NUMERICAL SIMULATION OF THE ALLUVIUM AND TERRACE AQUIFER ALONG THE NORTH CANADIAN RIVER FROM CANTON LAKE TO LAKE OVERHOLSER, CENTRAL OKLAHOMA

By Scott C. Christenson

U.S. GEOLOGICAL SURVEY
WATER-RESOURCES INVESTIGATIONS REPORT 83-4076

Prepared in cooperation with the
OKLAHOMA WATER RESOURCES BOARD

Oklahoma City, Oklahoma
1983

UNITED STATES DEPARTMENT OF THE INTERIOR
JAMES G. WATT, Secretary

GEOLOGICAL SURVEY
Dallas L. Peck, Director

For additional information write to:

James H. Irwin, District Chief
U.S. Geological Survey
Water Resources Division
Rm 621, Old Post Office Bldg.
Oklahoma City, Ok. 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 in pocket)

TABLES

CONVERSION FACTORS

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

Multiply	By	To obtain
acre	4,047	square meter
acre-foot (acre-ft)	1,233	cubic meter
acre-foot per acre per year ((acre-ft/acre)/yr)	304,800	cubic meter per kilometer per year
foot (ft)	0.3048	meter
foot per day (ft/d)	0.3048	meter per day
foot per mile (ft/mi)	0.1894	meter per kilometer
foot squared per day (ft^2/d)	0.0929	meter squared per day
cubic foot per second (ft^3/s)	0.0283	cubic meter per second
gallon per minute per foot ((gal/min)/ft)	0.207	liter per second per meter
inch (in.)	25.40	millimeter
inch per year (in./yr)	25.40	millimeter per year
mile (mi)	1.609	kilometer
mile per hour (mi/hr)	1.609	kilometer per hour
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 ALLUVIUM AND TERRACE AQUIFER ALONG THE NORTH CANADIAN RIVER FROM CANTON LAKE TO LAKE OVERHOLSER, CENTRAL OKLAHOMA

By Scott C. Christenson

ABSTRACT

Alluvium and terrace deposits of Quaternary age, which cover an area of about 400 square miles along the North Canadian River between Canton Lake and Lake Overholser, locally yield as much as 500 gallons per minute to wells. The deposits are as much as 100 feet thick and consist of clay, silt, sand, and gravel, with sand-sized material dominating. The underlying bedrock is Permian sandstone and shale. The amount of water stored in the aquifer during 1980 was estimated to be 4.00×10^{10} cubic feet.

A digital model was used to estimate the ability of the aquifer to continue to supply water for irrigation, industry, and domestic use. A block-centered, finite-difference model with 1 mile node spacing was used to project the amount and distribution of water in the aquifer in the future. The model was calibrated using the aquifer discharge to the North Canadian River and the difference between computed and measured heads. The model was calibrated using a recharge rate of 1 inch per year, a horizontal hydraulic conductivity of 4.5×10^{-4} feet per second and a specific yield of 0.16.

Model simulations using the 1979 pumping rate, a projected pumping rate (based on expected increases in water use), and double the projected increase in pumping rate were made to 1993. With the 1979 pumping rate, the volume of water in storage in 1993 is 3.88×10^{10} cubic feet and ground-water discharge to the North Canadian River is 10.9 cubic feet per second. With the projected pumping increase, the volume of water in storage is 3.81×10^{10} cubic feet and ground-water discharge to the stream is 6.91 cubic feet per second. At double the projected increase in pumping rate, the volume of water in storage is 3.74×10^{10} cubic feet and the ground-water discharge is 2.93 cubic feet per second.

INTRODUCTION

Background

The Oklahoma Ground Water Law (82 Oklahoma Statutes Sup. 1973, para.1020.2 et seq.) states:

> It is hereby declared to be the public policy of this state, in the interest of the agricultural stability, domestic, municipal, industrial and other beneficial uses, general economy, health and welfare of the state and its citizens, to utilize the ground water resources of the state, and for that purpose to provide reasonable regulations for the allocation for reasonable use based on hydrologic surveys of fresh ground water basins or subbasins to determine a restriction on the production, based upon the acres overlying the ground water basin or subbasin.

The Oklahoma Water Resources Board is required by law to "make a determination of the maximum annual yield of fresh water to be produced from each ground water basin or subbasin" based on a minimum life of 20 years from the effective date of the law, July 1, 1973. The maximum annual yield is to be based on the following information:

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

This study was undertaken in response to these specifications in the Oklahoma Ground Water Law. The U.S. Geological Survey, in cooperation with the Oklahoma Water Resources Board, studied the alluvium and terrace deposits along the North Canadian River from Canton Lake to Lake Overholser as a "ground water basin." The information required by law is specified in this report in the section, "Summary of information required by Oklahoma Ground Water Law."

Purpose and Scope

The purpose of this investigation is to define the hydrologic system that operates in the alluvium and terrace deposits along the North Canadian River to determine the maximum annual yield of ground water. Many factors must be considered to achieve this purpose, including physiography, climate, geology, surface water, ground water, and water use in the study area.

The study area consists of approximately 400 mi^2 of alluvium and terrace deposits along the North Canadian River from Canton Lake to Lake Overholser (plate 1). The "ground water basin," as defined by the Oklahoma Water Resources Board, is that portion of the study area underlain by 5 or more feet of saturated thickness of alluvium and terrace deposits. As there are areas within the study area that have less than 5 ft of saturation, the "ground water basin" has an area of approximately 331 mi^2.

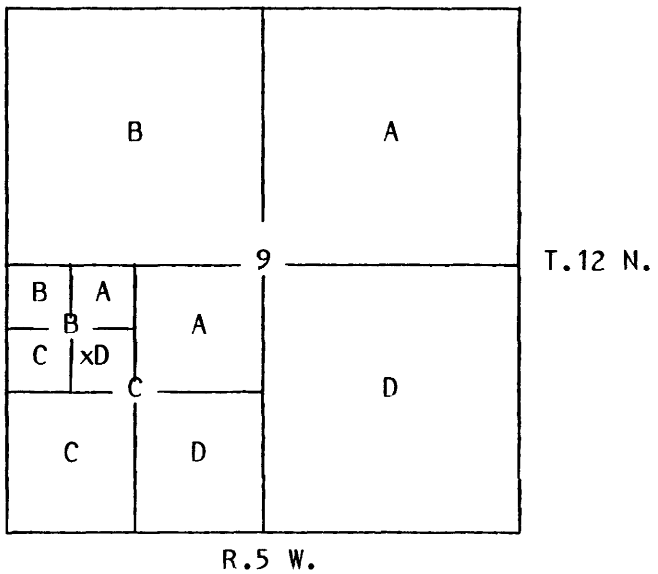
Methods of Investigation

Data were collected in order to describe quantitatively the physical characteristics of the ground-water system. These data came from several sources. Ground-water and stream-discharge data were collected in the field. Drillers' logs and water-use data were supplied by the Oklahoma Water Resources Board. Information on crop irrigation came from the Oklahoma State University Cooperative Extension Service and from conversations with irrigators in the study area.

Data collected for this study were analyzed using a computer. The high-speed digital computer was an excellent tool for estimating the maximum annual yield as specified by the Oklahoma Ground Water Law. A computer was needed to store large volumes of data and to solve the complex, repetitive mathematical equations that describe ground-water flow. Use of a computer made it possible to evaluate several different water-management plans.

Explanation of the 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 x would be described as SE1/4 NW1/4 SW1/4 sec. 9, T.12 N., R.5 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 12N-05W-09 CBD 1. The final digit (1) is the sequential number of the site within the smallest fractional subdivision.



Previous Studies

Several investigations have been made of all or parts of the study area. The Hydrologic Atlas series, reconnaissance-type atlases, covers parts of the study area on each of three atlases. The western section of the study is on the Woodward quadrangle (Morton, 1980), the central section is on the Clinton quadrangle (Carr and Bergman, 1976), and the eastern section is on the Oklahoma City quadrangle (Bingham and Moore, 1975). The ground-water resources of Canadian County were studied by Mogg, Schoff, and Reed (1960). Engineering Enterprises, a private consulting firm, has conducted ground-water studies for the municipalities of Bethany, El Reno, and Yukon (Engineering Enterprises, 1971, 1974, 1976, and 1980). Moench, Sauer, and Jennings (1974) used North Canadian River data in their study entitled, "Modification of routed streamflow by channel loss and base flow." More recently, Davis and Christenson (1981) studied the North Canadian River stream-aquifer system above Canton Lake.

Acknowledgments

The author wishes to express his gratitude to the residents of the study area for their cooperation.

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

DESCRIPTION OF THE STUDY AREA

Physiography and Drainage

The study area is part of the Western Sand-Dune Belt of the Great Plains physiographic province. The altitude of the study area ranges from about 1,700 ft in the northwest to about 1,200 ft in the southeast. Local relief generally is less than 100 ft.

The drainage area of the North Canadian River basin extends across northwestern Oklahoma, across the Oklahoma Panhandle, and into northeastern New Mexico. The drainage basin above the study area includes 12,484 mi^2. The drainage area between Canton Lake and Lake Overholser includes 738 mi^2. There are no perennial tributaries to the North Canadian River within the study area.

Climate

The study area has a dry subhumid climate. Average annual precipitation ranges from approximately 27 inches in the northwest to approximately 31 inches in the southeast. Precipitation is greatest in the spring and summer and least in the winter. Average annual pan evaporation is about 61 inches. Winds predominantly are southerly at 12 mi/h, although during winter months northerly and southerly winds prevail with equal frequency. Annual precipitation and the distribution of average monthly precipitation are shown in figures 1 and 2.

Geology

The North Canadian River between Canton Lake and Lake Overholser is bounded by a band of alluvium (pl. 1). To the north of the alluvium are terrace deposits, which generally extend to the northern drainage divide. South of the alluvium are low hills of Permian bedrock.

The Quaternary alluvium and terrace deposits are composed of clay, silt, sand, and gravel. The sand-size sediments dominate, consisting of poorly sorted, fine to coarse, unconsolidated quartz grains. Colors range from white to red, but buff or brown shades are the most common. The terrace deposits also contain minor amounts of volcanic ash, bentonite, and caliche.

The alluvium consists of channel and flood-plain deposits of the North Canadian River and its tributaries. The width of the band of alluvium ranges from one to four miles. Maximum thickness of the alluvium is about 65 feet, but the average thickness is approximately 30 feet. Some alluvium is present along the tributary creeks, but these deposits are very limited in extent.

