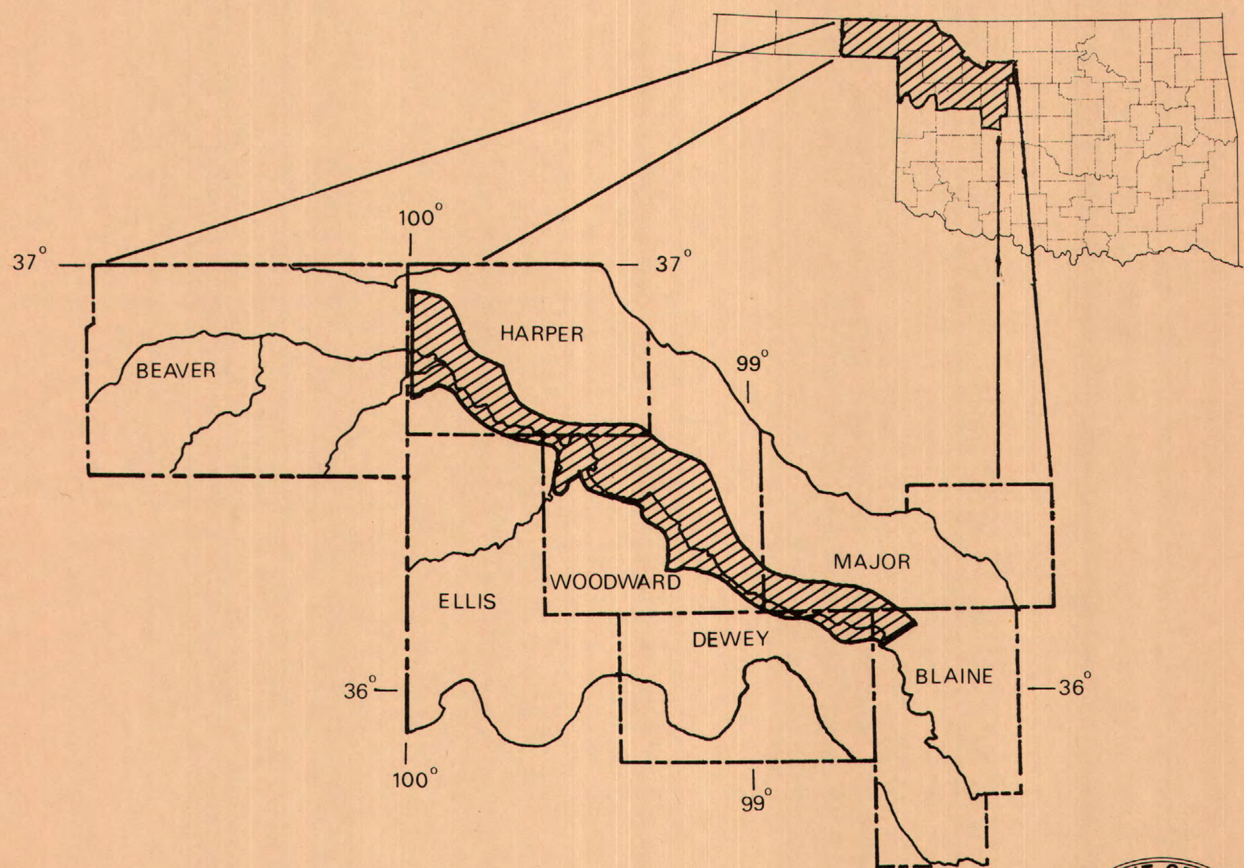
GEOHYDROLOGY AND NUMERICAL SIMULATION OF THE ALLUVIUM AND TERRACE AQUIFER ALONG THE BEAVER-NORTH CANADIAN RIVER FROM THE PANHANDLE TO CANTON LAKE, NORTHWESTERN OKLAHOMA

U.S. GEOLOGICAL SURVEY
Open-File Report 81-483



Prepared in cooperation with the
OKLAHOMA WATER RESOURCES BOARD

UNITED STATES
DEPARTMENT OF THE INTERIOR
GEOLOGICAL SURVEY

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By Robert E. Davis and Scott C. Christenson

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Oklahoma City, Oklahoma
October 1981

UNITED STATES DEPARTMENT OF THE INTERIOR
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CONTENTS

ILLUSTRATIONS

[Plates are in pocket]

CONTENTS

CONTENTS

CONTENTS

Page

TABLES

Page

CONVERSION FACTORS

The following factors may be used to convert the inch-pound units given herein to the International System (SI) of Metric Units.

Inch-pound units	Multiply by	Metric units
acre	4,047	square meter
acre-ft (acre-foot)	1,233	cubic meter
(acre-ft/acre)/yr (acre-foot per acre per year)	4.98995	cubic meter per square kilometer per year
ft (foot)	0.3048	meter
ft/d (foot per day)	0.3048	meter per day
ft^2/d (foot squared per day)	0.0929	meter squared per day
ft^3/s (cubic foot per second)	0.02832	cubic meter per second
ft/mi (foot per mile)	0.1894	meter per kilometer
(gal/min)/ft (gallon per minute per foot)	0.207	liter per second per meter
in. (inch)	25.4	millimeter
in./yr (inch per year)	25.4	millimeter per year
mi (mile)	1.609	kilometer
mi^2 (square mile)	2.590	square kilometer

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ABSTRACT

A quantitative description of the hydrologic system in alluvium and terrace deposits along the Beaver-North Canadian River in northwestern Oklahoma is needed as an aid for planning and management of the aquifer. A two-dimensional finite-difference model was used to describe the aquifer and to predict the effects of future ground-water withdrawals.

The aquifer principally consists of three geologic units: Alluvium with an average thickness of 30 feet, low terrace deposits with an average thickness of 50 feet, and high terrace deposits with an average thickness of 70 feet. A thin cover of dune sand overlies much of the area and provides an excellent catchment for recharge, but is generally unsaturated.

Hydraulic conductivity of the aquifer ranges from 0 to 160 feet per day and averages 59 feet per day. Specific yield is estimated to be 0.29. Recharge to the aquifer is approximately 1 inch annually. Under present conditions (1978), most discharge is the result of ground-water flow to the Beaver-North Canadian River at a rate of 36 cubic feet per second and to pumpage for public-supply, industrial, and irrigation use at a rate of 28 cubic feet per second. In 1978, the aquifer had an average saturated thickness of 31 feet and contained 4.07 million acre-feet of water.

The model was used to predict future head response in the aquifer to various pumping stresses. For any one area, the pumping stress was applied until the saturated thickness for that area was less than 5 feet, at which time the pumping ceased.

The results of the modeled projections show that if the aquifer is stressed from 1978 to 1993 at the 1977 pumpage rates and well distribution, the average saturated thickness will decrease 1.0 foot and the volume of water in storage will be 3.94 million acre-feet, or 97 percent of the 1978 volume. If the aquifer is stressed at this same rate until 2020, the average saturated thickness will decrease an additional 0.7 foot and the volume of water in storage will be 3.84 million acre-feet, or 94 percent of the 1978 volume.

If all areas of the aquifer having a 1978 saturated thickness of 5 feet or more are stressed from 1978 to 1993 at a rate of approximately 1.4 acre-feet per acre per year, the average saturated thickness will decrease by 20.9 feet and the volume of water in storage will be 1.28 million acre-feet, or 31 percent of the 1978 volume. If the aquifer is stressed at this same rate until 2020, the average saturated thickness will decrease an additional 2.2 feet and the volume of water in storage will be 980,000 acre-feet, or 24 percent of the 1978 volume.

The water in the aquifer is generally of the calcium bicarbonate type and is suitable for most uses. Most of the 30 water samples analyzed contained less than 500 milligrams of dissolved solids per liter.

SUMMARY OF INFORMATION REQUIRED FOR OKLAHOMA GROUND-WATER LAW

In order to provide equitable distribution of the State's ground water, the Oklahoma legislature passed certain laws pertaining to 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. Transmissivity of the basin or subbasin.
5. The possibility of pollution of the basin or subbasin from natural sources.

For this report, the term "ground-water basin" is defined as that part of the study area having 5 ft or more of saturated thickness as of July 1, 1973. According to the Oklahoma Water Resources Board (1979, p. 7) the term "maximum annual yield" is defined as the total amount of ground water that can be produced from the ground-water basin, allowing a minimum 20-year life span for the ground-water basin. According to data from the Oklahoma Water Resources Board, rights had been established prior to July 1, 1973, on 14,685 acres in the basin for a total of 28,938 acre-ft of ground water.

Based on this study, the following information is provided to assist the Oklahoma Water Resources Board to meet the requirements of Oklahoma Ground Water law:

1. The total land area overlying the basin is 666 mi^2, or 426,000 acres.
2. The amount of water in storage in the basin as of July 1, 1973, was approximately 4.11 million acre-ft.
3. The maximum annual yield was determined by a model simulation from July 1, 1973 to July 1, 1993, assuming an equal proportionate share throughout the basin except where prior rights have established a larger share, such that one-half of the land area of the basin had less than 5 ft of saturated thickness on July 1, 1993. Based on a recharge rate of 2.5 in./yr, the maximum annual rate of net pumpage was determined to be 0.8 (acre-ft/acre)/yr. If the estimated 20 percent return flow is added to the value of 0.8 (acre-ft/acre)/yr, the maximum annual yield is 1.0 (acre-ft/acre)/yr. The total net pumpage from the basin during the 20-year simulation period was 4.99 million acre-ft. If the estimated 20 percent return flow is added to the value of 4.99 million acre-ft, the total discharge from the basin during the 20 year simulation period was 6.23 million acre-ft.

4. In 1973, the transmissivity of the basin ranged from 5 to 8030 ft^2/d, and averaged 1,820 ft^2/d.
5. The digital model used in this study was not designed to model solute transport in a ground-water flow system. However, if the head in the alluvium and terrace aquifer is lowered to a level such that the head in the underlying Permian formations is higher, upward migration of water containing relatively large concentrations of dissolved solids may occur from the Permian formations into the alluvium and terrace aquifer. Pollution caused in this manner would probably be of limited extent.

INTRODUCTION

Purpose and Scope

The Quaternary alluvium and terrace deposits along of the Beaver and North Canadian Rivers in northwestern Oklahoma are an important source of water for irrigation, industrial, municipal, stock, and domestic supplies. Because of increasing demands for water, the U.S. Geological Survey, in cooperation with the Oklahoma Water Resources Board, conducted a study of these deposits that underlie an area of 830 mi^2 between the Beaver-Harper County line and the dam at Canton Lake (fig. 1). The purpose of this study is to provide a quantitative description of the hydrologic system essential to proper development and management of the aquifer.

Method of Study

Data from approximately 900 wells (pl. 1) were used to prepare potentiometric and base-of-aquifer contour maps. Low-flow stream-discharge measurements were used to estimate recharge to the aquifer. A modified version of the the Trescott 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. A further-modified version of the model was used to determine the maximum annual yield from the aquifer in accordance with Oklahoma's ground-water law (82 Oklahoma Statutes Supp. 1973, paragraph 1020.1 et seq.). Results of analyses of 30 water samples from wells were used to describe water quality.

Information used in this study was obtained during 1977-79 (Davis, Christenson, and Blumer, 1980), from the reports of previous studies (Marine and Schoff, 1962, Wood and Stacy, 1965, and Morton, 1980), and from the files of the Oklahoma Water Resources Board.

