GEOHYDROLOGY OF THE ALLUVIAL AND TERRACE DEPOSITS OF THE NORTH CANADIAN RIVER FROM OKLAHOMA CITY TO EUFAULA LAKE, CENTRAL OKLAHOMA

By John S. Havens

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CONVERSION FACTORS

For the 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)/year)	304,800	cubic meter per kilometer per year
foot (ft)	0.348	meter
foot per day (ft/d)	0.348	meter per day
foot squared per day (ft2/d)	0.029	meter squared per day
cubic foot per second (ft3/s)	0.083	cubic meter per second
inch (in.)	25.4	millimeter
inch per year (in./yr)	25.4	millimeter per year
mile (mi)	1.69	kilometer
square mile (mi2)	2.50	square kilometer

Temperature in degrees Fahrenheit (oF) can be converted to degrees Celsius (oC) as follows:

oF = 1.8(oC) + 32o

Sea Level: In this report "sea level" refers to the 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, formerly called "Mean Sea Level of 1929."

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ABSTRACT

This investigation was undertaken to describe the geohydrology of the alluvial and terrace deposits along the North Canadian River between Lake Overholser and Eufaula Lake, an area of about 1,835 square miles, and to determine the maximum annual yield of ground water.

A 1982 water-level map of the alluvial and terrace aquifer was prepared using field data and published records. Data from test holes and other data from the files of the U.S. Geological Survey and the Oklahoma Water Resources Board were used to establish the approximate thickness of the alluvial and terrace deposits.

The North Canadian River from Lake Overholser, near Oklahoma City, to Eufaula Lake is paralleled by a 2- to 3-mile wide band of alluvium. Scattered terrace deposits on either side of the alluvium reach an extreme width of 8 miles. Rocks of Permian age bound the alluvial and terrace deposits from the west to the midpoint of the study area; Pennsylvanian rocks bound the alluvial and terrace deposits from that point eastward.

Three major aquifers are present in the study area: the alluvial and terrace aquifer, consisting of alluvium and terrace deposits of Quaternary age in a narrow band on either side of the North Canadian River; the Garber-Wellington aquifer of Permian age, consisting of an upper unconfined zone and a lower confined zone separated by relatively impermeable shales; and the Ada-Vamoosa aquifer of Pennsylvanian age. At locations where the alluvial and terrace aquifer overlies

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either of the other aquifers, there is hydraulic continuity between the alluvial and terrace aquifer and the other aquifers, and water levels are the same.

Most large-scale municipal and industrial pumping from the Garber-Wellington aquifer is from the lower zone and has little discernible effect upon the alluvial and terrace aquifer.

The total estimated baseflow of the North Canadian River for the studied reach is 264 cubic feet per second. Evapotranspiration from the basin in August is about 60 cubic feet per second for the North Canadian River from Lake Overholser to a measuring station above Eufaula Lake. Estimated recharge rates to the alluvial and terrace aquifer in the basin range from 1.7 inches at the west edge of the study area to 7.0 inches at the east edge.

Total permitted withdrawal from the aquifer, according to records of the Oklahoma Water Resources Board, ranged from 2,107 acre-feet per year in 1942 to about 21,415 acre-feet per year in 1982.

Simulations of the alluvial and terrace aquifer from Lake Overholser to Eufaula Lake were made using a finite-difference model developed by McDonald and Harbaugh (1984). The area of the aquifers was subdivided into a finite-difference grid having 30 rows and 57 columns with cells measuring 1 mile in the north-south direction and 2 miles in the east-west direction. The model was calibrated in two steps: A steady-state calibration simulated head distribution prior to extensive pumping of the aquifer in 1942, and a transient calibration simulated head distribution after extensive pumpage. The final horizontal hydraulic conductivity used for the alluvial and terrace aquifer was 0.0036 feet per second (310 feet per day) at all locations. The recharge rate for the alluvial and terrace aquifer ranged from 1.7 inch per year in the west to 7.0 inch per year in the east, and averaged about 3.3 inch per year. A specific yield of 15 percent was used for the transient simulation.

Permitted pumpage for 1942 through 1982 was used in the digital model to estimate the annual volume of water in storage in the alluvial and terrace aquifer for the years for this time period. The 1982 permitted pumpage rates were used for projections from 1983 to 2020. The estimated volume of water in storage was 1,940,000 acre-feet in 1942 ; 1,910,000 acre--feet in 1973; and 1,890,000 acre-feet in 1982. Because the estimated recharge rate is equal to the allowed pumpage rate in 1982, the projected volume of water in storage in both 1993 and 2020 was 1,890,000 acre-feet.