Topographically above and adjoining the alluvium to the northeast are terrace deposits. The terrace deposits form a band that ranges from one-half mile in width to five miles in width. Maximum thickness of the terrace is approximately 100 feet. The minimum widths and thicknesses of the terrace deposits are in the southeastern part of the study area, while the maximum dimensions are in the northwestern part. The terrace deposits are probably channel and flood-plain sediments that were deposited during the Pleistocene Epoch, before the river channel had been incised to its present depth. In

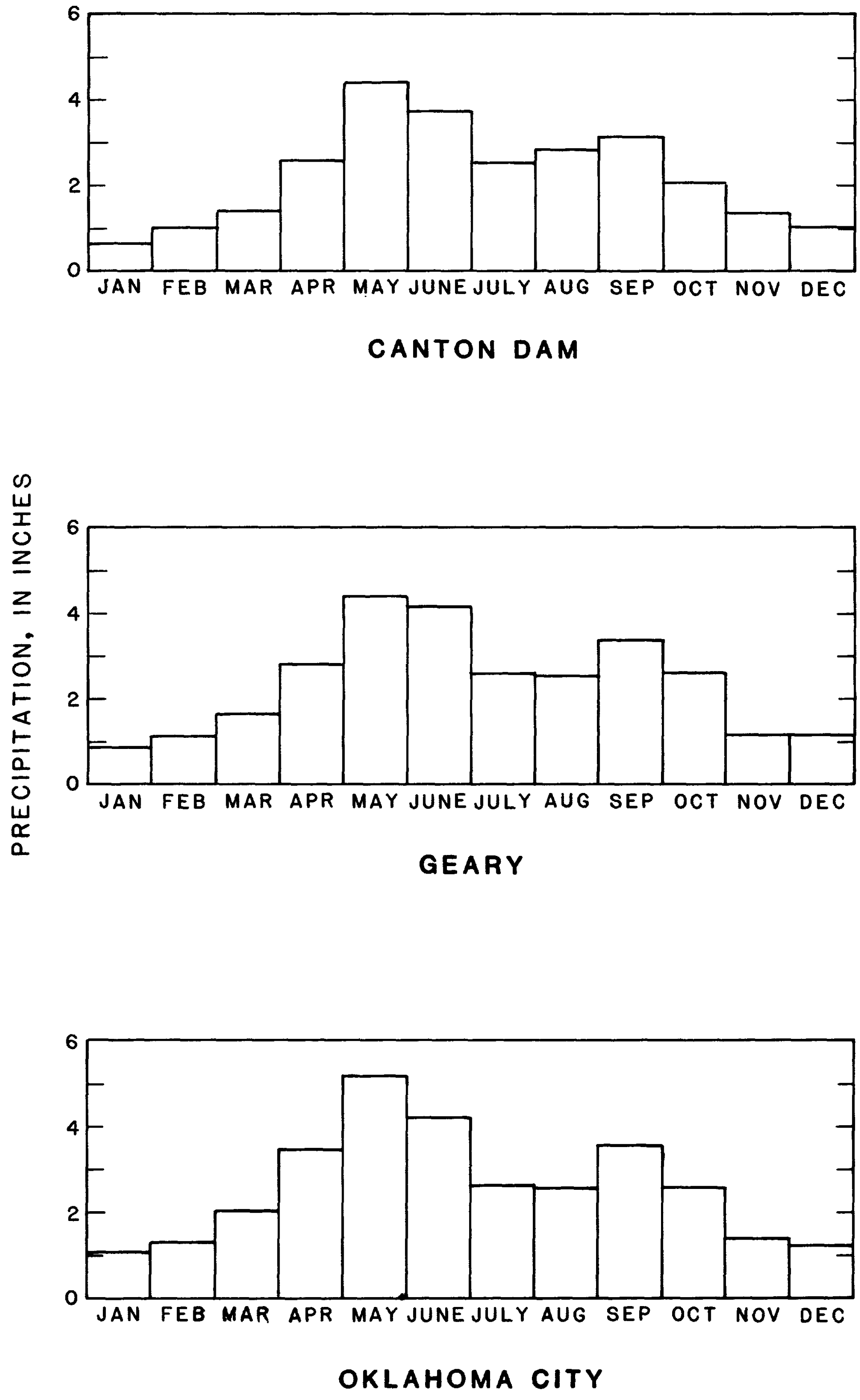


Figure 1.--Graphs showing average monthly precipitation at Canton Dam, Geary, and Oklahoma City, 1941-70.

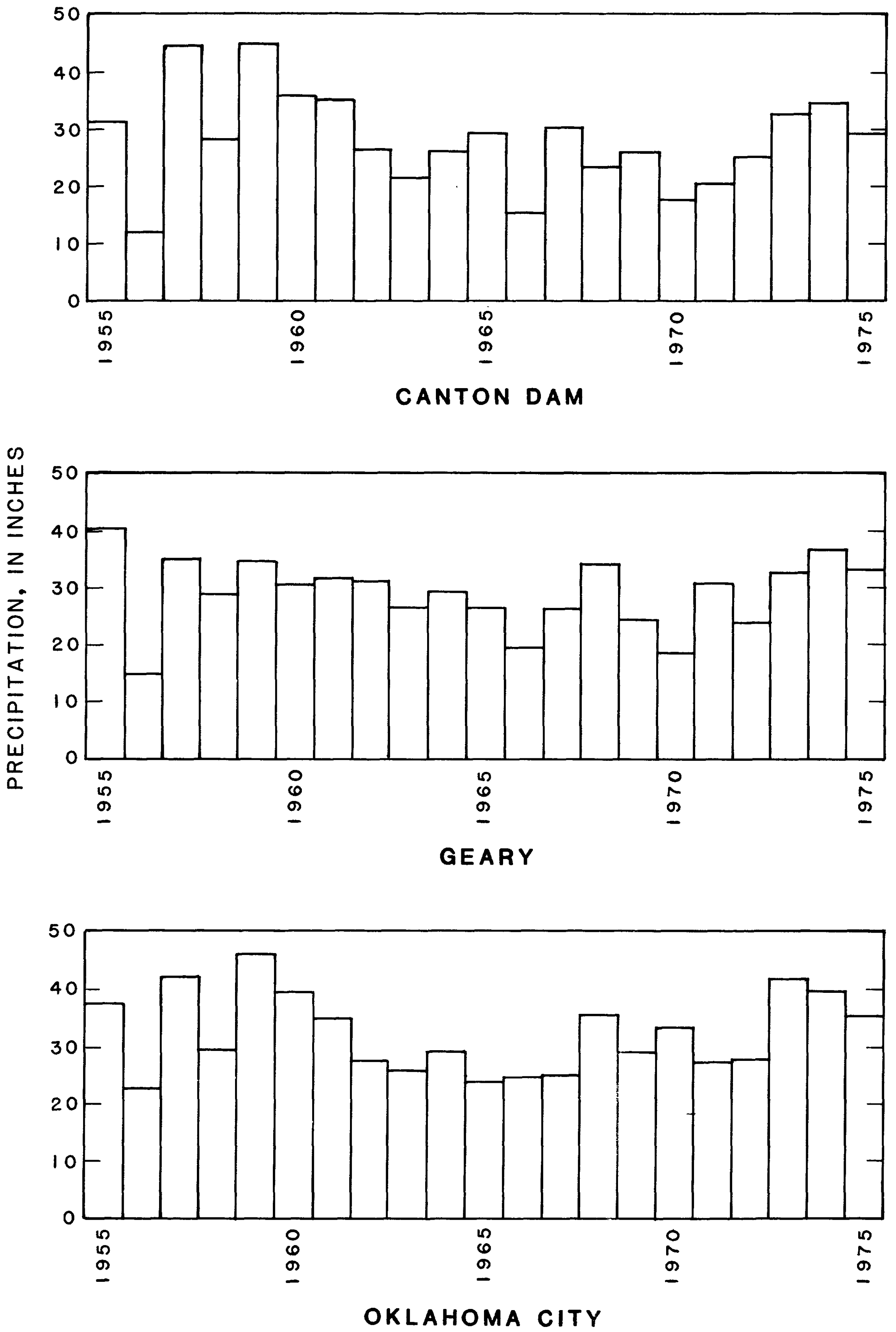


Figure 2.--Graph showing annual precipitation at Canton Dam, Geary, and Oklahoma City, 1955-75.

parts of the study area the alluvium and terrace deposits are covered with a layer of wind-blown sand. The sand is mainly a well-sorted, fine to medium, quartz sand. In certain areas this sand forms dunes, which are generally stabilized by vegetation. Thicknesses of these deposits are erratic, but are generally less than 20 feet.

Bedrock underlies the alluvium and terrace deposits in the study area. The Hennessey Formation, Flowerpot Shale, Blaine Formation, Dog Creek Shale, Marlow Formation, and Rush Springs Formation consist of Permian sandstones, siltstones, and shales with interbedded evaporites. These bedrock formations are locally referred to as redbeds, due to their universal red iron-oxide staining. In the eastern part of the study area, bedrock crops out within the alluvium and the terrace deposits due to protruding high spots on the irregular bedrock surface.

HYDROLOGY

Principles

Ground water occurs in the interstices (voids, pores, joints, etc.) in sediment and rock. At some depth below the earth's surface, usually referred to as the zone of saturation, ground water completely fills the interstices. In a well penetrating the zone of saturation, water will rise to a certain elevation. The height of this elevation above a standard datum, usually sea level, is the head of the water.

Head is a measure of the fluid potential at a given point and is the sum of three components: (1) elevation head, which is equal to the elevation of the point above a datum, (2) pressure head, which is the height of a column of water that can be supported by the static pressure at the point, and (3) velocity head, which is the height the kinetic energy of the liquid is capable of lifting the liquid (Lohman, 1972). Ground-water velocities are usually so low that the velocity head is negligible.

The head distribution in a formation forms a continuous surface known as the potentiometric surface. It can be defined by the levels to which water will rise in tightly cased wells. The slope of the potentiometric surface is referred to as the hydraulic gradient. Since the head distribution is a measure of the fluid potential, water flows from areas of higher head to areas of lower head.

The rate water flows through a formation is controlled by the transmissivity of the formation. Transmissivity is the rate at which water of the prevailing kinematic viscosity is transmitted through a unit width of the formation under a unit hydraulic gradient. Dividing the transmissivity by the thickness of saturated material in the formation gives the hydraulic conductivity of the formation. The hydraulic conductivity of a formation is defined as the volume of water at the prevailing kinematic viscosity that will move in unit time under a unit hydraulic gradient through a unit area measured at right angles to the direction of flow (Lohman, 1972).

In general, formations with greater transmissivities will yield more water to wells than formations with lesser transmissivity values. The amount of water yielded to wells is used to classify formations. An aquifer is a formation that will yield significant quantities of water to wells. There is no precise term for a formation that will not yield significant quantities of water to wells. The terms "aquitard" and "aquiclude" have been used in the past, but are not commonly used now. A confining bed is a formation of low transmissivity adjacent to an aquifer. Confining beds have particular significance because they can strongly influence the hydrologic responses of the adjacent aquifers.