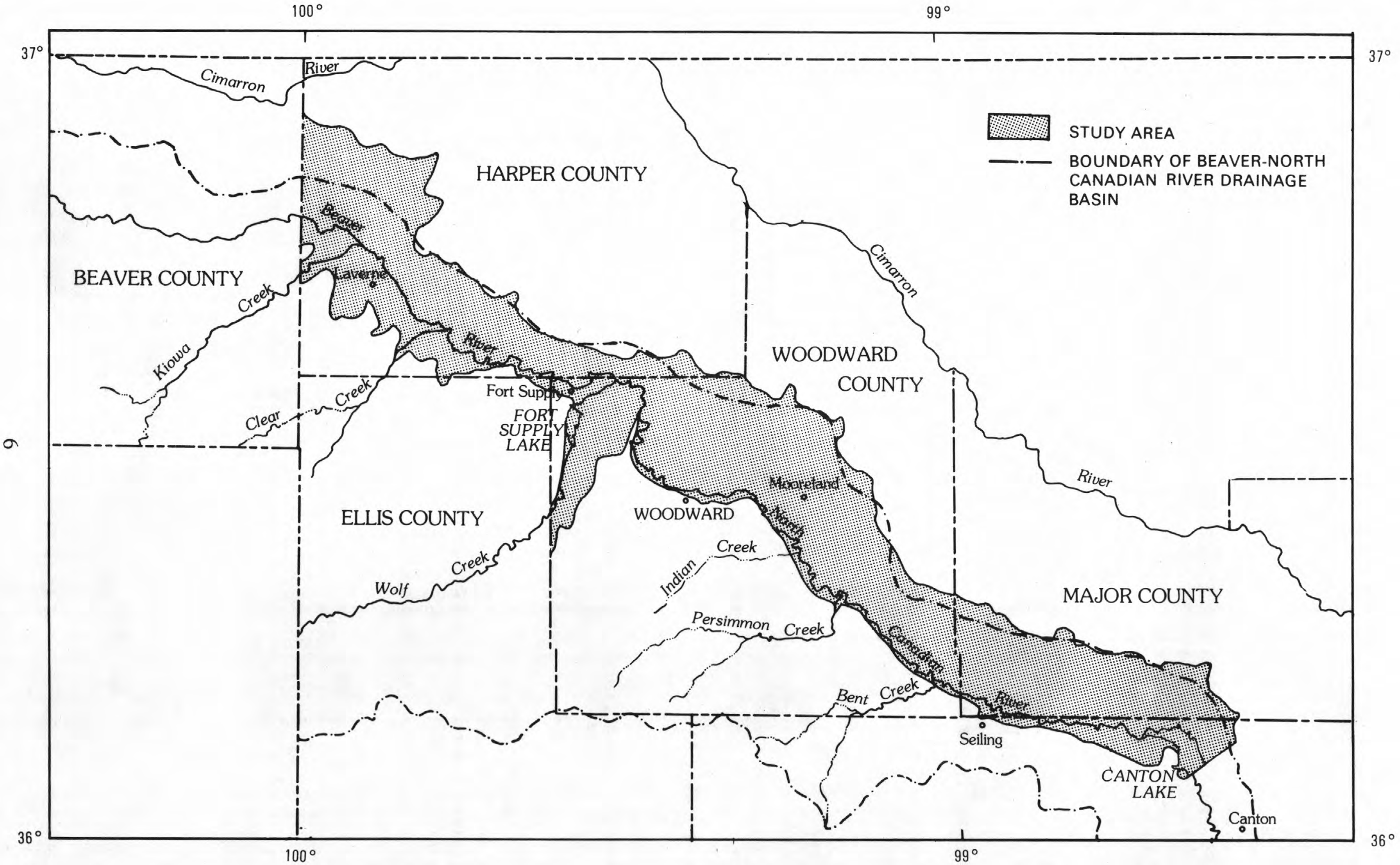
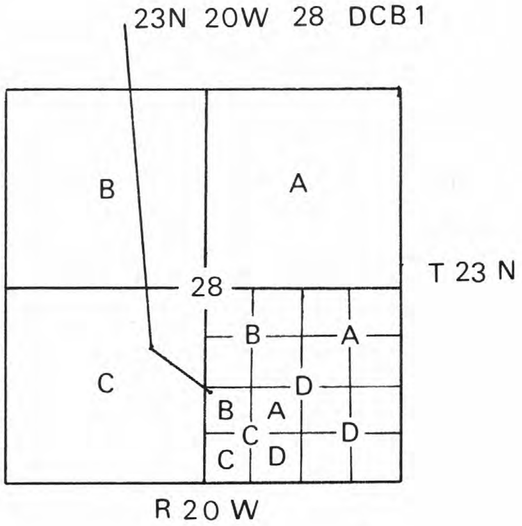


Figure 1.--Location of the study area and selected geographic features.

Explanation of Site-Numbering System

The standard legal method of giving 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 NW¼SW¼SE¼ sec. 28, T.23 N., R.20 W. The method used in this report reverses the order and indicates quarter subdivisions of the section by letters. By this method, the location of the site is given as 23N-20W-28 DCB 1. The final (1) is the sequential number of the site within the smallest fractional subdivision.



Physiography and Drainage

The study area is in the Northern Shelf Area geologic province and the Western Sand-Dune Belt geomorphic province of northwestern Oklahoma (Johnson and others, 1972, p. 1 and 3). The altitude of the study area ranges from about 2,300 ft in the northwest to about 1,600 ft in the southeast. Local relief is generally less than 100 ft.

The study area is drained by the Beaver and North Canadian Rivers. Near the town of Fort Supply (fig. 1), Wolf Creek and the Beaver River join to become the North Canadian River. In this report, the main river channel consisting of both the Beaver and the North Canadian Rivers is referred to as the Beaver-North Canadian River. The major tributaries to the Beaver-North Canadian River are Kiowa, Clear, Bent, Indian, Wolf, and Persimmon Creeks. These creeks drain the area underlain by Permian and Tertiary formations south of the Beaver-North Canadian River. No perennial streams drain the area of Quaternary deposits north of the river. In the study area, the Beaver-North Canadian River and its major tributaries are gaining streams.

Climate

The study area has a dry, sub-humid climate. Average annual precipitation for 1957-78 ranged from approximately 23 in. in the northwestern part of the area to approximately 29 in. in the southeastern part (U.S. Department of Commerce, 1957-78). The greatest amount of precipitation occurs during late spring and summer and the least during late autumn and early winter. Average annual lake evaporation ranges from 62 to 64 in. (Oklahoma Water Resources Board, 1973, p. 42). The distributions of average monthly precipitation and annual precipitation are shown in figures 2 and 3.

Previous Studies

Two previous studies have been made of the geology and ground-water resources of all or part of the study area. Wood and Stacy (1965) reported on the geology and hydrology of Woodward County in the central part of the study area. A reconnaissance-type atlas by Morton (1980) describes the geology and hydrology of the Woodward quadrangle, which includes the entire study area.

The digital model used in this investigation extends into Beaver County adjacent to the west side of the study area. A study by Marine and Schoff (1962) provided the data for Beaver County.

Acknowledgments

The authors wish to express their gratitude to the residents of the study area for their cooperation in obtaining the data presented in this report.

This investigation was made in cooperation with the Oklahoma Water Resources Board, James R. Barnett, Executive Director, Michael R. Melton, Assistant Director, and J.A. Wood, Chief, Ground Water Division. Other personnel of the Oklahoma Water Resources Board that provided assistance include Duane Smith, Dannie E. Spiser, Norma S. Aldridge, John Roles, Ginger Dean, and Betty Tyson. The cooperation and assistance of the personnel of the Oklahoma Water Resources Board is gratefully acknowledged.

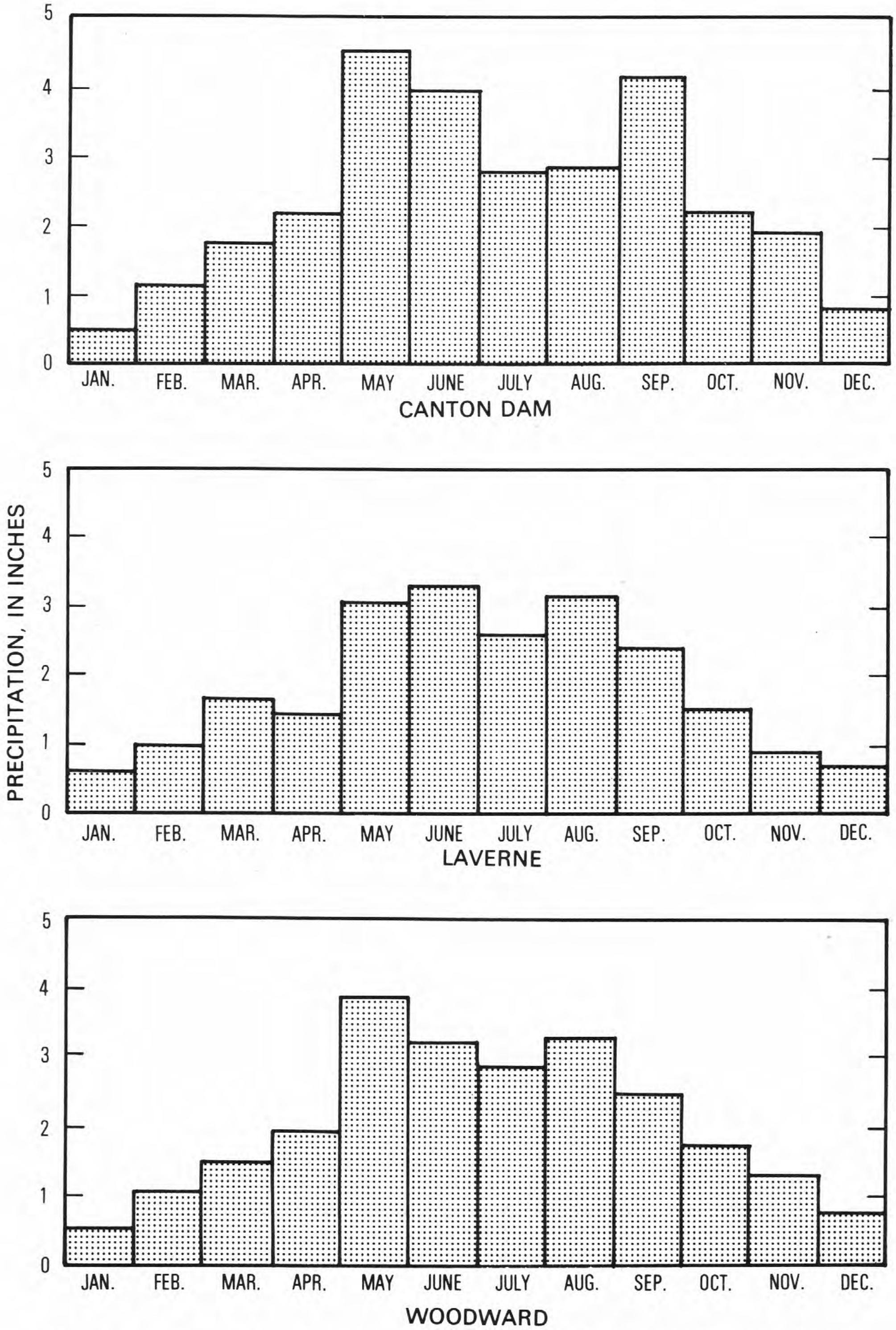


Figure 2.--Graphs showing average monthly precipitation at Canton Dam, Laverne, and Woodward, 1957-78.