INTRODUCTION

Information Required for Oklahoma Ground-Water Law

This study was undertaken in response to the following specifications in the Oklahoma Ground Water Law. The U.S. Geological Survey, in cooperation with the Oklahoma Water Resources Board, studied the alluvial and terrace aquifer and underlying aquifers--the Garber-Wellington aquifer and the Ada-Vamoosa aquifer--along the North Canadian River from Lake Overholser to Eufaula Lake as a "ground water basin."

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 sub--basins 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 of 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.

Purpose and Scope

The purpose of this investigation is to determine the maximum annual yield of ground water and to describe the geohydrology of the alluvial and terrace deposits along the North Canadian River. The area that was modeled for this study contains 3,420 square miles; the alluvial and terrace aquifer consists of 760 square miles along the course of the North

Canadian River and its tributaries from Lake Overholser, near Oklahoma City, to Eufaula Lake (fig. 1).

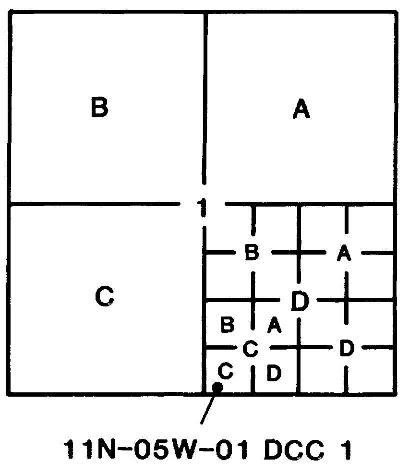
Measurements and data for the study

Water-level measurements were made for preparation of the 1982 water-level map of the alluvial and terrace aquifer. Earlier published records of water levels were used to supplement these data. During the summer of 1982, test holes were drilled in alluvial and terrace deposits along the North Canadian River from Lake Overholser to Eufaula Lake. Data from these test holes and other data from the files of the U.S. Geological Survey and the Oklahoma Water Resources Board were used to establish the thickness of the alluvial and terrace deposits. Most of the test holes were finished with plastic casing for use as observation wells; several wells were equipped with continuous water-level recorders.

Stream flows were measured during 1983-84 to determine low flow and base flow. Published records of stream flow were taken from reports by the U.S. Geological Survey. Records of water use were obtained from the Oklahoma Water Resources Board.

Explanation of site-numbering system

The standard legal method of describing locations 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 is described as SW 1/4 SW 1/4 SE 1/4 sec. 1, T.11 N., R.5 W. The method used in this report indicates quarter subdivisions of the section by letters and reverses the order of presentation of the subdivisions. By this method, location of the site is given as 11N-05W-01 DCC 1. The final digit (1) is the sequence number of the site within the smallest fractional subdivision. For example, if three data collection sites were located within the same quarter-quarter--quarter section, they would be uniquely identified as DCC 1, DCC 2, and DCC 3.



Previous studies

Model simulations of flow in alluvial and terrace aquifers along reaches of the North Canadian River west of the present study area were conducted by Davis and Christenson (1981) and by Christenson (1983). These reports and a data report (Davis, Christenson, and Blumer, 1980), include the reach of the North Canadian River from the Oklahoma Panhandle to Lake Overholser, near Oklahoma City.

The part of the Garber-Wellington aquifer lying between the North Canadian River in northern Oklahoma County and the Cimarron River in Logan County was studied by Carr and Marcher (1977); a data report for the project was published separately (Carr and Havens, 1976). An investigation of the Garber-Wellington aquifer lying between the North Canadian and Canadian Rivers in southern Oklahoma and Cleveland Counties and parts of Pottawatomie County was made by Wickersham (1979). Wood and Burton (1968) reported on aquifers in Permian and Quaternary rocks in Cleveland and Oklahoma Counties, including the Garber-Wellington and alluvial and terrace deposits along the North Canadian.

Data for the present project were published as U.S. Geological Survey Open-File Report 84-808, "Hydrologic data: North Canadian River from Lake Overholser to Lake Eufaula, central Oklahoma" (Havens, 1985). This report contains logs of test wells, water-quality data for wells and test holes, hydrographs of water levels in test wells, comparisons of water-level changes and river stages at nearby gaging stations, and a tabulation of low-flow and base-flow measurements on the North Canadian River and tributaries.

Acknowledgments

The author wishes to express his thanks to residents of the study area for their cooperation in providing access to wells and streams on their lands and for information furnished to the Geological Survey.

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 Water Resources Board who provided assistance include Dannie E. Spiser, John Roles, and Gary Glover. The cooperation of the Oklahoma Water Resources Board and staff is gratefully acknowledged.