Aquifers can be either unconfined or confined. In an unconfined aquifer the upper boundary of the aquifer is the end of the zone of saturation and at the boundary the water is at atmospheric pressure. The upper boundary of a confined aquifer is a confining bed, and at this boundary the water is at a pressure significantly above atmospheric pressure.

Another important concept is that of storage, the formation's ability to store water. The storage coefficient is the volume of water a formation releases from or takes into storage per unit surface area of the formation per unit change in head. In a confined formation water derived from storage with declining head comes from expansion of the water and compression of the sediment or rock in the formation. In an unconfined formation the water derived from storage with declining head comes from gravity drainage of the interstices. The term specific yield is generally used to describe storage in unconfined formations. Specific yield is more precisely defined as the ratio of the volume of water which rock or sediment, after being saturated, will yield by gravity drainage to the volume of rock or sediment (Lohman, 1972).

Hydrology of the Study Area

The aquifer in the study area consists of alluvium and terrace deposits along the North Canadian River. Well yields sufficient for domestic or stock supplies are obtainable almost anywhere that is underlain by these deposits, and in some areas municipal, industrial, and irrigation wells yield over 500 gallons per minute.

The Permian redbeds are not a good aquifer in the study area. Wells drilled into these formations generally have very small yields, not always sufficient for domestic or stock supplies. Because of the relatively small transmissivities of the redbeds, the volume of water flowing between them and the alluvium and terrace aquifer is considered to be insignificant for this study. The configuration of the contact between the redbeds and the alluvium and terrace aquifer is shown on plate 2.

The head distribution in the aquifer during 1980 is shown on the potentiometric surface map (pl. 3). The data used to make this map are shown in table 1. Water in the alluvium and terrace aquifer is unconfined.

At any given point, the vertical distance between the potentiometric surface and the contact with the redbeds is the thickness of saturated material in the aquifer. The saturated thickness of the aquifer ranges from 0 to 50 feet, and averages approximately 26 feet. The distribution of saturated material in the aquifer is shown in plate 4.

Water in the alluvium and terrace aquifer flows from areas of higher head toward the North Canadian River, which is the area of lowest head in the stream-aquifer system. Water discharging from the aquifer to the stream is termed baseflow. In the absence of storm runoff, baseflow alone sustains the flow in the stream.

During the spring, summer, and fall, plants growing along the North Canadian River intercept a large portion of the ground-water discharge. The water is transpired as part of their growing process. During the summer months when transpiration is greatest it is common for the North Canadian River to have no flow.

During the course of this investigation streamflow measurements were made to determine the amount of baseflow in the North Canadian River. Measurements were made in January, 1981, at a time when no storm runoff was in the river and the riparian vegetation was dormant. At that time, the flow increased 12.5 ft^3/s between the upper end of the study area, at the streamflow gage just downstream from Canton Dam, and the streamflow gage furthest downstream in the study area, at El Reno. The increase in streamflow between these two locations is the ground-water discharge from the aquifer for this reach of the river. All streamflow measurements are listed in table 2.

To determine if these measurements were representative of current baseflow conditions, historic streamflow data at the gages at Canton and El Reno were examined. The January and February 7-day low-flow value based on a two-year recurrence interval gives a good indication of baseflow. In any given year the probability is 50 percent that the average minimum for 7 consecutive days in January or February will be less than this value. Two ten-year periods, from 1959 to 1968 and from 1969 to 1978 (at the time of this investigation 1978 was the last year with records available) were examined. The 7-day low-flow values (in ft^3/s) are shown below:

	Canton	El Reno	Difference
1959-1968	7.27	19.83	12.56
1969-1978	3.20	14.73	11.53

Since the differences in the low-flow values between the two gaging stations are in good agreement with the difference in discharge measured in January, 1981, it was felt that 12.5 ft^3/s is representative of the ground-water discharge from the aquifer to this reach of the North Canadian River.

Recharge to the alluvium and terrace aquifer occurs when a portion of the water that falls on the land surface as precipitation infiltrates the soil (the remainder evaporates or runs off). Most of the soil water either evaporates or is transpired by plants. However, if enough moisture accumulates in the soil so that it becomes saturated, some water will move downward to recharge the aquifer. In the study area recharge probably occurs only in the winter, when plants are dormant. Except in winter, the native vegetation and agricultural crops grown in the area can transpire water at a rate that greatly exceeds the rate of precipitation.

Recharge to the aquifer is difficult to measure in the field. In an undeveloped aquifer (one with no pumpage), recharge is approximately equal to discharge, therefore baseflow is a good indication of the rate of recharge. However, as the aquifer becomes developed, the baseflow will begin to decrease. Drilling of wells in the study area probably began in the late 1800's. Early development is difficult to trace because before 1949, the year Oklahoma's first ground-water law was enacted, no permits were required to drill a well. Even under current law, metering of water use is not required (although many municipal and industrial users do so for their own purposes). Estimated ground-water pumpage in the study area is shown in figure 3.

Recharge to the alluvium and terrace aquifer is estimated to be 1 in./yr. A detailed discussion of how this value was calculated is presented in the section titled "Model Calibration".

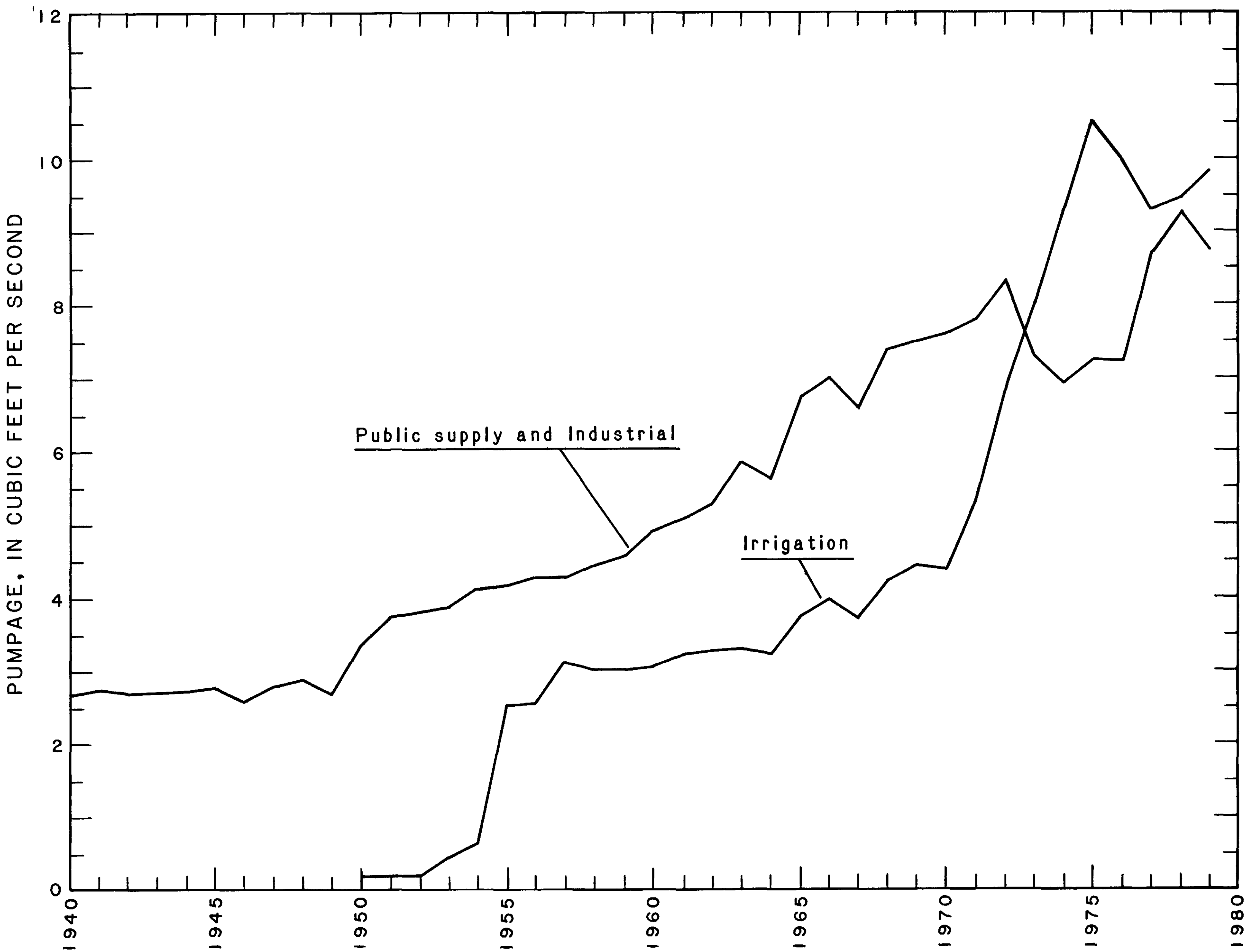


Figure 3.--Annual pumpage from the alluvium and terrace aquifer, 1940-79.

Water Quality

Water samples were taken from 33 wells in the alluvium and terrace aquifer. The wells were distributed across the aquifer (plate 1). These samples were analysed to determine the concentrations of common chemical constituents and selected trace elements. Results of the analyses are shown in table 3.

The analyses show that the aquifer contains water of several different chemical types. The chemical type is determined by the predominant cation and anion, predominant in this case meaning that the concentration in milliequivalents per liter is greater than 50 percent of the total concentration. If no cation or anion is predominant the type is said to be mixed. Of the 33 samples, 9 were calcium bicarbonate type water, 9 were mixed-cation bicarbonate, 9 were mixed-cation mixed-anion, 2 were calcium sulfate, 2 were calcium mixed-anion, 1 was sodium sulfate, and 1 was sodium mixed-anion type water.

Concentration limits for selected chemical constituents in water used for public supply, livestock, and irrigation are listed in table 4. Of the 33 samples from the alluvium and terrace aquifer, 27 have one or more chemical constituents that are greater than or equal to the specified limits. Ground water from the alluvium and terrace aquifer is used for many purposes. Users of ground water from the alluvium and terrace aquifer should determine if water from their wells is suitable for its intended use.

DIGITAL SIMULATION MODEL

Principles

A model is a representation of a real system that describes some aspect of the system. The description of the alluvium and terrace aquifer along the North Canadian River in the preceding pages represents a conceptual model of the aquifer system. Ground water flowing through a porous medium (such as alluvium and terrace deposits) can be described by a mathematical model:

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

in which

Txx, Txy, Tyx, Tyy	are 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 can be rewritten as:

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

in which

Kxx, Kyy	are the principal components of the hydraulic-conductivity tensor (L/T);
Sy	is the specific yield (dimensionless); and
b	is the saturated thickness (L).