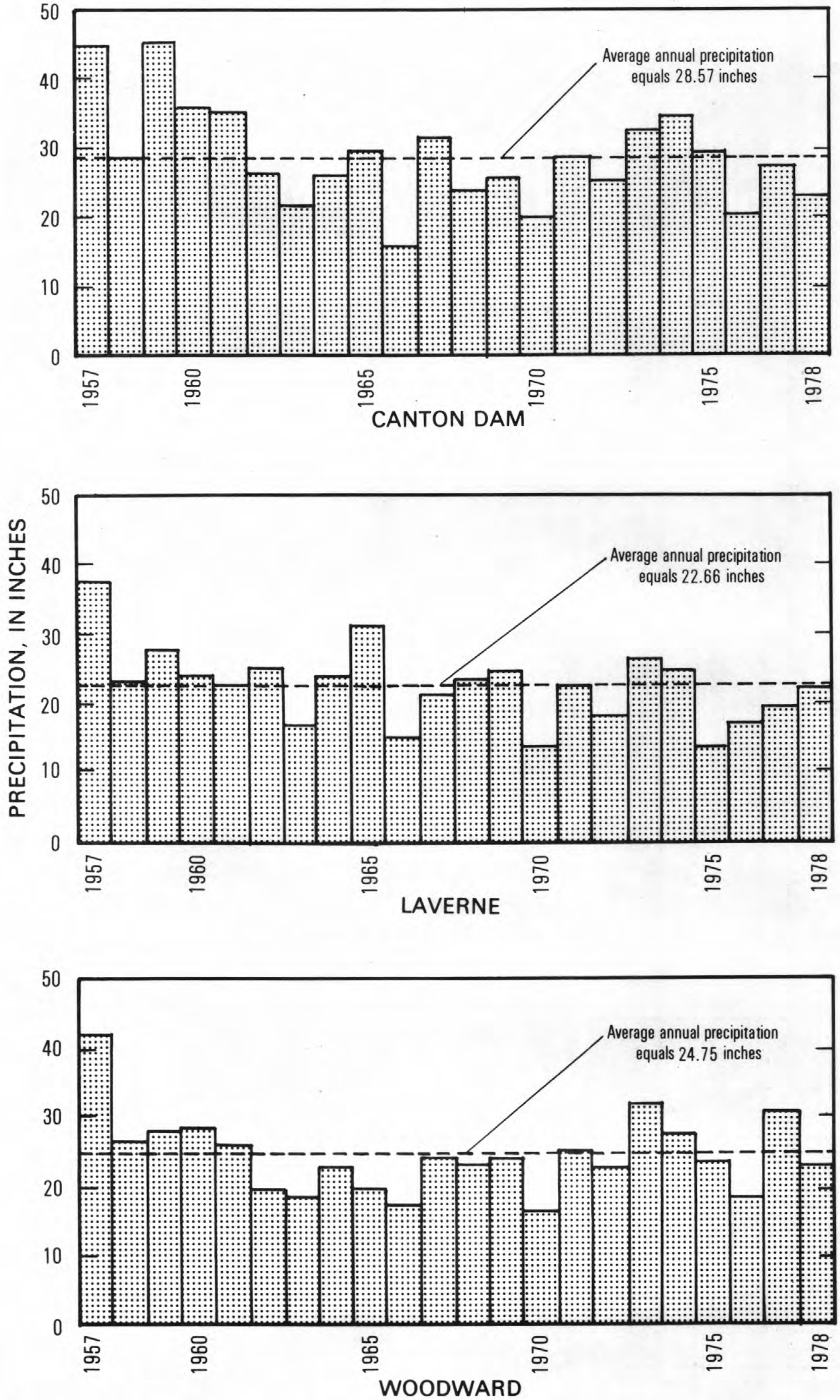


Figure 3.--Graphs showing annual precipitation at Canton Dam, Laverne, and Woodward, 1957-78.

GEOLOGY

The study area consists of 830 mi^2 of Quaternary deposits that occur mainly north of the Beaver-North Canadian River and unconformably overlie the Tertiary Ogallala Formation and Permian formations, or red beds (pl. 1). The location of the Quaternary deposits with respect to the river is probably due to the southerly migration of the river down the regional dip of the underlying red beds and to the prevailing southerly winds which deposit sand from the river channel in the form of dunes on top of the existing terrace deposits (R. O. Fay, Oklahoma Geological Survey, oral commun., 1979). The Quaternary deposits consist of four main units; high-terrace deposits, low-terrace deposits, alluvium, and dune sand.

The alluvium, low-terrace deposits, and high-terrace deposits have many similar lithologic characteristics. All three units consist principally of poorly sorted, fine to coarse, unconsolidated quartz sand with minor amounts of clay, silt, and basal gravel. Colors range from white to red, but buff or brown shades predominate. The high-terrace deposits also contain minor amounts of volcanic ash, bentonite, and soft caliche. The dune sand consists mainly of well-sorted, fine to medium quartz sand (Wood and Stacy, 1965, p. 40-47). All Quaternary deposits are shown as a single unit on plates 2-15.

The high-terrace deposits mainly occur in a band 1.5 to 11 mi wide. These deposits extend from near the north bank of the river to a line generally following the topographic divide between the Cimarron and Beaver-North Canadian Rivers (fig. 1). These deposits are of Pleistocene age and were derived by reworking of the Ogallala Formation and the adjacent Permian formations. Average thickness of the high-terrace deposits is about 70 ft. The maximum thickness, which is north of Rosston, is about 300 ft. However, the area north of Rosston has been previously mapped as the Meade Group (Meyers, 1959, pl. 2) and as the Ogallala Formation (Miser, 1954), so the entire thickness of sand in this area may not be exclusively high-terrace deposits.

The low-terrace deposits occur along both sides of the Beaver-North Canadian River and its tributaries. These deposits are of late Pleistocene age and have an average thickness of about 50 ft.

The alluvium consists of the Holocene channel and flood-plain deposits of the Beaver-North Canadian River and its major tributaries. Thickness of the alluvium averages about 30 ft. The alluvium and low-terrace deposits have a combined width of 0.5 to 2 mi.

Dune sand overlies the alluvium and terrace deposits throughout much of the study area. The dune sand probably is derived from these underlying deposits and is of Holocene age. The dunes reach a maximum height of about 20 ft and vary considerably in thickness.

Occurrence and Movement of Ground Water

The principal aquifer in the study area is composed of the hydrologically connected alluvium and terrace deposits. Water is contained in the voids between sand grains in the zone of saturation. Although the aquifer contains numerous clay layers, they are not areally extensive nor continuous, so that water in the aquifer generally is unconfined.

The general configuration of the base of the aquifer is shown on plate 2. The data used to prepare the map were obtained from Wood and Stacy (1965, p. A1-B25), from drillers' logs on file with the Oklahoma Water Resources Board, from gamma logs, and from well-owners' reports on the depth to the top of the red beds. Most wells in the study area are drilled to the top of the red beds. The base-of-aquifer contours in Woodward County are revised from plate 4 in Wood and Stacy (1965).

The aquifer is underlain in most places by relatively impermeable red beds that generally act as a barrier to vertical and lateral flow of water to and from the alluvium and terrace aquifer. However, hydrologic connection between the red beds and the alluvium and terrace aquifer may occur in T.28 N., R.25 W. where a possible collapse feature may have been caused by a solution of halite and gypsum within the red beds.

The approximate altitude of the potentiometric surface, or water table, in the alluvium and terrace aquifer during 1977-78 is shown on plate 3. The data used to prepare the map are presented in a report by Davis, Christenson, and Blumer, (1980).

Movement of water through the aquifer is from areas of higher head to areas of lower head. The term head, when used in this report, is understood to mean static head. The static head is the height above the National Geodetic Vertical Datum of 1929 of the surface of a column of water that can be supported by the static pressure at a given point (Lohman, 1972). The areas of higher head generally coincide with topographically high areas, or areas farthest from the river. Locally, the areas of lowest head are at or near the river. For an isotropic aquifer, the general direction of movement of water in an area can be determined by drawing flow lines at right angles to the potentiometric contours. Therefore, the general direction of flow is southwesterly, or toward the Beaver-North Canadian River. An exception to this generality is in the area north of Rosston, where the ground water flows in a northeasterly direction due to downward leakage into the red beds and presumably discharges to the Cimarron River. Comparison of plates 2 and 3 shows that the potentiometric surface and the base of the aquifer have similar configurations.

Records of 74 wells in which the water level was measured monthly show only slight variations in the water table from April 1978 to May 1979 (Davis, Christenson, and Blumer, 1980). Hydrographs for three of these wells are shown in figure 4.

Comparison of water-level data from 1977-78 with data from 1955-57 (Wood and Stacy, 1965, p. A1-A9) shows only slight variations in water levels in most parts of Woodward County. However, in the vicinity of T.23 N., R.19 W., water levels at some sites have declined more than 20 ft since 1957 probably due to large withdrawals for irrigation and industrial use.

Hydrologic Properties of Water-Bearing Materials

The quantity of ground water that an aquifer can yield to wells depends upon the hydrologic properties of the aquifer. The ability of an aquifer to transmit water is measured by its transmissivity (T) which is the rate at which water of the prevailing temperature is transmitted through a unit width of the aquifer under a unit hydraulic gradient and may be expressed in units of ft^2/d (Lohman and others, 1972, p. 13). The hydraulic conductivity (K) of an aquifer is the volume of water at the existing temperature that will move in unit time under a unit hydraulic gradient through a unit area measured at right angles to the direction of flow and may be expressed in units of ft/d (Lohman and others, 1972, p. 4). The storage coefficient (S) of an aquifer is the volume of water it releases from or takes into storage per unit surface area of the aquifer per unit change in head (Lohman and others, 1972, p. 13), and is a dimensionless number. Under water-table conditions the storage coefficient is practically equal to the specific yield (Sy) of the aquifer, which is defined as the ratio of the volume of water a saturated material will yield by gravity in proportion to its own volume (Lohman and others, 1972, p. 12).

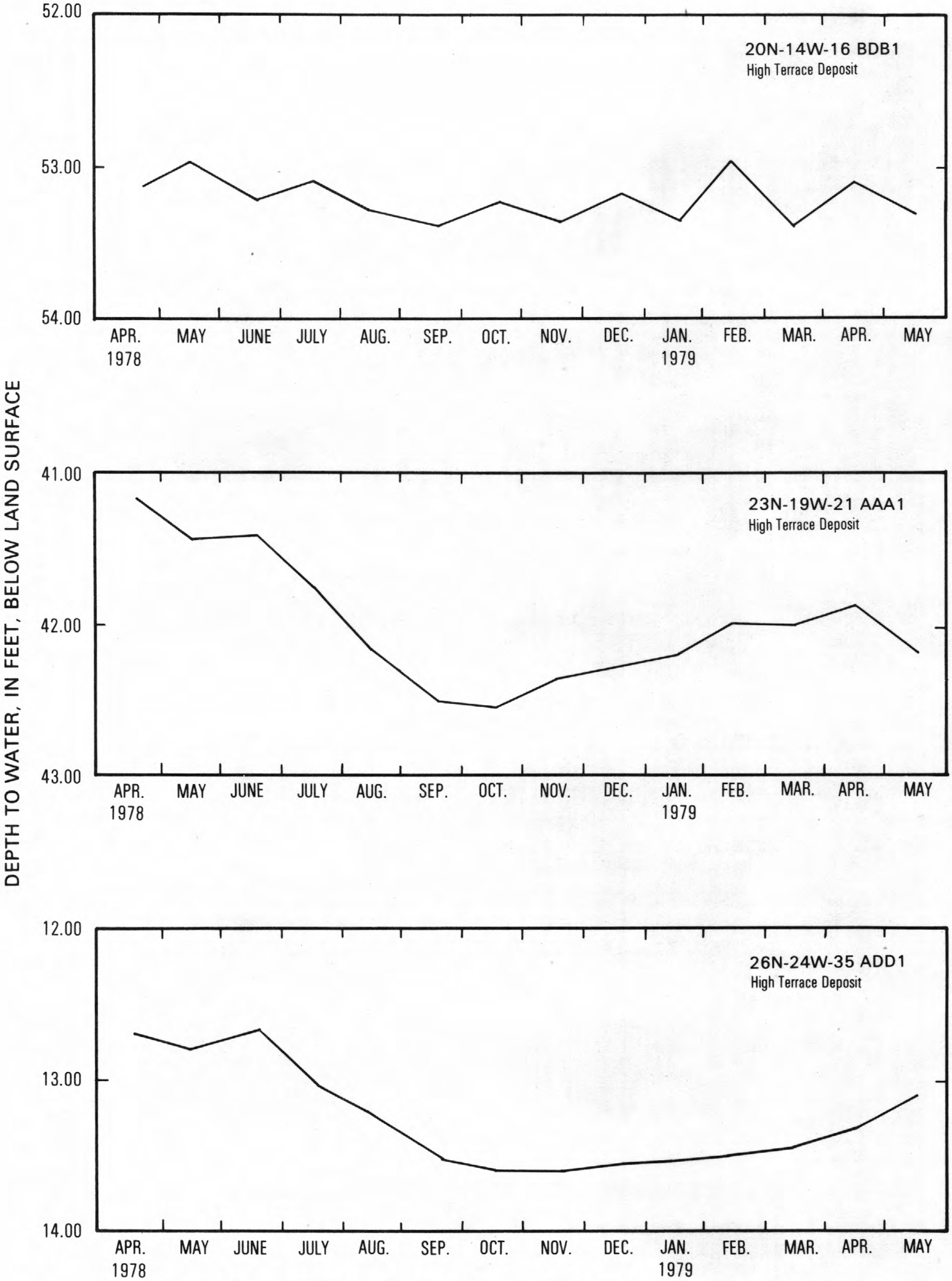


Figure 4.--Hydrographs of wells completed in the alluvium and terrace aquifer.