DESCRIPTION OF THE STUDY AREA

The study area consists of approximately 710 mi^2 of alluvial and terrace deposits along the North Canadian River from Lake Overholser, near Oklahoma City, to Eufaula Lake (fig. 1). The underlying Garber-Wellington and Ada-Vamoosa aquifers occupy areas of about 694 mi^2 and 174 mi^2, respectively, within the study area. These aquifers are connected hydrologically to the alluvial and terrace deposits where the river crosses outcrops of the Garber-Wellington and the Ada-Vamoosa, and are included in the study.

Physiography and Drainage

The study area lies within the Osage Plains section of the Central Lowland physiographic province. The altitude of the area ranges from about 1,340 feet in the west to about 585 feet in the east, the elevation of Eufaula Lake. Local relief is generally less than 100 feet. The most prominent physiographic features are bluffs along the North Canadian River, near Eufaula Lake.

The drainage area of the North Canadian River extends from Eufaula Lake northwestward to the Oklahoma Panhandle, across the Panhandle, where the river is named the Beaver River, and into New Mexico. The total drainage area of the North Canadian River above Eufaula Lake is 15,056 square miles of which 4,899 square miles are non-contributing. The total contributing drainage area is 10,157 square miles. The contributing drainage area between Lakes Overholser and Eufaula is about 1,835 square miles.

Climate

The climate of the study area is subhumid to humid, from west to east. Average annual precipitation, most of which falls during the spring and summer, ranges from about 31 inches in the northwestern part of the area to about 42 inches in the southeast. Average annual precipitation and distribution of average monthly precipitation are shown in figures 2 and 3.

Geology

From Lake Overholser, near Oklahoma City, to Eufaula Lake, the North Canadian River has deposited a narrow band of alluvium, ranging from less than 1 to more than 4 miles wide; usually the alluvium is from 2 to 3 miles wide. Terrace deposits on either side of the river reach a maximum width of 8 miles, but generally are a discontinuous band 2 to 3 miles