These equations have no general solutions. However, approximations 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 problem to a system of algebraic equations that can be solved for each node. The finite-difference approximation for equation 2 is:

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

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

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

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

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

where

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

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

in which

$Q_{w(i,j,k)}$	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).

The system of algebraic equations generated by this method is so large that a computer is needed to obtain a solution. A computer program used to solve this type of problem is called a digital model.

All models, whether conceptual, mathematical, or digital, are less complex than the system they describe. Simplifications and assumptions are necessarily made when a model is constructed. It is important to realize that these assumptions limit the accuracy of answers obtained from a model. This is particularly true of digital models. A digital model, which is based on the conceptual and mathematical models, has limitations based on the assumptions used to construct all three.

Application to the North Canadian River Alluvium and Terrace Aquifer

The alluvium and terrace aquifer from Canton Lake to Lake Overholser was modeled using a finite-difference model developed by Trescott, Pinder, and Larson (1976). Minor modifications were made to the FORTRAN code, so that entry and retrieval of data was more convenient, leakage would be printed node-by-node, and, in some model simulations, pumping would cease at a node when the aquifer's saturated thickness was less than 5 feet. The model iterated to a solution using the strongly-implicit procedure.

A list of some of the major assumptions used to construct the model of the alluvium and terrace aquifer along the North Canadian River is presented below:

1. Flow of water in the aquifer is consistent with Darcy's Law.
2. The aquifer is isotropic with respect to hydraulic conductivity in the horizontal direction.
3. The vertical-flow component in the aquifer is negligible in comparison to 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.
6. The formations that underlie the aquifer are impermeable.

The digital model was executed on a computer that maintains seven significant figures for ordinary computations. To enhance readability, some of the numerical output in this study is reported with as many as five significant figures. However, many of the data used in the model are accurate to only three or fewer significant figures.

Finite-Difference Grid and Boundary Conditions

The alluvium and terrace aquifer was modeled by subdividing the continuous area into a finite-difference grid having 20 rows and 72 columns (plate 5). Nodes are located at the centers of the grid blocks and are 1 mile apart. This node spacing affords good resolution for the study area as a whole and was computationally efficient, but was not close enough to study individual wells or well fields.

Several types of boundary conditions were used in the model. The computer program requires that the modeled area be surrounded by a no-flow boundary, which consists of nodes at which the transmissivity equals zero. Where the aquifer terminates against the relatively impermeable Permian redbeds, the no-flow boundary simulates actual conditions. At the upstream and downstream ends of the study area, the aquifer extends beyond the geographic limits of the study area. At the upstream end of the study area the model area was 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 upstream location of the no-flow boundary was tested by placing constant-head nodes just inside the no-flow boundary and stressing the aquifer. The differences in head in the study area with and without the constant head nodes were neglible.

Constant-head nodes were used to simulate Canton Lake and Lake Overholser. The pool at Canton Lake is maintained at or near an altitude of 1,615 ft, while Lake Overholser is held at 1,242 ft. Lake Overholser spans the entire width of the alluvium and terrace aquifer, which is narrow at that point. This prevents significant ground-water flow from by-passing the lake.

The North Canadian River was treated as a partially-penetrating stream with a leaky streambed. An area-vector weighting method was used to proportion the streambed leakage to the area of the stream within the one square mile grid block. Streambed leakage, which corresponds to ground-water discharge, was printed for every node in the model simulations. No values for streambed hydraulic conductivity along the North Canadian River could be found, so 1.0×10^{-5} ft/s (.86 ft/d) was used, as this value is in the range of values for streams similar to the North Canadian River.

Model Calibration

Calibration of a ground-water model consists of adjusting the coefficients in equation 3 so that the modeled head distribution and flow rates accurately simulate measured head distribution and flow rates. The coefficients in equation 3 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 recharge, hydraulic conductivity, and specific yield, are difficult to measure, so they may be adjusted within reasonable limits for this type of aquifer during calibration.

How closely the modeled response matches observed conditions is measured by several different criteria. The rate that water is leaving and entering the aquifer is called the mass balance. Rates computed in the model must closely agree with rates measured in the field. Comparing computed versus measured head distribution is done at every node. The average difference between computed and measured heads is computed, and the absolute values of the differences are summed. The average difference should be near to zero in a calibrated model, signifying that on the average computed and measured heads are the same. However, since differences are both positive and negative, it is possible to have the average difference equal to zero with large differences at individual nodes. The sum of the absolute values of the differences shows the total magnitude of the differences regardless of sign. The sum should be minimized during calibration.

Calibration of the alluvium and terrace aquifer model was done in two steps. A steady-state calibration simulated conditions prior to pumping, followed by a transient calibration to simulate conditions after significant pumpage developed in the aquifer. In the study area, unfortunately, very little information about head distribution prior to development was available. Head measurements for this investigation were the first for most of the study area. This lack of information about predevelopment head distribution was handled by identifying areas in the aquifer that were still at steady-state conditions and calibrating the steady-state model to those areas. It was assumed that the aquifer parameters that applied to the areas that were still at steady-state conditions were correct for the rest of the steady-state model. The entire model was then calibrated to transient conditions.

In order to find areas in the aquifer that were still at steady-state conditions it was necessary to compute the effects of pumpage on head distribution. If the head in an area of the aquifer has not been decreased by development, that area can be considered to be still at steady state, since by definition a system is at steady state if it has not changed with time. A model simulation was made from 1940 to 1980 using the specified boundary conditions (that is, the constant-head, stream, and no-flow nodes were positioned as shown on plate 5), a specific-yield of .10, and 1-year time steps. Since the model was not calibrated, the absolute values of the heads computed by this simulation were not significant. However, since the boundary conditions were defined, the effects of pumpage on head distribution could be computed by examining the decline in head from the beginning to the end of the simulation. A specific-yield of .10, which represents the lower limit of specific-yield values for this type of aquifer, will maximize drawdowns. Thus, if the head in a part of the aquifer does not decrease under conditions that maximize drawdown, it can be assumed that that part of the aquifer is still at steady state.

At the end of the simulation from 1940 to 1980, 83 nodes of the 336 nodes in the study area had head declines of less than 1 foot. Actually, more than 83 nodes showed declines of less than 1 foot, but constant-head and streambed nodes were not included in the tabulation, since these boundary conditions work to minimize head changes. In a fully developed aquifer, probably very few nodes would have less than 1 foot of drawdown. The alluvium and terrace aquifer along the North Canadian River has areas where development is minimal. At these small-decline nodes, heads measured in 1980 are probably representative of predevelopment heads.

A steady-state model then was calibrated by adjusting the aquifer parameters to match computed heads with the 1980 measured heads in the 83 small-decline nodes. An initial estimate for recharge for the steady-state model was made so that ground-water discharge from the aquifer would be correct after being decreased by pumping. During the simulation from 1940 to 1980 ground-water contribution to the North Canadian River was decreased by 12.0 ft^3/s, of which about 82 percent occurs from Canton to El Reno. By adding the product of .82 times 12.0 ft^3/s to 12.5 ft^3/s, (the measured ground-water discharge from Canton to El Reno), the initial estimate for predevelopment ground-water discharge from Canton Lake to El Reno was 22.3 ft^3/s. Dividing 22.3 ft^3/s by the area of the aquifer that discharges this flow, 300 mi^2, gave an estimated recharge of 1.01 in./yr, which was rounded to 1.00 in./yr (2.64×10^{-9} ft/s).

To calibrate the steady-state model, hydraulic conductivity then was adjusted to minimize the average head difference and the sum of the absolute values of the head differences in the small-decline nodes. The minimum values were obtained using a hydraulic conductivity of 4.5×10^{-4} ft/s. In the 83 small-decline nodes the average head difference was 0.220 ft and the sum of the absolute values of the differences was 468.5 ft. A mass balance for the steady-state model is shown below:

Storage	0.0
Recharge	25.685 ft^3/s
Pumpage	0.0
Constant head	-1.097 ft^3/s
Groundwater discharge	-24.567 ft^3/s
Sum of rates	0.021 ft^3/s

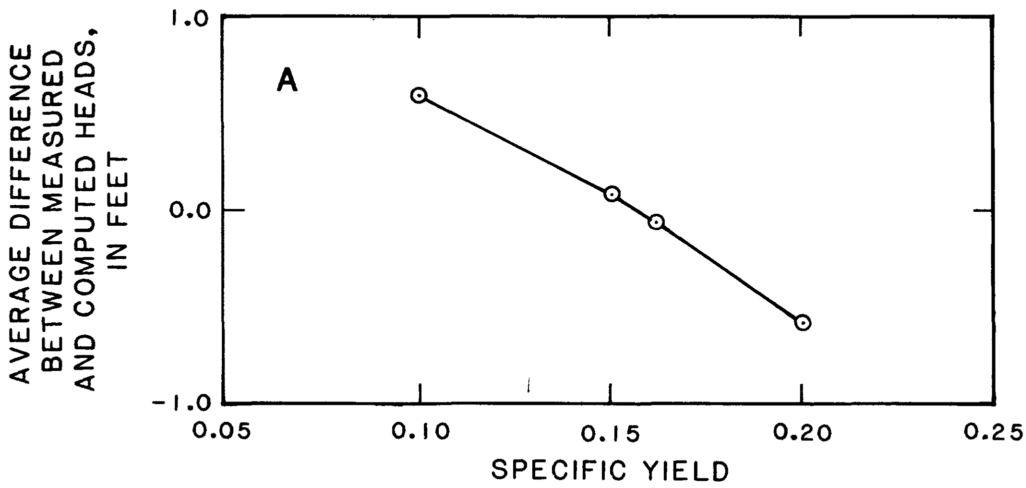
The sum is not zero due to round-off error.

The sensitivity of the model was tested to variations in hydraulic conductivity, recharge, and the vertical hydraulic conductivity of the leaky streambed. Variations in hydraulic conductivity and recharge rate cause the computed heads to change significantly, while the computed heads are relatively insensitive to changes in the vertical hydraulic conductivity of the leaky streambed.

A refinement was added while arriving at the steady-state model. The hydraulic conductivities of the first column of nodes outside the western end of the study area were set to 1 percent of the value used in the rest of the model, to 4.5×10^{-6} ft/s. This column of nodes simulates the dam axis of Canton Lake.

The model then was calibrated to transient conditions, using the pumping history from 1940 to 1980. The set of parameters developed in the steady-state model were retained for the transient simulation, and time advanced in one-year time steps. Specific yield was varied to give the best match between the computed heads and mass balance and 1980 measured heads and mass balance. The effects of varying the specific yield on the average head difference and the ground-water discharge is shown in figures 4a and 4b.