Digital Simulation Model

The operation of the hydrologic system of the alluvium and terrace aquifer is dependent upon the hydrologic properties of the aquifer and is described using a digital simulation model. The development of the model of the alluvium and terrace aquifer requires that certain assumptions be made. The major assumptions made in this study were:

1. Flow in the aquifer is consistent with Darcy's law.
2. The aquifer is isotropic with respect to hydraulic conductivity in the horizontal direction.
3. At any given point in the aquifer, flow is two-dimensional and the vertical-flow component is negligible in comparison to the horizontal-flow component.
4. The rocks underlying the aquifer form an impervious barrier to the flow of water in most places.
5. Density of the water is constant in time and space.
6. Recharge to the aquifer is constant with time.
7. Wells pumping at the start of a simulated pumping period will pump at the specified rate until the saturated thickness is less than 5 ft, at which time the well will no longer pump.
8. The rate of return flow of applied irrigation water is 20 percent.
9. The hydrological and meteorological conditions outside of the study area which contribute to the average flow and flow frequency of the Beaver-North Canadian River will not change appreciably.

Ground-water flow in two dimensions (assuming vertical flow is insignificant compared to horizontal flow) can be described by the following equation:

$$\frac{\partial}{\partial x}\left(T_{xx}\frac{\partial h}{\partial x}\right) + \frac{\partial}{\partial x}\left(T_{xy}\frac{\partial h}{\partial y}\right) + \frac{\partial}{\partial y}\left(T_{yx}\frac{\partial h}{\partial x}\right) + \frac{\partial}{\partial y}\left(T_{yy}\frac{\partial h}{\partial y}\right) = S\frac{\partial h}{\partial t} + W(x,y,t) \qquad (1)$$

where

T_{xx}, T_{xy}, T_{yx}, T_{yy}	are the components of the transmissivity tensor (L^2/T);
h	is the hydraulic head (L);
S	is the storage coefficient (dimensionless); and
$W(x,y,t)$	is the volumetric flux per unit surface area of the aquifer (L/T).

In an unconfined aquifer, transmissivity is a function of saturated thickness and hydraulic conductivity. By assuming that the Cartesian coordinate axes are aligned with the principal components of the hydraulic-conductivity tensor, the flow equation may be rewritten:

$$\frac{\partial}{\partial x}\left(K_{xx}\, b\frac{\partial h}{\partial x}\right) + \frac{\partial}{\partial y}\left(K_{yy}\, b\frac{\partial h}{\partial y}\right) = Sy\,\frac{\partial h}{\partial t} + W(x,y,t) \qquad (2)$$

where

K_{xx}, K_{yy} are the principal components of the hydraulic-conductivity tensor (L/T);

Sy is the specific yield of the aquifer (dimensionless); and

b is the saturated thickness of the aquifer (L).

Equation 2 has no general solution. However, an approximation for the continuous derivatives can be obtained by the method of finite differences. In this method, the governing differential equation is replaced by an approximating difference equation. The continuous region for which a solution is desired is replaced by an array of discrete points, or nodes. This reduces the probelm to a system of algebraic equations that can be solved for each node, generally by means of a digital computer due to the large size of the system of equations. The finite-difference approximation used is written as:

$$K_{xx(i-\frac{1}{2},j)}\; b^{n-1}_{(i-\frac{1}{2},j,k)}\; \frac{h^n_{(i-1,j,k)} - h^n_{(i,j,k)}}{(\Delta x)^2} \; +$$

$$K_{xx(i+\frac{1}{2},j)}\; b^{n-1}_{(i+\frac{1}{2},j,k)}\; \frac{h^n_{(i+1,j,k)} - h^n_{(i,j,k)}}{(\Delta x)^2} \; +$$

$$K_{yy(i,j-\frac{1}{2})}\; b^{n-1}_{(i,j-\frac{1}{2},k)}\; \frac{h^n_{(i,j-1,k)} - h^n_{(i,j,k)}}{(\Delta y)^2} \; +$$

$$K_{yy(i,j+\frac{1}{2})}\; b^{n-1}_{(i,j+\frac{1}{2},k)}\; \frac{h^n_{(i,j+1,k)} - h^n_{(i,j,k)}}{(\Delta y)^2} \; =$$

$$Sy\,\frac{h^n_{(i,j,k)} - h^n_{(i,j,k-1)}}{\Delta t} + W_{i,j,k} \qquad (3)$$

where

i,j,k	are indices in the x, y, and time dimensions;
n	is the iteration index; and
Δx, Δy, Δt	are the increments in the x, y, and time dimensions.

The source term W(x,y,t) consists of several components. For this study it was computed as:

$$W_{i,j,k} = \frac{Q_{w(i,j,k)}}{\Delta x_j \Delta y_i} - q_{re(i,j,k)} - q'_{(i,j,k)} \qquad (4)$$

where

$Q_{w(i,j,k)}$	is the well discharge (L^3/T);
$q_{re(i,j,k)}$	is the recharge flux from precipitation per unit area (L/T); and
$q'_{(i,j,k)}$	is the flux per unit area through a confining layer (L/T).

A computer program, generally referred to as a digital simulation model, written by Trescott, Pinder, and Larson (1976) was used for the analysis of the hydrologic system. The program was slightly modified by explicitly dimensioning arrays to minimize computer storage requirements, and by printing leakage volumes node-by-node instead of only a summation for the entire model. The data-input subroutine was modified to accept pumpage information in a more convenient format. The program also was modified to terminate pumpage at any node when the saturated thickness at the node decreased to less than 5 ft. If the saturated thickness decreased to zero, the node was excluded from the model and execution continued. Solution to the system of finite-difference equations was by the strongly implicit procedure (Stone, 1968).

Finite-Difference Grid and Boundary Conditions

The alluvium and terrace aquifer was modeled by subdividing the modeled area, which is larger than the study area, into a finite-difference grid having 17 rows and 105 columns (pl. 4). Nodes are located at the centers of the grid blocks. Within the study area, the grid blocks are 1 mi on a side. Most of the modeled area outside the study area has an expanded grid system.

Several types of boundaries were used in the model. The computer program requires that the modeled area be surrounded by a zero-flux, or no-flow boundary, which consists of nodes at which the transmissivity equals zero. Where the aquifer terminates against the relatively impermeable Permian red beds, the no-flow boundary simulates actual conditions. Where the aquifer extends beyond the geographic limit of the study area or generally where the aquifer is in hydrologic connection with the Ogallala Formation, the grid is extended to a distance sufficient to prevent the effects of the no-flow boundary from affecting the modeled response in the study area during the modeled time. The effect in the study area of the no-flow boundary at the edge of the model was checked by a simulation, similar to simulation 4, for the maximum time and at the maximum stress, except using a constant-head boundary adjacent to the edge. The head differences in the study area between this simulation and simulation 4 were negligible.

Constant-flux boundaries are used at two locations in the model. Ground-water flow to the southeast of Canton Dam is simulated by constant withdrawal-flux nodes. In southwestern Harper County and eastern Beaver County, constant flux nodes are used to simulate the flow from the Ogallala aquifer to the alluvium and terrace aquifer.

Constant-head nodes are used to simulate Canton Lake. The stage of Canton Lake is maintained by the U.S. Army, Corps of Engineers at or near an altitude of 1,615 ft. Constant-head nodes also are used to simulate the average stage of the Cimarron River in Beaver County, Okla. and Meade County, Kans.

Vertical leakage is incorporated in the model at several locations. The exchange of water between the aquifer and the Beaver-North Canadian River and Kiowa Creek is modeled as vertical leakage through a confining layer. The confining layer has a thickness of 5 ft and a hydraulic conductivity of 0.001 ft/d. Vertical leakage is used where the aquifer overlaps the northern drainage divide and water has been observed to be discharging from the aquifer to streams which flow toward the Cimarron River. Vertical leakage is also used in the area north of Rosston where the hydraulic gradient indicates that ground water is flowing northward out of the North Canadian River basin. For these last two areas, the confining layer has a hydraulic conductivity of 0.001 ft/d and a thickness ranging from 35 to 300 ft.

The alluvium and terrace deposits along Wolf Creek are not included in the model. A band of these deposits just south of the Beaver-North Canadian River has little or no saturated thickness (Wood and Stacy, 1965, plate 5), which precludes significant ground-water flow between them and the modeled area.

Calibration and Sensitivity Analysis

Calibration of the model consists of adjustment of the values of the hydrologic parameters represented in equation 3 so that the modeled head response accurately simulates measured head response in the aquifer. The data input to the model include the altitude of the base of the aquifer, initial altitude of the potentiometric surface, and discharge, which were measured and therefore not adjusted, and hydraulic conductivity, recharge, and specific yield, the values of which were principally derived from calibration of the model. The values of these parameters designated at a node are representative of the grid block and are within a reasonable range of values for the aquifer. Discussion of the values used for these parameters is included in following sections.

Calibration to steady-state conditions was achieved by simulating the 1957 head distribution in Woodward County and the 1977-78 head distribution in the rest of the study area. As shown on plate 5, water-level data for 1957 were not available for the area exclusive of Woodward County. The 1977-78 water-level data for the area outside of Woodward County are considered representative of 1957 conditions because residents report no significant water-level change and because of relatively small withdrawal rates in the area. Although ground water was being pumped in 1957, the rate of withdrawal was not large enough to cause the head distribution to be significantly different from the steady-state conditions. Therefore, the 1957 head distribution was deemed representative of steady-state conditions. Within Woodward County, the area along the northern boundary of the aquifer in T.21 N., R.17 W., had as much as 20 ft of saturated thickness during 1957 (Wood and Stacy, 1965, pl. 5) but had little or no measured saturated thickness in 1978. The lower head in T.21 N., R.17 W., during 1977-78 must be due to natural causes because no significant pumpage was observed in the area. Because most data on natural recharge and discharge are for 1977-78, the area in T.21 N., R.17 W., was considered as unsaturated for calibration.

The closeness of fit of the steady-state model is measured by the sum of the absolute values of the differences between measured and computed heads at the nodes in the model. For the 785 nodes in the study area, this sum is 3,665 ft, an average of 4.67 ft per node. However, because some of these differences are positive and some are negative, the mean difference between the measured heads and the computed heads at the nodes is only 0.5 ft. These differences are considered to be acceptable because the altitudes of wells used to construct the potentiometric surface are known only to ±10 ft.

As shown in figure 5, changes in the values of aquifer hydraulic conductivity of the confining layer resulted in an increase in the sum of the absolute values of the difference between measured and computed heads, and therefore a less accurate fit. Similarly, figure 6 shows how changes in these values result in changes in the mean difference between steady-state and computed heads. The slopes of the lines connecting the points in figure 6 is indicative of the sensitivity of the model to changes in these values. Changes in recharge rate and aquifer hydraulic conductivity result in substantial changes in the mean difference between measured and computed head, while changes in the hydraulic conductivity of the confining layer caused little change.