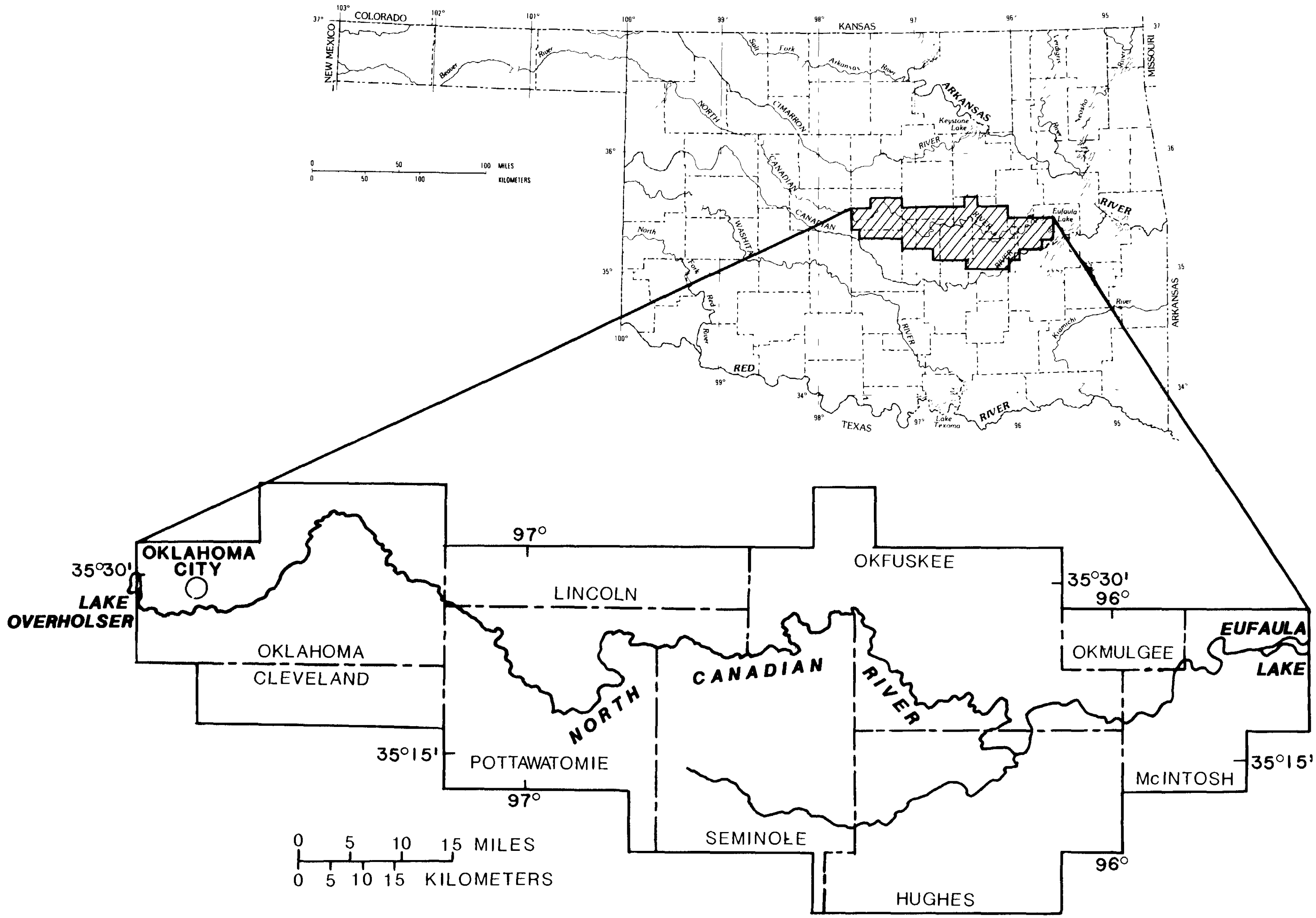


Figure 1.--Location of study area.

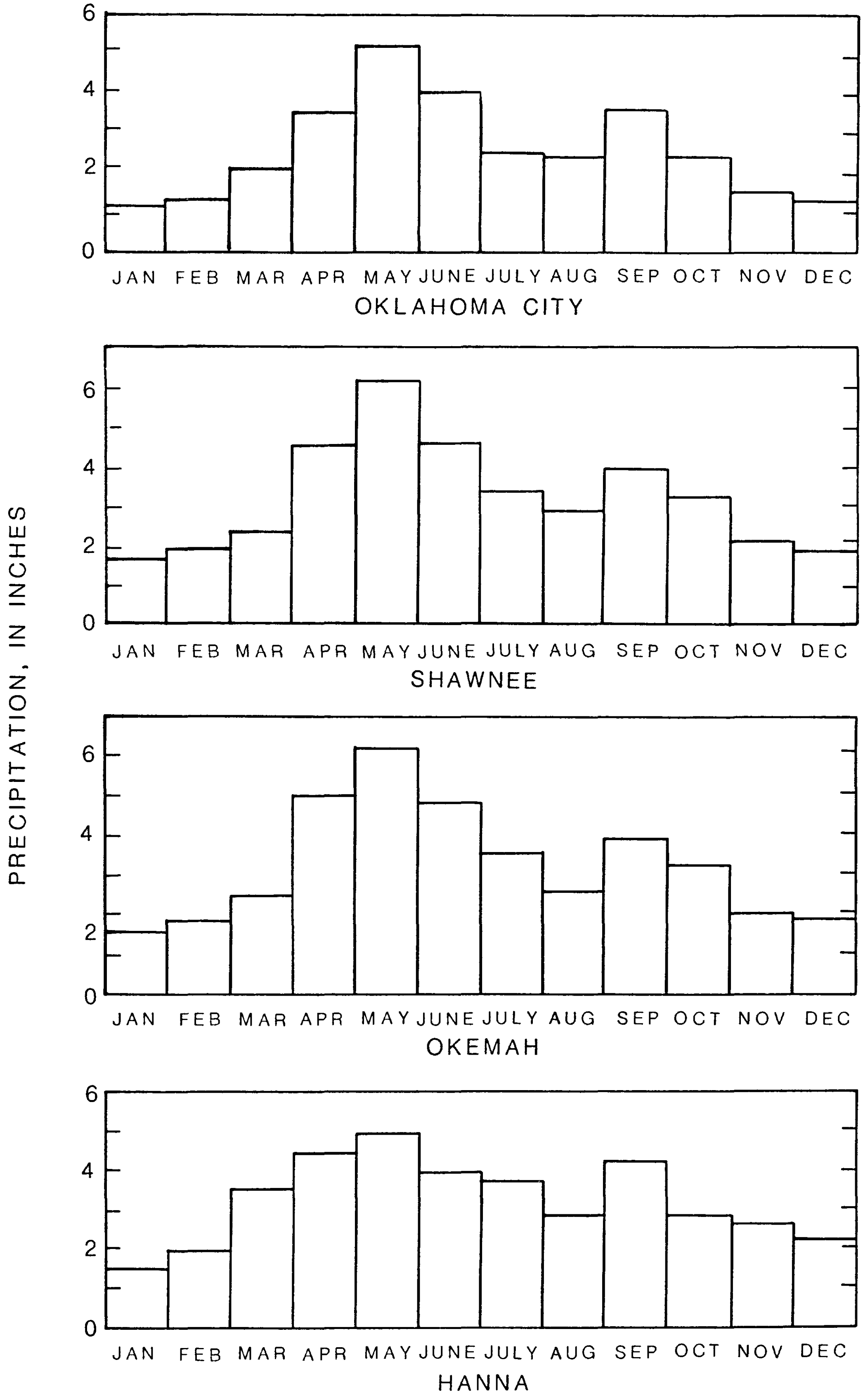


Figure 2.--Normal monthly precipitation at Oklahoma City, Shawanee, and Okemah, 1941-70, and average monthly precipitation at Hanna, 1951-70.