The best head match occured with a specific yield of .16. Using this value the average head difference was -0.023 ft and the sum of the absolute values of the differences was 2466.0 ft. Since there are 336 nodes in the study area, the average difference per node was 7.34 ft. This amount of error was considered acceptable, since the altitudes of the wells used to compute the heads were taken from topographic maps, and were known only to approximately 10 ft.



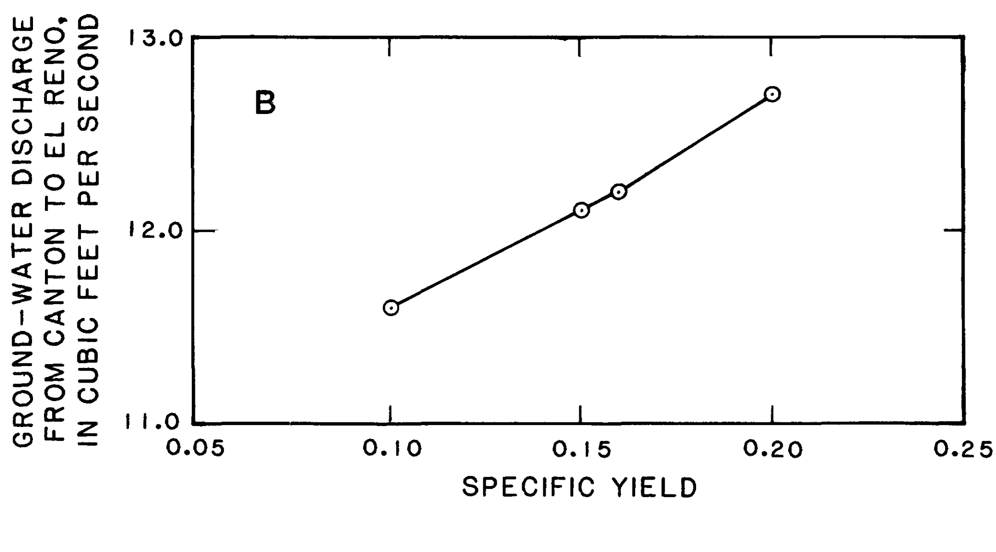


Figure 4.--Relationships between specific yield and average head difference (A) and between specific yield and ground-water discharge (B) during transient simulation of 1980 head distribution.

Computed ground-water discharge from Canton Lake to El Reno was 12.478 ft^3/s, comparable to the measured value of 12.5 ft^3/s. The mass balance (in ft^3/s) at the end of the transient simulation is shown below:

Storage	6.169
Recharge	25.685
Pumpage	-18.574
Constant head	-1.045
Groundwater discharge	
Canton to El Reno	-12.478
El Reno to Lake Overholser	0.266
Sum of rates	0.023

Model Projections of Saturated Thickness and Volume of Water in Storage

The ultimate objective of this investigation was, in hydrologic terms, to determine the distribution of saturated thickness and volume of water in storage in the alluvium and terrace aquifer at specific times. The digital computer is an excellent tool to make such determinations. It can be used to estimate future aquifer response to various projected conditions, and can do the necessary calculations quickly and inexpensively.

The volume of water in storage before well development began, as computed by the model, was 4.30×10^{10} ft^3 (987,000 acre-feet). The volume of water in storage at the end of the transient-model simulation was 4.00×10^{10} ft^3 (918,000 acre-ft). Thus, pumpage up to 1980 had depleted about 7 percent of the water in storage prior to development.

Due to provisions in the Oklahoma Ground Water Law, the distribution of saturated thickness and volume of water in storage on July 1, 1973, is significant. A simulation similar to the transient-model simulation was executed, only it was stopped at a time corresponding to July 1, 1973. This simulation used one-year time steps, except for the final time step, which was 181 days in duration. Plate 8 shows saturated thickness for each grid block in the model. The volume of water of water in storage calculated by this simulation is $4.14 \times 10^{10} ft^3$ (950,000 acre-ft).

This simulation is also used to define the "ground water basin" referred to in the Oklahoma Ground Water Law. As defined by the Oklahoma Water Resources Board, the "basin" is that part of the study area that has more than 5 feet of saturated thickness on July 1, 1973. Of the 336 nodes in the study area, 331 had more than 5 feet of saturated thickness. The area of the "ground water basin" is thus 331 mi^2 (211,840 acres). The volume of water in the "basin" is the same, to three significant figures, as the volume in the study area, 4.14×10^{10} ft^3.

The 20-year minimum aquifer lifespan provision of the Oklahoma Ground Water Law (the 20-year period began with the date the law went into effect, July 1, 1973) makes July 1, 1993, the logical date to examine future aquifer conditions. Since the amount of future development is unknown, several simulations were run to simulate a range of conditions. These simulations were run from the end of the transient-calibration model, which corresponds to

January 1, 1980, to July 1, 1993. One-year time steps were used, except for the first time-step, which was 181 days in duration. A check was built into the model code to test the amount of saturated thickness at every node at the beginning of each time step. If the saturated thickness was less than 5 feet, no pumping was allowed at that node.

A simulation was executed from January 1, 1980 to July 1, 1993, using the 1979 pumping rates, which remained constant throughout the simulation. The resulting distribution of saturated thickness is shown in plate 9. The volume of water in storage was 3.88 x 10^{10} ft^3 (891,000 acre-ft). By the end of the simulation the calculated value of ground-water discharge to the river decreased from 12.2 ft^3/s to 10.9 ft^3/s. Because saturated thickness at some nodes decreased to less than 5 feet, pumpage decreased from a total of 18.6 ft^3/s to 14.8 ft^3/s. Since aquifer development is expected to continue, this simulation probably represents the lower limit of future conditions.

Information published by the State of Oklahoma (Oklahoma Comprehensive Water Plan, 1975) projects a rate of growth in water use for the combined Central and Northwest Regions of the State, including the study area, of 5.07 percent per year for irrigation and 2.21 percent per year for municipal and industrial users. These values were incorporated into a simulation from January 1, 1980 to July 1, 1993, in an attempt to project future water use. At each well within a grid block pumping was increased by either 5.07 percent per year or 2.21 percent per year, depending on whether the well was an irrigation, municipal, or industrial well. Since the location of new wells cannot be predicted, increased pumpage was restricted to existing well sites. The resulting distribution of saturated thickness is shown in plate 10. The volume of water in storage at the end of the simulation was 3.81 x 10^{10} ft^3 (875,000 acre-ft). By the end of the simulation the calculated value for ground-water discharge to the river decreased from 12.2 ft^3/s to 6.91 ft^3/s. The combined effect of wells shutting off as saturated thickness decreased to less than 5 feet and projected pumping increases resulted in a net increase in pumping, from 18.6 ft^3/s to 20.9 ft^3/s. During this simulation, one node went dry, decreasing the number of nodes in the study area from 336 to 335.

A simulation with pumping rates double the state projected pumping increase was executed from January 1, 1980 to July 1,1993. The double rate, or 10.14 percent per year increase for irrigation wells and 4.42 percent per year for municipal and industrial wells, probably represents the upper limit of future aquifer development. The distribution of saturated thickness at the end of this simulation is shown on plate 11. The volume of water in storage was 3.74 x 10^{10} ft^3 (859,000 acre-ft). Ground-water discharge to the river was decreased to 2.93 ft^3/s. The combined effects of wells ceasing to pump as saturated thickness dropped below 5 feet and projected pumping increases was a net increase in pumpage from 18.6 ft^3/s to 26.1 ft^3/s. Two nodes went dry during this simulation, decreasing the total to 334.

A simulation was run from January 1, 1980 to July 1, 2020. It incorporated the state projected increases in pumping of 5.07 percent per year for irrigation wells and 2.21 percent per year for municipal and industrial wells. This simulation uses one-year time steps except for the first time step, which was 181 days in duration. The distribution of saturated thickness is shown on plate 12. The volume of water in storage was 3.64 x $10^{10}$$ft^3$ (836,000 acre-ft). Ground-water discharge to the river decreased from a net gain of 12.2 ft^3/s to a net loss of 0.560 ft^3/s, thereby indicating the river would become a losing stream. By the end of this simulation total pumping had increased to 24.3 ft^3/s. Two nodes went dry during the simulation.

A special simulation was made at the request of the Oklahoma Water Resources Board. This simulation begins on July 1, 1973, using the calculated head distribution and mass balance for that day, and runs to July 1, 1993 in one-year time steps. This simulation assumes that water is being withdrawn at each node at a rate sufficient to irrigate every acre in the grid block at a rate of 1.0 acre-ft/yr for every node in the "ground water basin". This simulation also assumes a recharge rate of 2.5 in./yr. The resulting distribution of saturated thickness is shown on plate 13. The number of nodes in the "ground water basin" decreased from 331 to 163, giving a surface area of the "basin" of 163 mi^2 (104,320 acres). The volume of water in storage in the "basin" decreased from $4.14 \times 10^{10} ft^3$ on July 1, 1973, to 1.21×10^{10} ft^3 (278,000 acre-ft) on July 1,1993. Pumpage decreased from 293 to 149 ft^3/s as saturated thickness decreased. Ground-water discharge to the North Canadian River decreased from a net gain of 14.1 ft^3/s to a net loss of 55.2 ft^3/s. This simulation is necessary for the administration of the Oklahoma Ground Water Law, and does not necessarily represent application of identical hydrologic principles to those used elsewhere in this report.

SUMMARY OF INFORMATION REQUIRED BY OKLAHOMA GROUND-WATER LAW

The Oklahoma Water Resources Board is required by the Oklahoma Ground Water Law to "make a determination of the maximum annual yield of fresh water to be produced from each ground water basin or subbasin" based on a minimum life of 20 years from the effective dates of the law, July 1, 1973. The maximum annual yield is to be based on the following information:

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

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

1. The total land area overlying the basin on July 1, 1973 was 331 mi^2, or 211,840 acres.
2. The amount of water in storage in the basin on July 1, 1973 was approximately 4.14×10^{10} ft^3, or 950,000 acre-ft.
3. Based on a recharge rate of 2.5 in./yr, the total discharge by pumping from the basin for the period from July 1, 1973 to July 1, 1993, was determined by a digital-model simulation to be 1.23×10^{11} ft^3, or 2,830,000 acre-ft.
4. The model-derived transmissivity for July 1, 1973 ranged from 0 to 2,050 ft^2/day in the basin. The average transmissivity was 1,080 ft^2/day.
5. There are several possible sources of pollution of fresh water in the ground-water basin:

   a) Water in the North Canadian River generally is of poorer quality than water in the alluvium and terrace aquifer. If the head in the river is higher than the head in the aquifer, surface water enters the aquifer and degrades the quality. This may already be happening and will increase as pumping lowers heads in the aquifer.
   b) Water in the redbeds adjacent to the aquifer generally is of poorer quality than water in the aquifer. As heads in the aquifer are lowered by pumping, flow from the redbeds into the aquifer may be induced.
   c) Agricultural or industrial chemicals may be entering the aquifer.