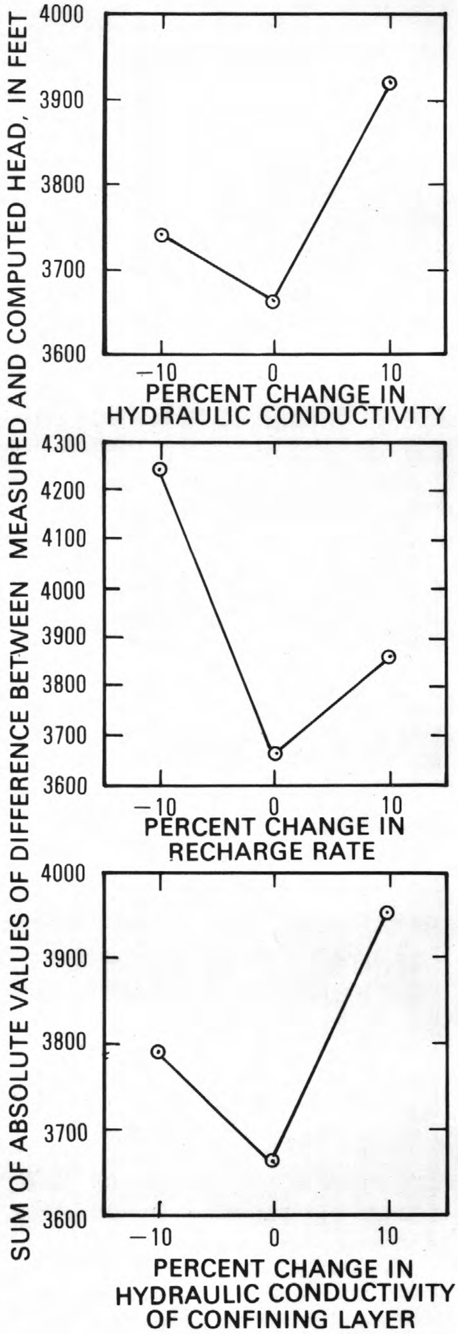


Figure 5.--Closeness of the fit of computed head in the study area as related to changes in aquifer hydraulic conductivity, recharge rate, and hydraulic conductivity of the confining layer, during steady-state simulation of 1957 head distribution.

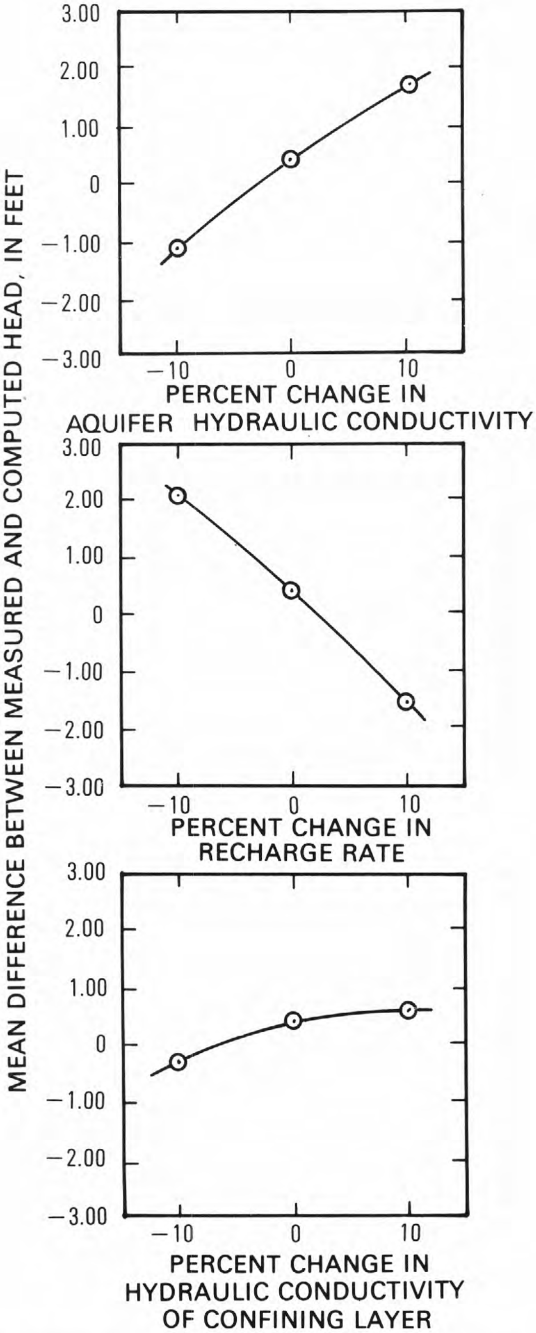


Figure 6.--Sensitivity of computed head in the study area to changes in aquifer hydraulic conductivity, recharge rate, and hydraulic conductivity of the confining layer during steady-state simulation of 1957 head distribution.

The calibration process requires that not only should measured and computed heads match but that measured and computed fluxes (flow rates) should match. A table of steady-state fluxes, usually referred to as a mass balance, is shown below:

Steady-State Mass Balance

	Rate (ft^3/s)
Recharge	+52.642
Boundary flux from Beaver County	+2.174
Constant flux from Ogallala Formation	+0.600
Discharge to streams and evapotranspiration	-44.582
Downward leakage to red beds	-6.818
Constant-head flux	2.687
Boundary flux around Canton Dam	1.323
Sum	+0.006

These fluxes are within the range of the rates estimated for the alluvium and terrace aquifer for 1957. The rates do not sum to zero due to round-off error.

Calibration to transient conditions was achieved by a simulation from 1957 to 1978, with six month time steps, using the specific yield value that resulted in the most accurate simulation of the measured 1978 head distribution, particularly in T.23 N., R.19 W. where the most reliable pumping and head data were available. The calculated head distribution during 1978 is shown in plate 6. The sum of the measured drawdowns during 1978 at nodes representing T.23 N., R.19 W. was 243 ft. The closeness of the fit in T.23 N., R.19 W., achieved by using various values for specific yield in the model during transient calibration, is shown in figure 7. The best fit in this area was achieved by using a specific yield of 0.29.

The sensitivity of the model to changes in specific yield under transient conditions is shown in figure 7. Although figures 7 and 6 are not directly comparable, figure 7 does show that the model is significantly sensitive to changes in specific yield.

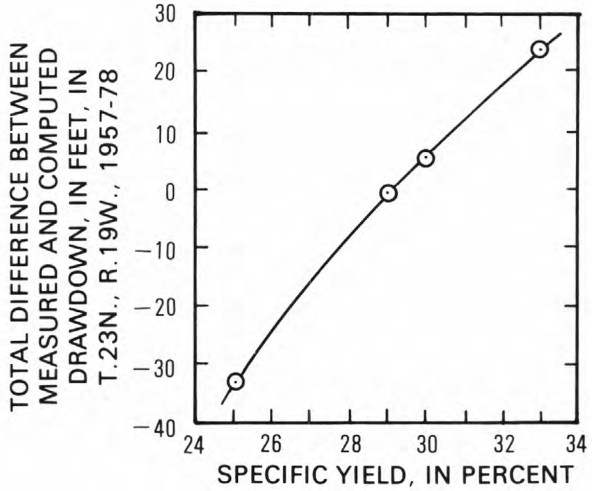


Figure 7.--Closeness of the fit of computed to measured drawdowns and sensitivity of the model as related to changes in specific yield during transient simulation of 1978 head distribution.

Hydraulic Conductivity

The average hydraulic conductivity from six aquifer tests in Woodward County is 131 ft/d (Wood and Stacy, 1965 p. 45). The results of these aquifer tests are shown below:

Location	Saturated thickness (ft)	Specific capacity (gpm/ft)	Hydraulic conductivity (ft/d)
22N-19W-35 CCA 4	39	37	201
23N-18W-30 DDC 1	58	14	80
23N-19W-23 CBD 1	50	26	134
23N-19W-28 ACA 1	35	13	174
23N-20W-07 DBD 5	22	17	147
24N-20W-06 CDB 1	42	5	47

The hydraulic-conductivity values used in the model were determined principally from the steady-state calibration process. The values for the alluvium and terrace aquifer range from 0 to 160 ft/d, and average 59 ft/d. The hydraulic conductivity values determined from the aquifer tests are greater than those used in the model, probably because the large-yield wells used for the aquifer tests generally are located in areas of relatively large hydraulic conductivity. The hydraulic-conductivity values used in the model tend to decrease as distance from the river increases. Where the model extends into Beaver County, the values for hydraulic conductivity remained within the same range of values used in the study area.

A 6th-order trend-surface analysis of the hydraulic conductivity values used in the model is shown on plate 7. Trend-surface analysis fits a surface using an approximating polynomial equation of a specified order to the data such that the squares of the differences between the trend surface and the data values are minimized. In other words, the trend surface represents a smoothing of the data and is used in this situation because it shows the data trends more clearly.

Transmissivity

Transmissivity is calculated by multiplying hydraulic conductivity by saturated thickness. The results of the six aquifer tests in Wood and Stacy (1965, p. 45) show a range in transmissivity from 2,144 to 8,710 ft^2/d, with an average of 5,315 ft^2/d. The 1978 transmissivity values for the alluvium and terrace aquifer used in the model range from 0 to 8,061 ft^2/d, and average 1,780 ft^2/d.

Specific Yield

Specific yield in unconfined aquifers of fine to medium sand generally ranges from 0.10 to 0.32 (Johnson and others, 1972, p. D70). The specific yield values determined from the aquifer tests in Wood and Stacy (1965, p. 45) range from 0.02 to 0.07, which are probably too small due to the relatively short length of the tests. However, specific yield was determined using the measured drawdown in T.23 N., R.19 W., and known pumping rates for industrial and irrigation use. A specific yield value of 0.29, when used in the model, most accurately simulated the measured drawdown in this area (fig. 6). No other area of significant drawdown, from which specific yield could be determined, was observed or reported within the study area. Therefore, a specific-yield value of 0.29 was used throughout the modeled area.

There are several possible sources of error in this specific yield determination. Any error in estimating recharge, pumping, or return flow from irrigation will cause error in the specific yield value. Considering all these possible sources of error, the maximum possible error in the specific yield value should be less than 20 percent.

Discharge

Discharge from the alluvium and terrace aquifer occurs as evapotranspiration, discharge to the Beaver-North Canadian River, leakage to adjacent formations, and as pumpage for public-supply, industrial, and irrigation use. Evapotranspiration occurs mainly near the river within a 140 mi^2 area where the water table is less than 10 ft below land surface. Most evapotranspiration occurs from March through October, as calculated by the Blaney-Criddle method (1962). The evapotranspiration rate from the saturated zone is determined by comparing the difference in low-flow discharge for summer and winter seasons. The difference in net contribution from the aquifer to the Beaver-North Canadian River is about 20 ft^3/s, as measured in August 1978 and March 1979 at 20N-16W-36 CB (Davis, Christenson, and Blumer, 1980). Due to the location of the measurement site, only 120 mi^2 of the evapotranspiration area are included. The difference in net contribution from the entire aquifer is estimated to be 24 ft^3/s. Therefore, the rate of evapotranspiration from the saturated zone is approximately 2.3 in./yr, or 0.19 (acre-ft/acre)/yr, in the 140 mi^2 area. Such a small rate of evapotranspiration from the saturated zone indicates that the water requirements of vegetation near the river are largely met by precipitation. In the model, evapotranspiration is included as part of the leakage to the river.

Of the 830 mi^2 included in the study area, only 700 mi^2 contribute ground water to the Beaver-North Canadian River. In an 80 mi^2 area north of Rosston, the hydraulic gradient is toward the Cimarron River (pl. 3). Because of the lack of surface discharge in the 80 mi^2 area, the water is assumed to be leaking into underlying formations. The rate of leakage was determined from steady-state calibration of the model to be 5.2 ft^3/s.

Several other small areas where the hydraulic gradient was observed to be away from the river were also modeled as leaking to underlying formations. In the steady-state model, the total flux to the underlying formations was 6.8 ft^3/s.

In an area of 50 mi^2 along Wolf Creek, the discharge is to the creek and Fort Supply Lake. The band of little or no saturated thickness at the northern edge of this area precludes significant flux from the area to the Beaver-North Canadian River.

The model-derived steady-state discharge from the aquifer to the river is 44.58 ft^3/s. No stream-discharge measurements are available from 1957 to verify that this value is correct. However, low-flow discharge from the aquifer to the Beaver-North Canadian River, as measured in March 1979 at 19N-14W-06 CA, is about 31 ft^3/s. Examination of long-term streamflow records indicated that discharges measured during March 1979 are representative of near-average conditions. Due to the location of the measurement sites, only 600 mi^2 of the aquifer are contributing to the measured flow. Proportionately, the ground-water flow from the 700 mi^2 contributing area of the aquifer to the river is estimated to be 36 ft^3/s. The model-calculated discharge value corresponding to March 1979 is 38.3 ft^3/s, slightly higher than the measured value. The stream-discharge measurement was done at a time when antecedent precipitation was below normal, so discharge from the aquifer to the stream was probably slightly lower than normal.