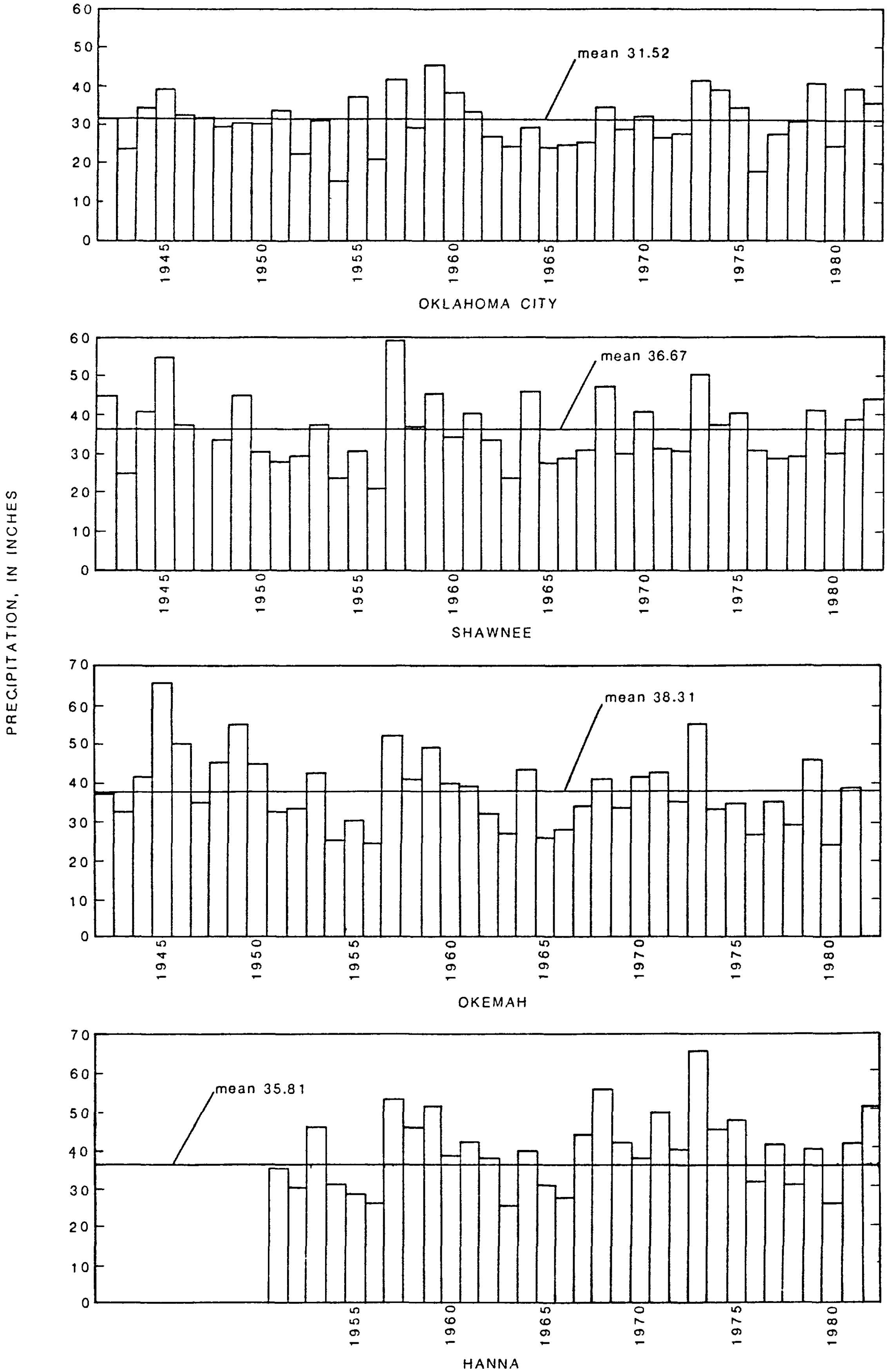


Figure 3.-- Annual precipitation at Oklahoma City, Shawnee, and Okemah, 1942-82, and Hanna, 1951-82.