The maximum annual yield was determined by a digital-model simulation from July 1, 1973, assuming an equal proportionate share throughout the basin, except where prior rights had established a larger share, such that one-half of the land area of the basin had less than 5 feet of saturated thickness on July 1, 1993. The equal proportionate share was determined to be 1.0 (acre-ft/acre)/yr, and total discharge by pumping during the 20-year period was determined to be 1.23×10^{11} ft^3, or 2,830,000 acre-ft.

CONCLUSIONS

The results of the numerical simulations indicate that the alluvium and terrace aquifer will continue to be an important source of ground water into the first part of the twenty-first century if development continues at or near the present rate. However, ground-water discharge to the North Canadian River has been decreasing since the aquifer has been developed, and will continue to decrease. As the surface waters of the North Canadian River are almost completely appropriated for irrigation, municipal, and industrial supplies (Ghermazien and Zipser, 1980), this decrease in ground-water contribution from the aquifer may create a potential problem.

SELECTED REFERENCES

Bingham, R. H., and Moore, R. L., 1975, Reconnaissance of the water resources of the Oklahoma City quadrangle, central Oklahoma: Oklahoma Geological Survey Hydrologic Atlas 4, scale 1:250,000, 4 sheets.

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., and Christenson, S. C., 1981, 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, 42 p.

Engineering Enterprises, 1971, City of Bethany, Water Supply, Phase I: Norman, 35 p.

_____ 1974, City of Bethany, Water Supply, Phase II & III: Norman, 102 p.

_____ 1976, City of Yukon, Summary of Water Study: Norman, 18 p.

_____ 1980, City of El Reno, 20-year Water Supply Plan 1980-2000: Norman, 50 p.

Ghermazien, T., and Zipser, R. A., 1980, Hydrologic investigations of the North Canadian River basin, Oklahoma Water Resources Board Publication 103, 26 p.

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

Moench, A. F., Sauer, V. B., and Jennings, M. E., 1974, Modification of routed streamflow by channel loss and base flow: Water Resources Research, vol. 10, no. 5, pp 963-968.

Mogg, J. L., Schoff, S. L., and Reed, E. W., 1960, Ground-water Resources of Canadian County, Oklahoma: Oklahoma Geological Survey Bulletin 87, 112 p.

Morton, R. B., 1980, Reconnaissance of the water resources of the Woodward quadrangle, northwestern Oklahoma: Oklahoma Geological Survey Hydrologic Atlas 8, scale 1:250,000, 4 sheets.

National Academy of Science, National Academy of Engineering, 1973 [1974], Water Quality Criteria, 1972: U.S. Government Printing Office, 594 p.

Oklahoma Water Resources Board, 1975, Oklahoma Comprehensive Water Plan, Publication 60, 108 p.

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

U.S. Environmental Protection Agency, 1976, National interim primary drinking water regulations: U.S. Environmental Protection Agency EPA-580/9-76-003, 159 p.

Table 1.--Records of wells and test-holes.

Site-ID: Unique identification number that usually coincides with the latitude, longitude, and sequence number for the site.
Water level: Feet below land surface. D, dry; P, pumping; R, reported; S, measured with steel tape.
Depth of well: Feet below land surface.

Principal aquifer: 110ALVM, alluvium; 110TRRCL, low terrace deposits; 112TRRCH, high terrace deposits; 313DGCK; Dog Creek Shale of the El Reno Group; 313ELRN, El Reno Group.
Use of water: H, domestic; I, irrigation; N, industrial; P, public supply; S, stock; U, unused.

SITE-ID	LOCAL NUMBER	DATE WATER LEVEL MEASURED	WATER LEVEL (FEET)		DEPTH OF WELL (FEET)	PRINCIPAL AQUIFER	ALTITUDE OF LAND SURFACE (FEET)	USE OF WATER
353233097391601	12N-04W-06 DAA 1	04/22/1980	55.73	S	78.00	112TRRCH	1272.00	U
353233097394501	12N-04W-06 DBB 1	04/16/1980	56.30	S	73.50	112TRRCH	1276.00	U
353059097394801	12N-04W-18 BDD 1	04/16/1980	8.44	S	53.60	110ALVM	1249	U
353218097401801	12N-05W-01 DDD 2	03/31/1954	27.00	R	63.30	110ALVM	1266	P
353221097412301	12N-05W-02 DDA 1	11/07/1941	7.92	S	45.00	110ALVM	1252	U
353221097463601	12N-05W-06 CCB 1	11/06/1941	17.61	S	66.00	110ALVM	1274	--
353216097454201	12N-05W-06 DDD 1	06/10/1980	6.79	S	43.20	110TRRCL	1266	N
353136097442201	12N-05W-09 CBD 1	04/14/1980	8.16	S	41.30	110TRRCL	1263	U
353137097423101	12N-05W-10 DAD 1	04/16/1980	8.63	S	49.90	110TRRCL	1256	U
353206097420901	12N-05W-11 BBD 2	--	9.70	R	47.50	110ALVM	1254	P
353153097410401	12N-05W-12 BCA 1	04/16/1980	5.30	S	45.30	110TRRCL	1250	U
353149097405401	12N-05W-12 BDD 1	03/31/1954	24.92	S	49.10	110ALVM	1251	P
353046097405701	12N-05W-13 CAC 2	10/23/1954	15.97	S	64.20	110ALVM	1250	P
353107097453701	12N-05W-18 ADA 1	04/14/1980	11.66	S	47.20	110TRRCL	1270	U
353213097505301	12N-06W-04 CCC 1	04/22/1980	4.93	S	33.30	110TRRCL	1283	U
353304097561001	12N-07W-03 BBB 1	04/22/1980	12.01	S	46.70	110ALVM	1312	U
353156097540901	12N-07W-11 ADA 1	04/22/1980	13.05	S	42.90	110TRRCL	1306	U
353401097440601	13N-05W-28 DCC 1	04/16/1980	23.83	S	25.80	112TRRCH	1300	U
353358097435001	13N-05W-28 DDC 1	04/16/1980	43.04	S	51.80	112TRRCH	1330	U
353325097454701	13N-05W-31 DAA 1	04/17/1980	11.94	S	43.40	112TRRCH	1326.00	U
353332097412701	13N-05W-36 BCC 1	04/16/1980	64.35	S	86.40	112TRRCH	1312	S
353456097521001	13N-06W-20 CCB 1	04/22/1980	28.39	S	30.50	112TRRCH	1383	U
353432097481001	13N-06W-26 ACA 1	04/17/1980	18.60	S	53.80	112TRRCH	1355	H
353442097510801	13N-06W-29 AAD 1	04/22/1980	14.07	S	68.30	112TRRCH	1350	S
353415097521001	13N-06W-29 CBC 1	04/22/1980	34.44	S	43.80	112TRRCH	1383	U
353310097475101	13N-06W-36 CCC 1	04/17/1980	14.62	S	116.70	112TRRCH	1331	H
353543097555201	13N-07W-15 DCC 1	04/23/1980	31.79	S	34.60	112TRRCH	1395	H
353414097542501	13N-07W-26 DAD 1	04/22/1980	42.16	S	89.80	313ELRN	1390	U
353437097564301	13N-07W-28 ABD 1	07/14/1980	40.50	SP	--	110ALVM	1318	I
353443097593801	13N-07W-30 BBB 1	04/23/1980	16.08	S	39.10	110TRRCL	1331	S
353333097571701	13N-07W-33 BDC 1	04/22/1980	26.15	S	49.30	110TRRCL	1317	U
353735098014501	13N-08W-02 CCB 1	04/22/1980	3.15	S	14.40	112TRRCH	1427	U
353754098024901	13N-08W-03 BCC 1	04/03/1980	8.26	S	38.76	112TRRCH	1413	S
353635098051501	13N-08W-07 DDC 1	--	16.00	R	50.00	110ALVM	1360	H
353635098012701	13N-08W-11 CDC 1	04/03/1980	44.62	S	65.93	313DGCK	1380	U
353643098004401	13N-08W-12 CCB 1	04/23/1980	29.06	S	37.80	112TRRCH	1423	U
353605098004701	13N-08W-14 DAA 1	--		D	45.00	110ALVM	1389	U
353632098035501	13N-08W-16 BBB 1	--	--		32.00	110ALVM	1350	--
353541098025201	13N-08W-16 DDD 1	04/23/1980	9.25	S	34.60	110TRRCL	1337	U
353621098041301	13N-08W-17 ABD 1	04/23/1980	14.71	S	42.80	110TRRCL	1350	U