Discharge from the aquifer into Canton Lake is simulated by placing constant-head nodes at the location of Canton Lake. The model-derived value of this flux is 2.69 ft^3/s.

Discharge also occurs through the artificial boundary that extends parallel to Canton Dam at the southeastern edge of the study area. The rate of discharge across this boundary was determined from steady-state calibration to be approximately 1.3 ft^3/s. Subsurface flow through the artificial boundary at the western edge of the study area was similarly determined to be approximately 2.2 ft^3/s.

Rates of pumpage for public-supply, industrial, and irrigation use from the aquifer during 1958-77 are shown in figure 8. Industrial use is based on data from the Oklahoma Water Resources Board. Public-supply use is based on data from the Oklahoma Water Resources Board and from city water managers. Irrigation use is based on on-site irrigated-acreage data and data from the Oklahoma Water Resources Board and a pumping rate of 1.4 (acre-ft/acre)/yr. This pumping rate was determined using the Blaney-Criddle method (1962), and also by comparing power-consumption records from 1970-77 with estimated yields for wells having electric pumps. Total pumpage from the aquifer increased from about 11 ft^3/s, or 8,000 acre-ft per year, during 1958 to about 28 ft^3/s, or 20,300 acre-ft per year, during 1977.

The return flow to the aquifer of irrigation water is estimated to be 20 percent of the pumpage. This water is not included as recharge but is subtracted from the irrigation withdrawal in the model.

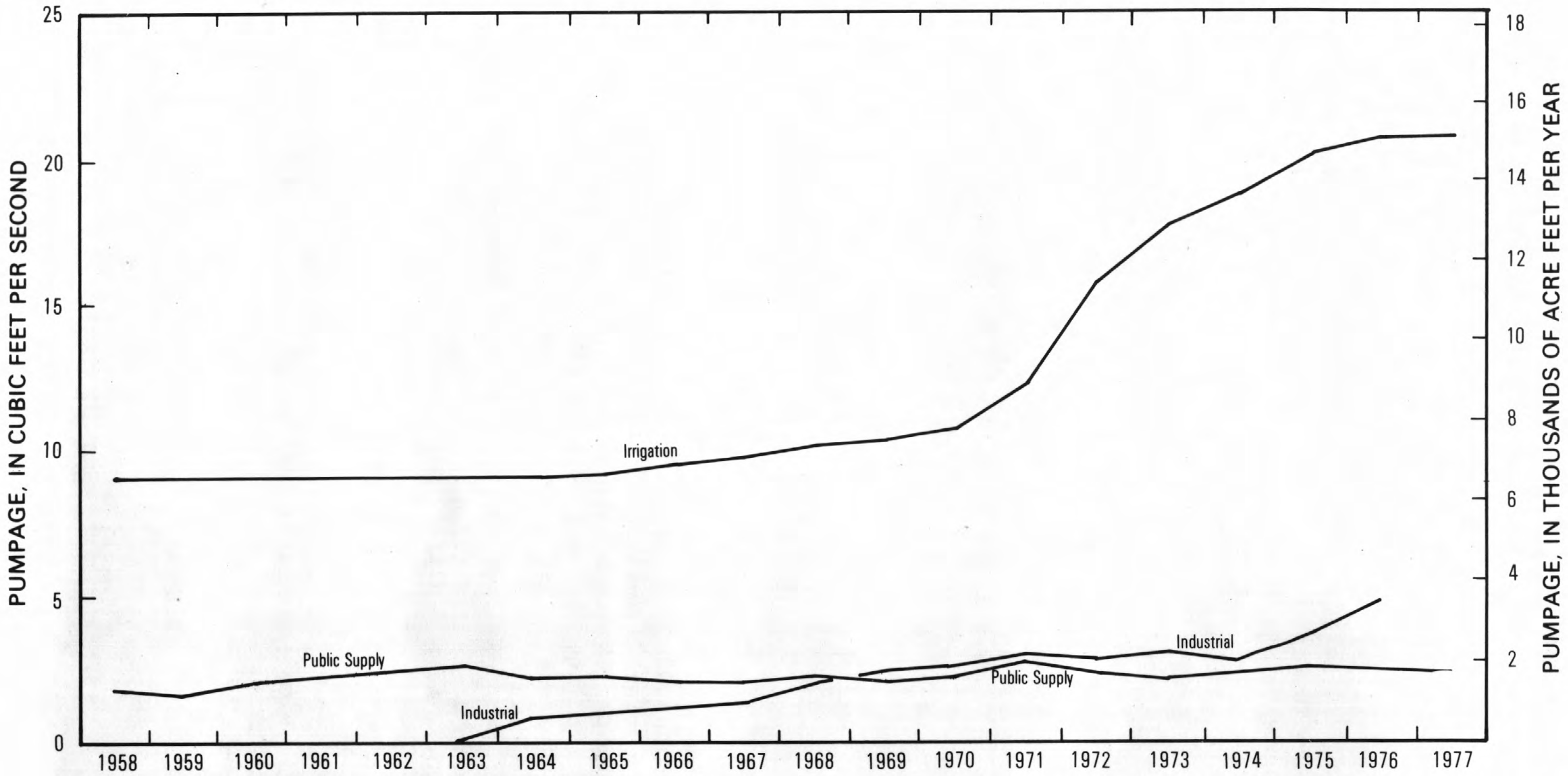


Figure 8.--Annual pumpage from the alluvium and terrace aquifer for public-supply, industrial, and irrigation use, 1958-1977.

Recharge

Recharge to the aquifer is from infiltration of precipitation. Most recharge occurs from November through February when evapotranspiration is small. Even though precipitation is greatest during the late spring and summer, the demand for water by evapotranspiration during this time greatly exceeds the amount available from precipitation. Locally, the amount of recharge is a function of soil type. The soil types in the study area do not vary appreciably (U.S. Department of Agriculture, 1960; 1963a; 1966; 1968a,b), so recharge is assumed to be uniform throughout the study area.

Recharge can be estimated from winter stream discharge. During the winter, when evapotranspiration and irrigation pumpage cease, the main discharge from the aquifer is base flow to the stream. Because the rate of outflow is equal to the rate of inflow, base flow to the river gives a good estimate of recharge. As stated previously, the net discharge from the aquifer to the Beaver-North Canadian River was estimated to be 36 ft^3/s during March 1979. Distributed over the 700 mi^2 contribution area, discharge, and therefore recharge, equals 0.70 in./yr. However, this recharge value probably is small because: (1) Model simulations indicate that ground-water pumpage has decreased base-flow (from 44.6 to 38.3 ft^3/s), and (2) precipitation at Woodward, Canton Dam, and Laverne from November 1978 through February 1979 averaged 74 percent of the 1957-78 normal.

Recharge also can be estimated using a monthly water balance, as described by Thornthwaite (1948). By this method it is assumed that recharge from precipitation occurs only when the soil is completely saturated. The degree of saturation is determined by the rates of precipitation and evapotranspiration. Potential evapotranspiration is estimated by the method of Blaney and Criddle (1962), which gives good results for the sub-humid environment of the study area. Based on the monthly water balance, potential recharge for an area near Woodward is estimated at 1.15 in./yr.

Considering both the base-flow method and the monthly-water-balance method of estimating recharge, and the degree of accuracy of these methods, a value of 1 in./yr was used uniformly throughout the modeled area.

Saturated Thickness and Volume of Water in Storage

Saturated thickness at any location is calculated by subtracting the altitude of the base of the aquifer from the altitude of the potentiometric surface at that location. Because these data are known with reasonable accuracy, they were not adjusted in the calibration process. The 1978 saturated thickness (pl. 8) was determined by the results of a model simulation from 1957 to 1978 using the pumping rates shown in figure 8. The greatest saturated thickness is generally centrally located between the Beaver-North Canadian River and the topographic divide north of the river. During 1978, saturated thickness ranged from 0 to 101 ft, and averaged 30.6 ft with a standard deviation of 17 ft. Based on calculated saturated thickness values and a specific yield of 0.29, the aquifer contained 4.07 million acre-ft of water during 1978.

Modeled Projections of Saturated Thickness and Storage

The model was used to simulate the head response in the aquifer to various pumping stresses during several simulation periods. A total of six simulations were made. All simulations used six-month time steps.

Simulation 1 was a simulation from 1978 to 1993, using the 1977 pumping rates and well distribution and a 1 in./yr recharge rate. The 1993 saturated thickness projected by simulation 1 is shown on plate 9. The projected amount of water in storage in 1993 is 3.94 million acre-ft and the projected average saturated thickness is 29.6 ft. At the end of simulation 1, the rate of leakage from the aquifer to the river was 36 ft^3/s.

Simulation 2 was a continuation of simulation 1 to 2020, using the 1977 pumping rates and well distribution. The 2020 saturated thickness projected by simulation 2 is shown on plate 10. The projected amount of water in storage in 2020 is 3.84 million acre-ft and the projected average saturated thickness is 28.9 ft. At the end of simulation 2, the rate of leakage from the aquifer to the river was 33^{3}ft /s.

Comparison of the average saturated thickness and the volume of water in storage in 1978 with the results of simulations 1 and 2 shows that continuation of the 1977 pumping stress through 2020 will have little effect on the aquifer as a whole.

Simulation 3 was a simulation from 1978 to 1993, using a 1 in./yr recharge rate and an initial pumping rate of 1.4 acre-ft/acre for every node in the study area unless the 1977 rate was greater, in which instance the greater value was used. Due to the saturated thickness at some nodes decreasing to less than 5 ft, the average pumping rate for simulation 3 was 0.70 (acre-ft/acre)/yr. The 1993 saturated thickness projected by simulation 3 is shown in plate 11. The projected amount of water in storage in 1993 is 1.28 million acre-ft and the projected average saturated thickness is 9.7 ft. At the end of simulation 3, the rate of leakage from the river to the aquifer was 53 ft^3/s.

Simulation 4 was a continuation of simulation 3 to 2020. The average pumping rate for simulation 4, from 1993 to 2020, was 0.39 (acre-ft/acre)/yr. The 2020 saturated thickness projected by simulation 4 is shown on plate 12. The projected amount of water in storage in 2020 is 980,000 acre-ft and the projected average saturated thickness is 7.5 ft. At the end of simulation 4, the rate of leakage from the river to the aquifer was 60 ft^3/s.

Simulations 3 and 4 were used to simulate extreme pumping-stress conditions. Comparison of the average saturated thickness and the volume of water in storage during 1978 to the results of simulations 3 and 4 shows that such an extreme pumping stress would greatly reduce the saturated thickness and volume of water in storage in the aquifer. The extreme pumping stress would also change the Beaver-North Canadian River from a gaining stream to a losing stream.

Simulation 5 and 6 were made at the request of the Oklahoma Water Resources Board in order to provide information for use in the application of Oklahoma's ground-water law. Simulation 5 was a simulation from 1957 to 1973 using a 1 in./yr recharge rate and the pumping rates shown in figure 8. The 1973 saturated thickness projected by simulation 5 is shown on plate 13. As determined by this simulation, the amount of water in storage in the ground-water basin in 1973 was 4.11 million acre-ft and the average saturated thickness was 32.6 ft.

Simulation 6 was a simulation from 1973 to 1993 to determine the pumping rate necessary to reduce the 1973 saturated thickness to less than 5 ft for one-half of the acreage in the ground-water basin. At the request of the Oklahoma Water Resources Board, in this simulation the boundary of the study area was simulated as a no-flow boundary and the recharge rate was increased to 2.5 in./yr. The initial pumping rate was assumed to be equal throughout the ground-water basin except where prior rights had allocated a greater share. The saturated thickness in all areas was checked by the model at the beginning of every simulated six-month period. For all areas having 5 ft or more of saturated thickness, pumpage was maintained at the initial rate for the entire succeeding six-month period. The initial pumping rate was 1.0 (acre-ft/acre)/yr. Due to the saturated thickness at some nodes decreasing to less than 5 ft, the average pumping rate for the 20-year period was 0.73 (acre-ft/acre)/yr. The saturated thickness projected by simulation 6 is shown on plate 14. As determined by this simulation, the amount of water in the ground-water basin in 1993 is 1.21 million acre-ft and the average saturated thickness is 9.6 ft. Simulation 6 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 the report.