wide. From the midpoint of the study area at Shawnee, the alluvial and terrace deposits mantle rocks of Permian age everywhere to the west and overlie Pennsylvanian rocks from that point eastward. Surface geology of the study area is shown on plate 1. Discussion of the various units follows:

Quaternary alluvial and terrace deposits.--Alluvium in the channel and flood plain of the North Canadian River represents the present cycle of erosion and redeposition of sediments by the river; terrace deposits represent deposition by streams ancestral to the present river system and usually occur at higher altitudes than alluvium. The Quaternary alluvial and terrace deposits consist of sand, silt, clay, and gravel. Sand-size sediments predominate and consist generally of very fine- to medium-grained brown and tan sand, with occasional stringers of coarse-grained sand (Havens, 1985). Terrace deposits "consist mostly of lenticular beds of sand, silt, clay, and gravel, which vary greatly in thickness within short lateral distances" (Wood and Burton, 1968).

Maximum thickness of the alluvium penetrated in test drilling is about 50 feet; the average thickness is 30-40 feet (Havens, 1985). No test holes were drilled into the terrace deposits for this study; the terrace in the vicinity of Oklahoma City reportedly has a maximum thickness of about 80 feet (Wood and Burton, 1968). Collectively, the alluvial and terrace deposits probably have an average thickness of about 30 feet.

In some places, thin layers of wind-blown sand may mantle the alluvial and terrace deposits. In general, these sand layers lie above the water table and may act as areas of more rapid infiltration for precipitation falling upon the land surface.

Permian rocks.--In the vicinity of Oklahoma City, the alluvial and terrace deposits are underlain, in descending order, by the Hennessey Group, the Garber Sandstone, and Wellington Formation. The Hennessey consists of about 350 feet of shale and siltstones; it acts as a confining bed above the Garber in the western part of the Oklahoma City area. The Garber and Wellington consist of as much as 900 feet of interbedded sandstones, mudstones, and shales and the two formations constitute the major aquifer in the Oklahoma City area (Bingham and Moore, 1975).

Pennsylvanian rocks.--Underlying the Wellington Formation are shales, sandstones, and thin interbedded limestones of Pennsylvanian age (usage of Bingham and Moore, 1975): the Oscar, Vanoss, and Ada Groups, and Vamoosa Formation, in descending order. The Ada and Vamoosa constitute the third principal aquifer in the study area. The Vamoosa consists of fine- to coarse-grained sandstone and sandy, silty shale containing some chert conglomerate. The thickness of the Vamoosa ranges from about 200 to about 700 feet (Bingham and Moore, 1975). The Vamoosa is underlain by other Pennsylvanian strata which are not of hydrologic significance to this study.

GROUND-WATER HYDROLOGY

Relationship of the Major Aquifers

Three major aquifers are present in the study area: the alluvial and terrace aquifer consisting of Quaternary alluvial and terrace deposits in a narrow band on either side of the North Canadian River; the Garber-Wellington aquifer in Permian rocks, which consists of an upper unconfined or semiconfined zone and a lower confined zone; and the Ada-Vamoosa aquifer in Pennsylvanian rocks. Both the Garber-Wellington and the Ada-Vamoosa crop out in bands extending generally north-south at right angles to the generally east-west course of the North Canadian River (pl. 1). The upper zone of the Garber-Wellington aquifer and the Ada-Vamoosa aquifer are each in hydraulic continuity with the overlying alluvial and terrace aquifer and the water levels are the same.

Other formations traversed by the North Canadian River consist of Permian- and Pennsylvanian-age rocks of low permeability which have little or no hydrologic effect upon the major aquifers in the area. Wells drilled into these low-permeability formations may yield limited quantities of water for domestic or stock supply.

The Garber-Wellington aquifer is divided into an upper and a lower zone by relatively impermeable shales. Throughout most of its extent, the upper zone is unconfined or semiconfined. The recharge area of the confined lower zone is in the eastern part of the Garber-Wellington outcrop area. Where both zones are present, the potentiometric surface of the lower zone is below the potentiometric surface of the upper zone. The potentiometric surface of the confined lower zone is below the water table in the alluvial and terrace aquifer. Large-scale municipal and industrial pumping from the lower zone of the Garber-Wellington has caused large cones of depression surrounding some well fields, but this pumping has little discernible effect upon the alluvial and terrace aquifer.

Potentiometric Surfaces of the Aquifers

Earlier measurements of the terrace aquifer in the vicinity of Oklahoma City (Wood and Burton, 1968) were combined with measurements of the observed potentiometric surface of the alluvial and terrace aquifer during 1982 (Havens, 1985) to give a head-distribution map of the alluvial and terrace aquifer for 1982 (pl. 2). The 1982 data points are shown on plate 1. Head distribution in the Garber-Wellington and Ada-Vamoosa aquifers (pl. 3) was taken from earlier reports (Carr and Marcher, 1977, Wickersham, 1979, and Morton, 1986). The configuration of the base of the alluvial and terrace aquifer is shown in plate 4.