Table 1.--Records of wells and test-holes.--Continued

SITE-ID	LOCAL NUMBER	DATE WATER LEVEL MEASURED	WATER LEVEL (FEET)		DEPTH OF WELL (FEET)	PRINCIPAL AQUIFER	ALTITUDE OF LAND SURFACE (FEET)	USE OF WATER
353632098060201	13N-08W-18 BBB 1	04/23/1980	15.70	S	23.50	110TRRCL	1367	S
353531098004501	13N-08W-23 AAD 1	04/03/1980	17.58	S	39.74	110ALVM	1339	U
353446098010301	13N-08W-26 ABA 1	11/25/1949	20.00	R	56.00	110ALVM	1335	I
353815098064101	13N-09W-01 BAA 1	04/03/1980	10.05	SP	28.82	110TRRCL	1364	H
353706098070201	13N-09W-12 BCB 1	--	21.00	R	52.00	110ALVM	1371	H
353828098045601	14N-08W-32 CCB 1	04/23/1980	18.19	S	60.90	112TRRCH	1430	U
354132098110801	14N-09W-17 BCA 1	04/01/1980	25.99	S	68.00	112TRRCH	1428	U
354017098102601	14N-09W-20 DAC 1	04/01/1980	15.74	S	111.47	112TRRCH	1415	U
354006098084601	14N-09W-22 CDD 1	04/01/1980	16.15	S	37.20	112TRRCH	1418	U
353944098065901	14N-09W-25 BCB 1	04/23/1980	30.39	S	123.30	112TRRCH	1430	U
353912098060501	14N-09W-25 DDD 1	1953	24.00	R	77.00	112TRRCH	1409	H
353857098111901	14N-09W-32 BBC 1	04/01/1980	10.84	S	44.07	110TRRCL	1385	U
354252098131301	14N-10W-01 CAC 1	03/20/1980	23.95	S	44.63	112TRRCH	1490	S
354259098150901	14N-10W-03 CAA 1	03/19/1980	59.08	S	90.30	112TRRCH	1510	S
354150098174501	14N-10W-07 DDD 1	03/31/1980	3.98	S	34.90	110TRRCL	1413	P
354121098122601	14N-10W-13 ADD 1	04/01/1980	36.52	S	73.07	112TRRCH	1436	S
354133098151801	14N-10W-16 ACA 1	03/19/1980	7.15	S	37.00	110TRRCL	1413	N
354030098153201	14N-10W-22 BCC 1	--	--		38.00	110ALVM	1406	--
354014098131401	14N-10W-24 CCA 1	03/19/1980	11.91	S	73.70	110TRRCL	1402	U
353956098151601	14N-10W-27 BAB 1	03/19/1980	5.13	S	47.20	110TRRCL	1403	U
353851098132201	14N-10W-36 BCB 1	03/19/1980	6.59	S	38.80	110TRRCL	1392	U
354225098193301	14N-11W-12 BAC 1	03/10/1980	10.50	S	86.30	110ALVM	1433	U
354753098175001	15N-10W-06 DDD 1	03/10/1980	25.01	S	37.50	112TRRCH	1528	U
354621098162501	15N-10W-16 CBD 1	04/01/1980	28.90	S	46.00	112TRRCH	1513	U
354515098150401	15N-10W-27 ABB 1	04/01/1980	16.30	S	21.50	112TRRCH	1502	U
354501098180201	15N-10W-30 ACA 1	03/10/1980	35.03	S	60.50	112TRRCH	1488	U
354412098165401	15N-10W-32 AAC 1	03/10/1980	38.63	S	72.20	112TRRCH	1490	U
354412098172701	15N-10W-32 BAC 1	05/02/1980	19.72	S	51.55	112TRRCH	1465	U
354832098220201	15N-11W-04 AAD 1	03/10/1980	12.59	S	44.00	112TRRCH	1503	U
354620098185101	15N-11W-13 DAD 1	03/10/1980	21.57	S	56.50	112TRRCH	1490	U
354626098195101	15N-11W-14 DAA 1	03/10/1980	39.30	S	74.40	112TRRCH	1512	S
354650098210201	15N-11W-15 AAD 1	04/01/1980	13.83	S	55.20	112TRRCH	1493	U
354540098235401	15N-11W-20 CBA 1	03/13/1980	21.48	S	53.90	110TRRCL	1470	U
354449098230101	15N-11W-28 BCC 1	03/10/1980	18.10	S	52.10	110ALVM	1462	U
354409098190301	15N-11W-36 ACA 1	03/10/1980	8.58	S	41.00	110TRRCL	1440	U
354749098261301	15N-12W-11 AAA 1	03/10/1980	12.40	S	42.50	110ALVM	1502	S
355253098234701	16N-11W-08 BAC 1	03/14/1980	29.47	S	133.30	112TRRCH	1590	U
355249098224601	16N-11W-09 BCA 1	03/11/1980	27.75	S	99.60	112TRRCH	1585	U
355213098213501	16N-11W-10 CDC 1	03/11/1980	42.67	S	68.80	112TRRCH	1590	U
355044098243601	16N-11W-19 DBC 1	03/31/1980	20.66	S	49.00	112TRRCH	1512	P

Table 1.--Records of wells and test-holes.--Continued

SITE-ID	LOCAL NUMBER	DATE WATER LEVEL MEASURED	WATER LEVEL (FEET)		DEPTH OF WELL (FEET)	PRINCIPAL AQUIFER	ALTITUDE OF LAND SURFACE (FEET)	USE OF WATER
355035098232501	16N-11W-20 DCA 1	03/11/1980	18.84	S	64.60	112TRRCH	1527	U
355029098203301	16N-11W-23 CDC 1	03/14/1980	39.59	S	121.60	112TRRCH	1570	U
354921098230401	16N-11W-32 ADA 1	04/01/1980	15.65	S	107.30	112TRRCH	1516	U
354851098195801	16N-11W-35 DDB 1	03/11/1980	46.81	S	72.40	112TRRCH	1565	U
355214098270201	16N-12W-11 CCD 1	04/01/1980	7.78	S	24.60	110TRRCL	1499	S
355121098251001	16N-12W-13 DDD 1	03/31/1980	23.53	S	47.60	112TRRCH	1520	P
355157098290801	16N-12W-16 BDB 1	03/13/1980	23.79	S	46.70	110TRRCL	1520	U
355027098272101	16N-12W-27 AAA 1	09/05/1956	13.86	S	21.00	110ALVM	1480	--
355356098225301	17N-11W-33 CDC 1	03/14/1980	41.01	S	46.80	112TRRCH	1605	U
355906098291501	17N-12W-04 BAB 1	03/11/1980	62.35	S	66.00	112TRRCH	1640	U
355906098304301	17N-12W-06 AAA 1	03/11/1980	25.07	S	93.70	112TRRCH	1569	U
355733098284201	17N-12W-09 DDB 1	03/11/1980	53.20	S	76.20	112TRRCH	1621	U
355718098293701	17N-12W-16 BBB 1	03/13/1980	44.40	S	57.10	112TRRCH	1575	S
355552098305401	17N-12W-19 DDB 1	03/13/1980	9.02	S	86.60	110TRRCL	1515	S
355616098271201	17N-12W-23 BDB 1	03/11/1980	55.53	S	76.00	112TRRCH	1608	U
355434098285001	17N-12W-33 ACA 1	03/13/1980	7.84	S	31.10	110ALVM	1510	U
355356098271401	17N-12W-35 CDC 1	03/25/1980	41.30	S	47.80	112TRRCH	1591	S
360329098312601	18N-12W-06 CDC 1	04/04/1980	52.37	S	65.90	112TRRCH	1622	U
360249098293301	18N-12W-09 CBC 1	03/11/1980	66.10	S	76.50	112TRRCH	1660	U
360054098304701	18N-12W-19 DDD 1	03/13/1980	29.30	S	58.40	112TRRCH	1585	U
360111098302401	18N-12W-20 CAB 1	05/05/1980	39.01	S	76.10	112TRRCH	1599	U
360025098283201	18N-12W-27 BCC 1	03/13/1980	60.40	S	93.30	112TRRCH	1648	U
360222098325101	18N-13W-14 ADA 1	03/13/1980	13.25	S	15.20	112TRRCH	1575	U
360130098343001	18N-13W-22 BAD 1	03/13/1980	11.13	S	50.40	110ALVM	1565	U
355945098315501	18N-13W-36 ADB 1	03/11/1980	5.02	S	52.40	110ALVM	1555	S
360604098310201	19N-12W-19 DCD 1	03/13/1980	40.60	S	50.40	112TRRCH	1649	S
360426098304501	19N-12W-31 DDA 1	03/13/1980	41.63	S	68.20	112TRRCH	1655	S
360434098291301	19N-12W-33 CAD 1	03/13/1980	54.80	S	58.20	112TRRCH	1650	S
360840098355201	19N-13W-09 BBA 1	03/01/1978	17.03	S	37.00	112TRRCH	1635	U
360812098320601	19N-13W-12 DBA 1	03/20/1978	16.87	S	22.00	112TRRCH	1650	H
360711098332401	19N-13W-14 CAD 1	02/24/1978	42.00	R	80.00	112TRRCH	1650	P
360600098324701	19N-13W-25 BBB 1	03/03/1978	29.89	S	54.00	112TRRCH	1628	I
360423098340801	19N-13W-34 DDC 1	02/28/1978	1.92	S	40.00	110ALVM	1572	I

Table 2.--Low-flow discharge measurements along the North Canadian River.

Location of measurement site	Date	Discharge, in cubic feet per second
19N-13W-33 CB	1/28/81	6.06
17N-13W-11 AA	1/28/81	10.9
16N-12W-22 DC	1/28/81	12.0
15N-11W-27 CD	1/28/81	14.7
14N-10W-25 CD	1/28/81	14.3
13N-08W-08 DA	1/29/81	15.6
13N-07W-32 AA	1/29/81	18.6
12N-05W-05 DD	1/29/81	20.1
12N-05W-01 DC	1/29/81	20.3

Table 3.--Concentration of common constituents and selected trace elements, and physical properties of water from wells completed in the alluvium and terrace aquifer.

(UMHOS, micromhos per centimeter at 25°C; MG/L, milligrams per liter; UG/L, micrograms per liter.)

Geologic units: 110ALVM, alluvium; 110TRRCL, low terrace deposits; 112TRRCH, high terrace deposits.