Water Quality

Specific conductance, in micromhos per centimeter at 25° Celsius of water from 70 wells completed in the alluvium and terrace aquifer is shown in plate 15. Water samples from 30 of these wells were analyzed to determine the concentration of the common chemical constituents in the water (table 1). Fifteen of the 30 samples also were analyzed for trace constituents. All sampling was done during the summer of 1978.

The specific conductance of water is a measure of the dissolved-solids concentration. The relationship of specific conductance to dissolved-solids concentration of the water from the alluvium and terrace aquifer is shown in figure 9. The specific conductance values on plate 15 may be converted to dissolved-solids concentration, in milligrams per liter, using the information in figure 9.

In general, the water in the aquifer is a calcium bicarbonate type and is suitable for most uses; most of the samples contained less than 500 mg/L (milligrams per liter) of dissolved solids. In the area north of Rosston, the water is mainly a sodium chloride type; two samples from this area contained greater than 1,000 mg/L of dissolved solids. Samples from two wells (24N-22W-06 DAC 1 and 25N-24W-05 DBD 1) were of a calcium sulfate type and contained more than 1,600 mg/L of dissolved solids. Some water in the Permian formations of Woodward County is of a calcium sulfate type (Wood and Stacy, 1965, p. 71). Therefore, Permian formations, which crop out within the study area near these wells, are probably the source of the sulfate.

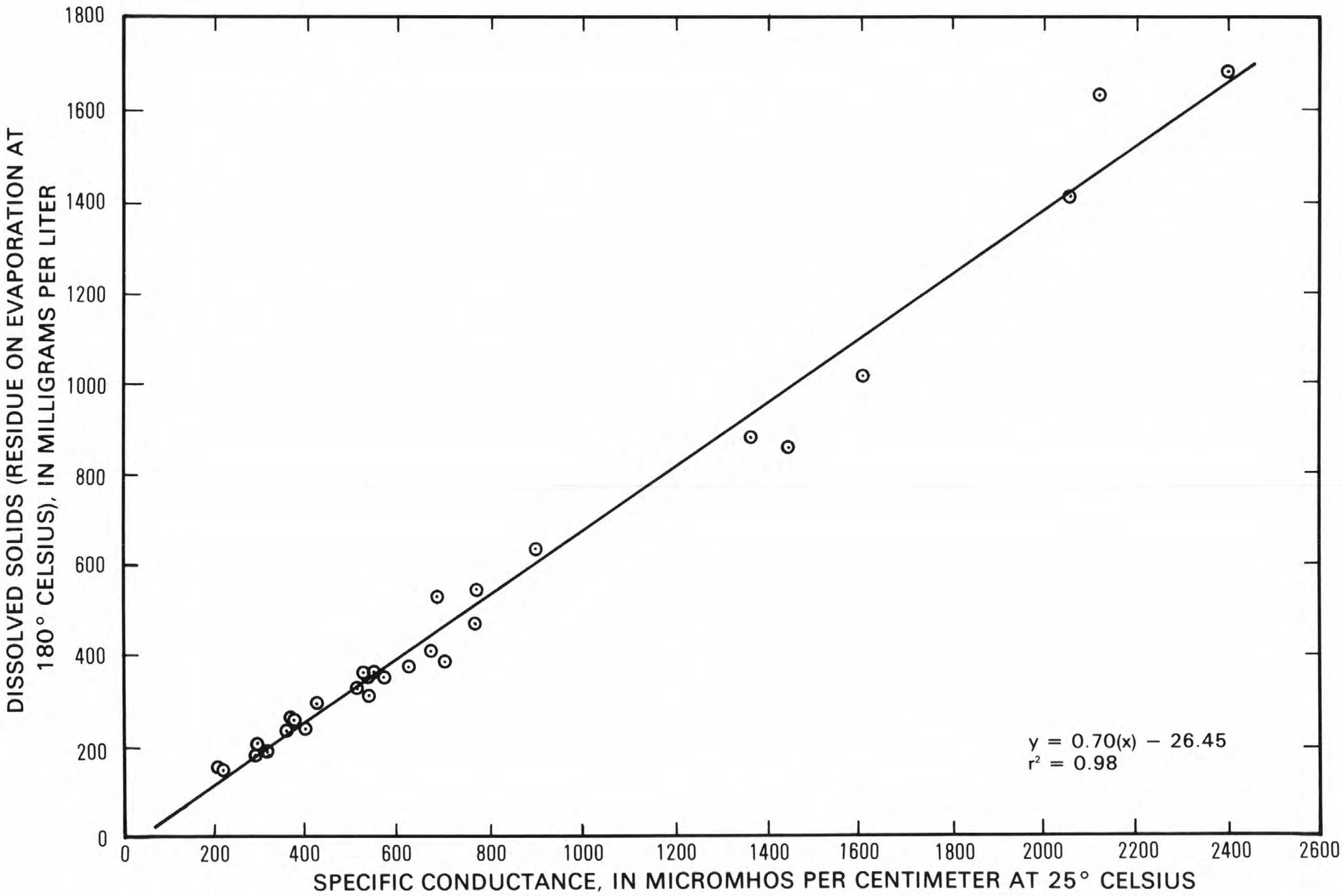


Figure 9.--Relationship between specific conductance and dissolved-solids concentration of water from the alluvium and terrace aquifer.

Concentration limits for selected chemical constituents in water for public supply, livestock, and irrigation uses are listed in table 2. All limits are those required by the U.S. Environmental Protection Agency (1975, p. 59570) or those recommended by the National Academy of Science and National Academy of Engineering (1972), as indicated in the table. The constituent concentrations that exceeded these limits are noted in table 1. Most of the samples had a low sodium hazard and a medium salinity hazard for use as irrigation water (U.S. Salinity Laboratory Staff, 1954).

Eight samples contained concentrations of total nitrogen in excess of the limit required by the U.S. Environmental Protection Agency (1975, p. 59570) for public supply (tables 1 and 2). Seven of these samples were from wells used for livestock watering. Due to the preponderance of livestock near the wells, livestock waste is possibly the source of the high nitrogen concentrations.

OUTLOOK FOR THE FUTURE

In general, the aquifer is and will continue to be an important source of water with quality suitable for all uses if development continues at or near the present rate. However, a large-scale increase in pumpage from the aquifer will result in a large decrease in head and subsequent decreases in saturated thickness and volume of water in storage. A decrease in saturated thickness will result in decreased well yields and may necessitate the use of manifold-type well systems by users requiring relatively large yields. A large-scale increase in pumpage from the aquifer also will reduce the flow in the Beaver-North Canadian River.

FUTURE USE OF THE MODEL

The quantitative data and results presented in this paper are only a small part of the information available through use of the model. Should changes in stress or environmental conditions occur, the model can be modified and used again.

This model was designed to simulate relatively large-scale effects. In the future, detailed studies of smaller areas may be desirable or necessary to determine the local effects of relatively large pumping rates.

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Table 1.--Concentrations of common constituents and selected trace elements, and physical properties of water from selected wells completed in the alluvium and terrace aquifer.

[DEG. C, degrees Celsius; MICROMHOS, micromhos per centimeter at 25°C; MG/L, milligrams per liter; UG/L, micrograms per liter.]

LOCAL IDENT-I-FIER	STATION NUMBER	DATE OF SAMPLE	GEO-LOGIC UNIT	TEMPER-ATURE (DEG C)	PH (UNITS)	SPE-CIFIC CON-DUCT-ANCE (MICRO-MHOS)	SOLIDS, RESIDUE AT 180 DEG. C DIS-SOLVED (MG/L)	SOLIDS, DIS-SOLVED (TONS PER AC-FT)	ALKA-LINITY (MG/L AS CACO3)
19N-13W-02 ADA 1	360919098325201	78-08-22	112TRRCH	18.0	6.7	510	327	.44	92
19N-15W-01 BDA 1	360917098451101	78-08-22	110ALVM	18.0	7.3	1361	872	1.19	310
20N-14W-19 BBC 1	361202098442901	78-08-22	112TRRCH	17.5	6.4	535	349	.47	130
20N-14W-36 ABB 2	361022098384001	78-08-22	112TRRCH	17.0	6.9	530	353	.48	150
20N-15W-01 BCB 1	361429098453701	78-08-22	112TRRCH	18.0	6.6	895	634	.86	170
20N-15W-06 BCC 1	361423098505501	78-08-22	112TRRCH	17.5	6.9	400	234	.32	190
20N-15W-26 CCD 1	361025098462801	78-08-22	112TRRCH	16.5	6.6	425	293	.40	130
21N-17W-22 AAD 1	361713098594601	78-08-22	112TRRCH	17.0	6.9	285	183	.25	140
21N-17W-35 DDD 1	361453098584301	78-08-22	112TRRCH	17.0	6.4	375	252	.34	99
21N-18W-12 BBA 1	361905099045601	78-08-23	112TRRCH	17.0	7.2	360	230	.31	160
22N-18W-06 AAB 1	362513099093601	78-08-23	112TRRCH	16.0	6.8	370	255	.35	89
22N-19W-10 DDD 1	362337099124401	78-08-23	112TRRCH	16.5	7.3	625	375	.51	210
23N-18W-28 CBB 1	362630099081601	78-08-23	112TRRCH	16.5	7.0	550	357	.49	200
24N-20W-09 ABB 2	363440099203802	78-08-23	112TRRCH	18.0	6.8	220	149	.20	65
24N-20W-24 ABA 1	363259099171501	78-08-23	112TRRCH	18.0	6.5	290	209	.28	50
24N-20W-31 CCC 1	363023099231901	78-08-22	112TRRCH	16.5	6.9	210	151	.21	64
24N-21W-14 CDA 1	363308099245801	78-08-22	112TRRCH	16.5	7.2	222	148	.20	82
24N-22W-06 DAC 1	363502099352101	78-08-23	110TRRCL	18.0	7.4	2118	1630	2.22	220
24N-22W-26 AAC 1	363156099310401	78-08-23	112TRRCH	23.5	7.1	310	191	.26	130
25N-23W-04 BAB 1	364049099411301	78-08-23	112TRRCH	18.0	7.4	530	352	.48	250
25N-23W-24 BBC 1	363802099381201	78-08-23	112TRRCH	17.0	7.5	670	527	.72	170
25N-24W-05 DBD 1	364012099482101	78-08-23	110TRRCL	16.0	7.1	2400	1690	2.30	280
26N-25W-26 CCC 1	364144099521501	78-08-23	110TRRCL	16.5	7.4	650	387	.53	210
26N-26W-01 CDB 1	364520099572901	78-08-23	112TRRCH	20.0	7.4	770	470	.64	200
27N-25W-35 BAA 1	364654099515301	78-08-23	112TRRCH	16.5	7.1	772	543	.74	230
27N-25W-35 CAB 1	364627099520101	78-08-23	112TRRCH	17.0	7.3	2050	1410	1.92	200
27N-26W-12 DAD 1	364954099564201	78-08-23	112TRRCH	17.0	7.4	569	349	.47	240
27N-26W-22 CDB 1	364759099593701	78-08-23	112TRRCH	16.0	7.3	1605	1010	1.37	210
28N-26W-23 ABD 1	365348099580401	78-08-23	112TRRCH	16.5	7.1	671	412	.56	190
28N-26W-34 ABA 1	365211099591301	78-08-23	112TRRCH	17.5	7.3	1440	851	1.16	230

See footnotes at end of table, p. 41.

Table 1.--Concentrations of common constituents and selected trace elements, and physical properties of water from selected wells completed in the alluvium and terrace aquifer--Continued.