The difference between the 1982 potentiometric surface and the base of the alluvial and terrace aquifer gives the saturated thickness of the aquifer. The 1982 observed saturated thickness is shown in plate 5.

Aquifer Inflow and Outflow

A part of the precipitation which falls on the land surface infiltrates through the soil overlying the aquifer and recharges the aquifer. The amount of recharge to the aquifer is difficult to measure. For this report, preliminary estimates of recharge to the aquifers were taken from Pettyjohn (1983). Estimates of recharge rates ranged from about 1 inch at the west edge of the study area to 4 inches at the east edge.

Evapotranspiration, the combined use of precipitation by plants and evaporation from the land surface, accounts for much of the precipitation falling on the land surface. During the growing season, water is used by vegetation growing in the flood plain of the river or evaporates if the water table is at or near the land surface. Evapotranspiration thus consumes water which would otherwise appear in the North Canadian River as baseflow.

In an aquifer such as the alluvial and terrace aquifer with little pumpage, recharge is approximately equal to discharge, which in this case is equal to baseflow. In the reach of the river from Lake Overholser to the measuring site west of Eufaula Lake, baseflow was approximately 209 ft^3/s, based on measurements in February 1984 (table 1). Total baseflow for the entire study area is approximately 264 ft^3/s, about 4.72 in./yr of recharge. Measurements of flow during the period August 29-31, 1983, showing the flow in the river during a period of high evapotranspiration, appear in the same table. Evapotranspiration, the difference in the two measurements, was about 60 ft^3/s (about 1.0 in./yr) for the measured reach.

Table 1.--*Measurements of flow in the North Canadian River, 1983 and 1984.*

Station	8/29-8/31/83 Discharge (ft3/s)	8/29-8/31/83 Difference (ft3/s)	2/23-2/24/84 Discharge (ft3/s)	2/23-2/24/84 Differenc (ft3/s)
North Canadian River below Lake Overholser	9.62		45.3	
North Canadian River at I-35 Bridge	28.3	18.7	63.6	18.3
North Canadian River near Harrah	142	114	188	124
North Canadian River at Shawnee Bridge	132	-10	168	-20
North Canadian River northeast of Shawnee	134	2	191	23
North Canadian River near Prague	154	20	194	3
North Canadian River west of Okemah	171	17	247	53
North Canadian River near Wetumka	167	-4	314	67
North Canadian River above Eufaula Lake	239	72	336	22
Inflow from Oklahoma City sewage	-82**		-82**	
Net increase in flow, Lake Overholser to measuring site 16 mi west of Eufaula Lake		148		209

** Sewage inflow from Oklahoma City is subtracted from the total flow.

The measuring station 16 miles west of Eufaula Lake was the last accessible site before back water from the lake influenced the measurements.

Due to flooding in previous years during the winter and spring, only one set of measurements, on February 23-24, 1984, could be made to determine base flow in the river. The measured flow is probably accurate within 5 percent.

Evapotranspiration estimated by this method still may not represent total evapotranspiration. During the winter months, the non-growing season, some plants may continue to transpire small quantities of water and evaporation from water surfaces and saturated soil will continue.

Some of the water normally lost to transpiration may be salvaged if pumping lowers the water table in the aquifer below the reach of growing plants. Also, evaporation from saturated soil will cease when water levels in the aquifer fall below the point at which evaporation can occur. Evapotranspiration and salvaged evapotranspiration have not been estimated for this report.

Water Use

The alluvial and terrace aquifer has not been heavily pumped, probably due to several conditions such as the long narrow shape of the aquifer and the availability of water from the river. Data are not available for the actual volume of water withdrawn from the alluvial and terrace aquifer. Table 2 shows the total annual permitted pumpage (1942-82) from the alluvial and terrace aquifer as taken from the records of the Oklahoma Water Resources Board. The figures represent maximum permitted withdrawal rates and are probably somewhat greater than the quantities of water actually withdrawn.

Davis and Christenson (1981) use a pumping rate of 1.4 (acre-ft/acre)/year in an upstream reach of the North Canadian River. This rate was determined using power records from wells and by applying consumptive use by crops. The average rainfall for this reach of the river is about 26 in./year; the average rainfall for the present study area from Lake Overholser to Eufaula Lake is about 36 in./year, a ratio of about 0.70. If the pumping rate is reduced by this ratio to allow for the additional precipitation, the pumping rate may be as little as 1.0 (acre-ft/acre)/year for the area from Lake Overholser to Eufaula Lake.