STATION NUMBER	LOCAL IDENT-I-FIER	DATE OF SAMPLE	GEO-LOGIC UNIT	SPE-CIFIC CON-DUCT-ANCE (UMHOS)	PH (UNITS)	TEMPER-ATURE (DEG C)	HARD-NESS (MG/L AS CACO3)	CALCIUM DIS-SOLVED (MG/L AS CA)	MAGNE-SIUM, DIS-SOLVED (MG/L AS MG)
353135097412101	12N-05W-11 DAD 1	80-07-28	110ALVM	1000	7.1	18.5	500	110	54
353215097545201	12N-07W-02 CDC 1	80-07-28	110ALVM	1100	7.2	20.0	510	130	44
353231097463501	12N-05W-06 CBC 1	80-07-28	110ALVM	910	6.9	22.0	360	92	32
353303097514901	12N-06W-05 BBA	80-07-28	110ALVM	630	7.1	22.5	260	72	19
353314097442301	13N-05W-33 CDB 1	80-07-28	112TRRCH	950	7.0	22.0	360	88	34
353358097583801	13N-07W-30 DDD1	80-07-28	110ALVM	2700	7.6	22.0	700	140	84
353439097475101	13N-06W-25 BBC 1	80-07-31	112TRRCH	558	7.0	22.4	240	62	20
353457098025001	13N-08W-22 CCB 1	80-07-29	110ALVM	1300	7.1	20.0	490	120	46
353635098052501	13N-08W-07 DCC 1	80-07-29	110ALVM	980	7.1	19.0	340	85	30
353815098033801	13N-08W-04 BAB 1	80-07-29	112TRRCH	795	6.5	17.5	310	84	24
353836098070201	14N-09W-36 CBC 1	80-07-29	110ALVM	780	6.9	25.0	290	82	20
353959098100101	14N-09W-28 BAB 1	80-07-29	112TRRCH	520	6.7	21.5	200	55	14
354054098153801	14N-10W-21 AAA 1	80-07-29	110ALVM	1590	6.8	19.2	430	97	46
354151098140701	14N-10W-11 CDD 1	80-07-31	112TRRCH	1030	7.1	19.9	490	130	39
354440098214901	15N-11W-27 CBD 1	80-07-28	110ALVM	2230	6.9	22.5	750	180	73
354448098152801	15N-10W-27 CBB 1	80-07-31	112TRRCH	624	6.6	23.4	260	74	19
354658098243801	15N-11W-18 BAA 1	80-07-28	110ALVM	1690	7.0	22.7	480	100	55
354741098210701	15N-11W-10 AAC 1	80-07-31	112TRRCH	444	6.9	26.5	140	41	10
354945098205601	16N-11W-27 DDA 1	80-07-31	112TRRCH	469	6.7	27.8	160	46	11
355053098273501	16N-12W-22 DBA 1	80-07-28	110ALVM	2650	6.7	22.3	980	240	92
355220098205101	16N-11W-11 CCB 1	80-07-28	112TRRCH	800	7.3	19.4	270	67	24
355302098222701	16N-11W-09 ABB 1	80-07-28	112TRRCH	1160	6.9	19.4	350	99	26
355303098275001	16N-12W-10 BAA 1	80-07-29	110ALVM	2500	7.0	22.1	980	260	80
355445098300801	17N-12W-32 ABB 1	80-07-29	110ALVM	473	7.8	20.9	240	59	23
355657098274501	17N-12W-15 DAB 1	80-07-28	112TRRCH	391	7.1	23.0	140	42	9.1
355856098304901	17N-12W-06 AAD 1	80-08-01	112TRRCH	705	7.1	18.7	320	96	19
355958098325501	18N-13W-35 AAA 1	80-07-29	110ALVM	925	7.5	22.0	260	68	21
360048098283201	18N-12W-27 BBB 1	80-07-28	112TRRCH	775	6.7	25.1	300	86	20
360301098324801	18N-13W-12 CBB 1	80-08-01	112TRRCH	1060	7.2	26.4	440	130	28
360305098351801	18N-13W-09 ACD 1	80-07-29	110ALVM	1900	7.2	25.5	810	250	45
360436098283301	19N-12W-34 CBC 1	80-07-28	112TRRCH	1160	7.4	28.2	420	110	35
360515098302601	19N-12W-29 CDC 1	80-07-29	112TRRCH	725	7.2	29.3	270	79	18
360621098324401	19N-13W-24 CBC 1	80-08-01	112TRRCH	345	7.0	27.3	140	42	9.2

Table 3.--Concentration of selected constituents and physical properties of water from wells tapping the alluvium and terrace aquifer.--Continued

STATION NUMBER	SODIUM, DIS-SOLVED (MG/L AS NA)	SODIUM AD-SORP-TION RATIO	POTAS-SIUM, DIS-SOLVED (MG/L AS K)	ALKA-LINITY FIELD (MG/L AS CACO3)	SULFATE DIS-SOLVED (MG/L AS SO4)	CHLO-RIDE, DIS-SOLVED (MG/L AS CL)	FLUO-RIDE, DIS-SOLVED (MG/L AS F)	SILICA, DIS-SOLVED (MG/L AS SIO2)	SOLIDS, RESIDUE AT 180 DEG. C DIS-SOLVED (MG/L)	SOLIDS, SUM OF CONSTI-TUENTS, DIS-SOLVED (MG/L)	NITRO-GEN, NO2+NO3 DIS-SOLVED (MG/L AS N)
353135097412101	110	2.1	4.7	400	170	98	1.1	23	759	820	1.7
353215097545201	90	1.7	3.8	360	250	79	1.0	30	888	850	.55
353231097463501	52	1.2	1.4	320	89	25	.7	27	547	545	7.4
353303097514901	34	.9	1.1	230	77	9.2	.5	22	399	383	2.2
353314097442301	51	1.2	1.4	260	21	40	.6	22	562	570	35
353358097583801	520	8.6	5.1	550	870	200	1.2	17	2180	2190	3.8
353439097475101	35	1.0	1.0	250	10	14	.7	22	342	335	4.4
353457098025001	150	3.6	3.3	380	330	80	.5	22	1010	987	1.4
353635098052501	87	2.1	3.4	320	140	33	.9	33	648	617	2.5
353815098033801	24	.6	3.3	51	150	34	.2	24	559	516	32
353836098070201	45	1.2	3.1	240	86	28	.7	16	467	447	4.9
353959098100101	37	1.2	1.4	140	41	34	.5	22	362	347	13
354054098153801	200	4.2	3.9	360	240	190	1.3	31	1050	1030	.10
354151098140701	97	1.9	2.5	270	190	33	.6	22	973	881	46
354440098214901	240	3.8	6.4	460	490	200	.9	20	1480	1490	.06
354448098152801	37	1.0	3.0	170	44	58	.4	23	432	410	11
354658098243801	200	4.0	2.1	370	420	61	.5	34	1190	1140	9.3
354741098210701	38	1.8	1.2	130	57	14	.5	23	308	265	.42
354945098205601	36	1.2	2.9	110	36	31	.4	23	323	301	11
355053098273501	240	3.3	23	440	660	240	.7	13	1830	1780	.12
355220098205101	63	1.7	4.4	230	110	31	.5	20	498	487	6.5
355302098222701	99	2.3	3.2	220	100	83	.5	21	749	715	34
355303098275001	170	2.4	14	280	500	400	.9	11	1750	1620	3.2
355445098300801	21	.6	1.9	200	47	16	.9	24	336	333	4.3
355657098274501	16	.6	2.0	43	23	13	.3	29	299	262	23
355856098304901	31	.8	1.9	220	58	51	.7	14	489	448	10
355958098325501	100	2.7	2.7	250	160	24	.9	24	578	568	3.8
360048098283201	29	.7	3.5	150	67	53	.4	25	475	441	15
360301098324801	110	2.3	3.1	270	260	43	.6	20	884	837	18
360305098351801	100	1.5	8.0	360	510	75	.5	20	1170	1270	9.3
360436098283301	64	1.4	4.7	270	200	30	.5	32	769	701	14
360515098302601	23	.6	2.8	130	65	73	.3	26	472	409	9.4
360621098324401	20	.7	1.5	110	28	11	.5	22	240	230	6.7

Table 3.--Concentration of selected constituents and physical properties of water from wells tapping the alluvium and terrace aquifer.--Continued

STATION NUMBER	ARSENIC DIS-SOLVED (UG/L AS AS)	BORON, DIS-SOLVED (UG/L AS B)	CADMIUM DIS-SOLVED (UG/L AS CD)	CHRO-MIUM, DIS-SOLVED (UG/L AS CR)	COPPER, DIS-SOLVED (UG/L AS CU)	IRON, DIS-SOLVED (UG/L AS FE)	LEAD, DIS-SOLVED (UG/L AS PB)	MANGA-NESE, DIS-SOLVED (UG/L AS MN)	MERCURY DIS-SOLVED (UG/L AS HG)	SELE-NIUM, DIS-SOLVED (UG/L AS SE)	ZINC, DIS-SOLVED (UG/L AS ZN)
353135097412101	4	390	<1	10	29	30	4	600	.1	2	30
353215097545201	2	390	2	0	8	1900	2	860	.0	0	60
353231097463501	3	260	4	0	12	40	3	20	.0	4	60
353303097514901	3	250	3	10	41	40	4	50	.0	3	120
353314097442301	2	210	3	0	10	20	3	20	.0	0	70
353358097583801	2	1100	2	10	3	170	2	520	.0	1	60
353439097475101	3	120	<1	10	18	10	5	3	.0	0	140
353457098025001	4	610	2	20	2	170	3	110	.0	2	40
353635098052501	2	250	1	0	0	400	3	450	.0	0	30
353815098033801	2	110	3	10	2	<10	1	<1	.0	1	60
353836098070201	4	150	3	0	5	<10	2	10	.0	4	110
353959098100101	2	90	<1	10	60	10	3	10	.0	1	110
354054098153801	2	390	2	10	3	850	3	350	.0	0	50
354151098140701	2	160	2	10	10	40	4	4	.1	2	310
354440098214901	2	330	1	20	11	1700	3	1000	.0	0	330
354448098152801	2	80	<1	10	23	70	3	5	.1	1	160
354658098243801	15	910	<1	20	8	<10	3	2	.0	25	30
354741098210701	2	80	<1	0	92	20	2	3	.0	2	80
354945098205601	2	70	<1	10	24	<10	2	4	.1	2	210
355053098273501	3	280	3	10	3	2200	2	1100	.0	0	3700
355220098205101	4	220	<1	10	4	50	5	9	.0	6	170
355302098222701	2	140	2	10	14	<10	7	6	.2	3	110
355303098275001	5	180	1	10	2	80	2	720	.2	0	120
355445098300801	3	150	1	10	7	90	3	130	.0	0	20
355657098274501	2	30	2	10	7	60	0	5	.0	0	80
355856098304901	2	80	1	10	21	<10	3	2	.1	2	20
355958098325501	1	290	2	10	14	<10	4	180	.0	0	10
360048098283201	2	80	2	10	38	170	3	10	.4	1	280
360301098324801	2	190	<1	10	430	10	4	2	.0	13	60
360305098351801	2	190	4	10	20	460	4	360	.1	4	270
360436098283301	4	130	<1	10	8	10	4	20	.3	3	60
360515098302601	1	90	2	20	39	30	2	60	.0	3	2300
360621098324401	2	70	<1	10	34	<10	1	4	.0	1	50

Table 4.--Concentration limits for selected chemical constituents in water to be used for public suppply, livestock, and irrigation purposes.

[Limits are those recommended by the National Academy of Science, National Academy of Engineering, 1973, except as indicted; mg/L, milligrams per liter; µg/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, (µg/L)	50 [1]	200	100	2,000
Boron, (µg/L)	--	5,000	Tolerant crops--------- 2,000	2,000
			Semi-tolerant crops---- 1,000	2,000
			Sensitive crops-------- 750	2,000
Cadmium (µg/L)	10 [1]	50	10	50
Chloride (µg/L)	250	(2)	--	--
Chromium (µg/L)	50 [1]	1,000	100	1,000
Copper (µg/L)	1,000	500	200	5,000
Iron (µg/L)	300	--	5,000	20,000
Lead (µg/L)	50 [1]	100	5,000	10,000
Manganese (µg/L)	50	--	200	10,000
Mercury (µg/L)	2 [1]	10	--	--
Nitrogen, as N (mg/L)	10 [1]	100	--	--
Selenium (µg/L)	10	50	20	20
Sulfate (mg/L)	250	(2)	--	--
Zinc (µg/L)	5,000	25,000	2,000	10,000

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

[2] Total soluable salts should be less then 3,000 milligrams per liter for livestock use as recommended by the National Academy of Scince, National Academy of Engineering, 1973.