LOCAL IDENT-I-FIER	DATE OF SAMPLE	ARSENIC DIS-SOLVED (UG/L AS AS)	BORON, DIS-SOLVED (UG/L AS B)	CADMIUM DIS-SOLVED (UG/L AS CD)	CALCIUM DIS-SOLVED (MG/L AS CA)	CHLO-RIDE, DIS-SOLVED (MG/L AS CL)	CHRO-MIUM, DIS-SOLVED (UG/L AS CR)	COPPER, DIS-SOLVED (UG/L AS CU)	FLUO-RIDE, DIS-SOLVED (MG/L AS F)	HARD-NESS (MG/L AS CACO3)
19N-13W-02 ADA 1	78-08-22	--	60	--	52	20	--	--	.2	180
19N-15W-01 BDA 1	78-08-22	1	130	0	120	120	0	0	1.1	460
20N-14W-19 BBC 1	78-08-22	1	30	0	72	32	0	0	.3	240
20N-14W-36 ABB 2	78-08-22	--	40	--	68	23	--	--	.4	230
20N-15W-01 BCB 1	78-08-22	2	70	0	110	65	0	0	.2	370
20N-15W-06 BCC 1	78-08-22	--	30	--	51	13	--	--	.2	200
20N-15W-26 CCD 1	78-08-22	1	30	0	60	13	10	20	.3	200
21N-17W-22 AAD 1	78-08-22	--	30	--	46	5.8	--	--	.3	150
21N-17W-35 DDD 1	78-08-22	2	20	0	50	11	0	0	.2	160
21N-18W-12 BBA 1	78-08-23	--	30	--	52	8.1	--	--	.2	180
22N-18W-06 AAB 1	78-08-23	1	20	0	48	11	0	0	.4	150
22N-19W-10 DDD 1	78-08-23	4	60	0	68	30	10	0	.5	230
23N-18W-28 CBB 1	78-08-23	1	90	0	79	11	0	0	.3	250
24N-20W-09 ABB 2	78-08-23	--	20	--	25	4.0	--	--	.2	85
24N-20W-24 ABA 1	78-08-23	--	20	--	32	7.7	--	--	.1	100
24N-20W-31 CCC 1	78-08-22	2	20	0	26	6.6	0	0	.2	81
24N-21W-14 CDA 1	78-08-22	--	20	--	30	7.2	--	--	.4	93
24N-22W-06 DAC 1	78-08-23	--	170	--	240	130	--	--	.7	970
24N-22W-26 AAC 1	78-08-23	--	20	--	41	3.9	--	--	.6	140
25N-23W-04 BAB 1	78-08-23	--	30	--	65	11	--	--	.5	280
25N-23W-24 BBC 1	78-08-23	3	60	0	85	18	0	0	.3	350
25N-24W-05 DBD 1	78-08-23	3	210	10	270	230	0	0	.9	950
26N-25W-26 CCC 1	78-08-23	--	80	--	84	21	--	--	.8	300
26N-26W-01 CDB 1	78-08-23	--	70	--	90	100	--	--	.7	290
27N-25W-35 BAA 1	78-08-23	--	50	--	120	32	--	--	.2	350
27N-25W-35 CAB 1	78-08-23	--	50	--	200	570[b]	--	--	.5	580
27N-26W-12 DAD 1	78-08-23	3	130	0	54	8.7	0	0	.8	180
27N-26W-22 CDB 1	78-08-23	2	150	0	99	330[b]	0	0	1.2	400
28N-26W-23 ABD 1	78-08-23	4	100	0	89	42	10	70	.4	280
28N-26W-34 ABA 1	78-08-23	2	170	0	93	230	0	0	.9	360

See footnotes at end of table, p. 41.

Table 1.--Concentrations of common constituents and selected trace elements, and physical properties of water from selected wells completed in the alluvium and terrace aquifer--Continued.

LOCAL IDENT-I-FIER	DATE OF SAMPLE	IRON, DIS-SOLVED (UG/L AS FE)	LEAD, DIS-SOLVED (UG/L AS PB)	MAGNE-SIUM, DIS-SOLVED (MG/L AS MG)	MANGA-NESE, DIS-SOLVED (UG/L AS MN)	MERCURY DIS-SOLVED (UG/L AS HG)	NITRO-GEN, NO2+NO3 DIS-SOLVED (MG/L AS N)	POTAS-SIUM, DIS-SOLVED (MG/L AS K)	SELE-NIUM, DIS-SOLVED (UG/L AS SE)	SILICA, DIS-SOLVED (MG/L AS SIO2)
19N-13W-02 ADA 1	78-08-22	--	--	13	--	--	21[a]	1.7	--	20
19N-15W-01 BDA 1	78-08-22	720[b]	0	40	420[bc]	.0	.28	3.3	0	31
20N-14W-19 BBC 1	78-08-22	20	0	14	0	.0	5.0	2.3	3	24
20N-14W-36 ABB 2	78-08-22	--	--	14	--	--	12[a]	1.8	--	24
20N-15W-01 BCB 1	78-08-22	50	0	23	10	.0	35[a]	2.5	0	27
20N-15W-06 BCC 1	78-08-22	--	--	17	--	--	.84	1.9	--	27
20N-15W-26 CCD 1	78-08-22	50	0	11	10	.0	5.4	1.4	2	25
21N-17W-22 AAD 1	78-08-22	--	--	8.6	--	--	1.3	4.6	--	23
21N-17W-35 DDD 1	78-08-22	20	0	9.3	0	.0	14[a]	1.3	1	28
21N-18W-12 BBA 1	78-08-23	--	--	11	--	--	3.0	1.2	--	27
22N-18W-06 AAB 1	78-08-23	20	0	6.9	0	.0	14[a]	.9	1	24
22N-19W-10 DDD 1	78-08-23	50	0	15	0	.0	3.9	1.8	2	26
23N-18W-28 CBB 1	78-08-23	430[b]	0	12	10	.0	8.2	2.0	1	27
24N-20W-09 ABB 2	78-08-23	--	--	5.4	--	--	6.6	2.2	--	26
24N-20W-24 ABA 1	78-08-23	--	--	5.2	--	--	12[a]	2.9	--	28
24N-20W-31 CCC 1	78-08-22	20	0	3.9	0	.0	4.7	1.2	2	34
24N-21W-14 CDA 1	78-08-22	--	--	4.4	--	--	3.4	1.5	--	29
24N-22W-06 DAC 1	78-08-23	--	--	90	--	--	9.2	2.8	--	34
24N-22W-26 AAC 1	78-08-23	--	--	9.0	--	--	3.1	.9	--	29
25N-23W-04 BAB 1	78-08-23	--	--	29	--	--	4.3	1.2	--	48
25N-23W-24 BBC 1	78-08-23	20	0	33	10	.0	12[a]	1.8	0	41
25N-24W-05 DBD 1	78-08-23	50	0	67	120[b]	.0	.12	3.9	0	28
26N-25W-26 CCC 1	78-08-23	--	--	21	--	--	9.1	1.7	--	31
26N-26W-01 CDB 1	78-08-23	--	--	15	--	--	.83	2.6	--	29
27N-25W-35 BAA 1	78-08-23	--	--	13	--	--	28[a]	2.6	--	29
27N-25W-35 CAB 1	78-08-23	--	--	20	--	--	6.5	3.8	--	25
27N-26W-12 DAD 1	78-08-23	20	0	10	0	.0	7.5	2.9	3	23
27N-26W-22 CDB 1	78-08-23	20	0	37	10	.0	.11	4.6	0	26
28N-26W-23 ABD 1	78-08-23	20	0	14	0	.0	9.9	4.0	6	24
28N-26W-34 ABA 1	78-08-23	50	0	30	0	.0	4.2	3.9	25[bc]	20

See footnotes at end of table, p. 41.

Table 1.--Concentrations of common constituents and selected trace elements, and physical properties of water from selected wells completed in the alluvium and terrace aquifer--Continued.

LOCAL IDENT- I- FIER	DATE OF SAMPLE	SODIUM, DIS- SOLVED (MG/L AS NA)	SODIUM PERCENT	SODIUM AD- SORP- TION RATIO	SULFATE DIS- SOLVED (MG/L AS SO4)	ZINC, DIS- SOLVED (UG/L AS ZN)
19N-13W-02 ADA 1	78-08-22	32	27	1.0	48	--
19N-15W-01 BDA 1	78-08-22	120	36	2.4	240	50
20N-14W-19 BBC 1	78-08-22	15	12	.4	89	60
20N-14W-36 ABB 2	78-08-22	14	12	.4	46	--
20N-15W-01 BCB 1	78-08-22	22	11	.5	43	220
20N-15W-06 BCC 1	78-08-22	14	13	.4	8.1	--
20N-15W-26 CCD 1	78-08-22	12	12	.4	62	620
21N-17W-22 AAD 1	78-08-22	5.5	7	.2	8.3	--
21N-17W-35 DDD 1	78-08-22	6.5	8	.2	19	20
21N-18W-12 BBA 1	78-08-23	8.8	10	.3	12	--
22N-18W-06 AAB 1	78-08-23	9.8	13	.4	23	20
22N-19W-10 DDD 1	78-08-23	42	28	1.2	50	40
23N-18W-28 CBB 1	78-08-23	20	15	.6	47	110
24N-20W-09 ABB 2	78-08-23	10	20	.5	14	--
24N-20W-24 ABA 1	78-08-23	10	17	.4	30	--
24N-20W-31 CCC 1	78-08-22	7.1	16	.3	6.3	30
24N-21W-14 CDA 1	78-08-22	10	19	.5	4.7	--
24N-22W-06 DAC 1	78-08-23	94	17	1.3	750 [b]	--
24N-22W-26 AAC 1	78-08-23	7.0	10	.3	11	--
25N-23W-04 BAB 1	78-08-23	6.7	5	.2	16	--
25N-23W-24 BBC 1	78-08-23	8.7	5	.2	130	20
25N-24W-05 DBD 1	78-08-23	170	28	2.4	630 [b]	10
26N-25W-26 CCC 1	78-08-23	21	13	.5	44	--
26N-26W-01 CDB 1	78-08-23	47	26	1.2	52	--
27N-25W-35 BAA 1	78-08-23	9.9	6	.2	15	--
27N-25W-35 CAB 1	78-08-23	230	46	4.2	69	--
27N-26W-12 DAD 1	78-08-23	61	43	2.0	23	10
27N-26W-22 CDB 1	78-08-23	210	53	4.6	170	50
28N-26W-23 ABD 1	78-08-23	31	19	.8	51	100
28N-26W-34 ABA 1	78-08-23	160	49	3.7	130	310

[a] Exceeds limit as required by the U.S. Environmental Protection Agency (1975) for public supply.

[b] Exceeds limit as recommended by the National Academy of Science and National Academy of Engineering (1972) for public supply.

[c] Exceeds limit as recommended by the National Academy of Science and National Academy of Engineering (1972) for continuous irrigation use on all soils.

Table 2.--Concentration limits for selected chemical constituents in water to be used for public supply, livestock, and irrigation purposes.

[Limits are those recommended by the National Academy of Science, National Academy of Engineering, 1972, except as indicated; mg/L, milligrams per liter; ug/L, micrograms per liter.]

Dissolved constituent	Limits				
			Irrigation		
	Public supply	General livestock		For continuous use on all soils	For use as much as 20 years on fine-textured soils of pH 6.0 to 8.5
Arsenic (ug/L)	50[1]	200		100	2,000
Boron (ug/L)	--	5,000	tolerant crops	2,000	2,000
			semitolerant crops	1,000	2,000
			sensitive crops	750	2,000
Cadmium (ug/L)	10[1]	50		10	50
Chloride (ug/L)	250	--[2]		--	--
Chromium (ug/L)	50[1]	1,000		100	1,000
Copper (ug/L)	1,000	500		200	5,000
Iron (ug/L)	300	--		5,000	20,000
Lead (ug/L)	50[1]	100		5,000	10,000
Manganese (ug/L)	50	--		200	10,000
Mercury (ug/L)	2[1]	10		--	--
Nitrogen, as N (mg/L)	10[1]	100		--	--
Selenium (ug/L)	10	50		20	20
Sulfate (mg/L)	250	--[2]		--	--
Zinc (ug/L)	5,000	25,000		2,000	10,000

[1] Limits as required by the U.S. Environmental Protection Agency, 1975.

[2] Total soluble salts should be less than 3,000 milligrams per liter for livestock use as recommended by the National Academy of Science, National Academy of Engineering, 1972.