Table 2.--*Alloted withdrawals from the alluvial and terrace aquifer, North Canadian River from Lake Overholser to Eufaula Lake, 1942-82.*

	Withdrawals	
Year	ft^3/s	acre-ft/yr
1942	2.91	2,107
1943	2.91	2,107
1944	2.91	2,107
1945	2.91	2,107
1946	2.91	2,107
1947	2.91	2,107
1948	2.91	2,107
1949	2.91	2,107
1950	3.90	2,823
1951	4.05	2,932
1952	4.08	2,854
1953	4.17	3,019
1954	5.64	4,083
1955	8.84	6,400
1956	9.53	6,899
1957	10.37	7,508
1958	10.37	7,508
1959	10.37	7,508
1960	10.43	7,551
1961	10.43	7,551
1962	12.37	8,956
1963	12.37	8,956
1964	12.95	9,375
1965	13.56	9,817
1966	13.92	10,078
1967	14.28	10,338
1968	14.58	10,555
1969	17.58	12,727
1970	17.94	13,010
1971	18.61	13,517
1972	19.06	13,799
1973	19.57	14,168
1974	21.66	15,681
1975	21.68	15,696
1976	22.18	16,058
1977	27.29	19,757
1978	27.81	20,134
1979	28.15	20,380
1980	28.90	20,923
1981	29.23	21,162
1982	29.58	21,415

Water Quality

Field water-quality parameters--specific conductance, pH, and temperature--were measured for wells and test holes in the project area. Analyses of water samples from the North Canadian River and tributaries were collected at the low-flow and base-flow measuring sites. These data are published in Havens (1985).

Specific conductance for ground-water samples ranged from 150 to 10,169 μsiemens/cm (microsiemens per centimeter); most samples ranged from 400 to 900. The pH ranged from 5.7 to 8.4; the pH of most of the samples fell within the range of 6.5 to 7.2.

The specific conductances of water samples from the North Canadian River and tributaries ranged from 184 to 6,170 μsiemens/cm; most samples fell within the 700 to 1,400 range. The pH of stream samples ranged from 6.5 to 9.2; the usual range was from 7.2 to 8.2.

Water in the North Canadian River generally is of poorer quality than water in the adjoining alluvial and terrace aquifer. If, during periods of low to moderate flow in the river, the head of the river is higher than the head in the aquifer, surface water may enter the aquifer and degrade the quality of water in the alluvial and terrace aquifer. Along some reaches of the river, the river is a losing stream, and water from the river ordinarily recharges the aquifer.

Water in the Garber-Wellington and Ada-Vamoosa aquifers enters the alluvial and terrace aquifer and, because water in the Garber-Wellington and Ada-Vamoosa is generally harder than water in the alluvial and terrace aquifer, the quality of water in the alluvial and terrace aquifer is slightly degraded.

DIGITAL SIMULATION MODEL

Application to the Study Area

The alluvial and terrace aquifer from Lake Overholser to Eufaula Lake was modeled using a finite-difference model developed by McDonald and Harbaugh (1984). Minor modifications were made to the FORTRAN code so that, in simulations for the Oklahoma Water Resources Board, pumping would cease at a cell 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 in the model simulations of the alluvial and terrace aquifer, the Garber-Wellington aquifer, and the Ada-Vamoosa aquifer are given below:

1. Flow of water in the aquifers is described by Darcy's Law.
2. The aquifers are isotropic with respect to hydraulic conductivity in the horizontal direction.
3. The vertical-flow component in the aquifers is negligible in comparison to the horizontal-flow component.
4. The density of water in the aquifers is constant in time and space.
5. Recharge to the aquifers is constant with time.
6. The formations that underlie the aquifers are impermeable.

Finite-Difference Grid and Boundary Conditions

The alluvial and terrace aquifer, the Garber-Wellington aquifer, and the Ada-Vamoosa aquifer were modeled by subdividing the study area into a finite-difference grid having 30 rows and 57 columns (pl. 6 and 7). Each of the grid blocks or cells is a rectangle measuring 1 mile in the north-south direction by 2 miles in the east-west direction. This grid spacing gives good resolution for the study area without having an excessive number of blocks, but it does not give sufficient resolution to study head profiles around individual wells.

The model was subdivided vertically into three layers: Layer 1 consisted of the alluvial and terrace aquifer; layer 2 consisted of the upper zone of the Garber-Wellington aquifer and the Ada-Vamoosa aquifer; and layer 3 consisted of the lower zone of the Garber-Wellington aquifer (fig. 4). Simulation of the upper Garber-Wellington aquifer and the stratigraphically lower Ada-Vamoosa aquifer as parts of the same model layer is appropriate because the Garber-Wellington

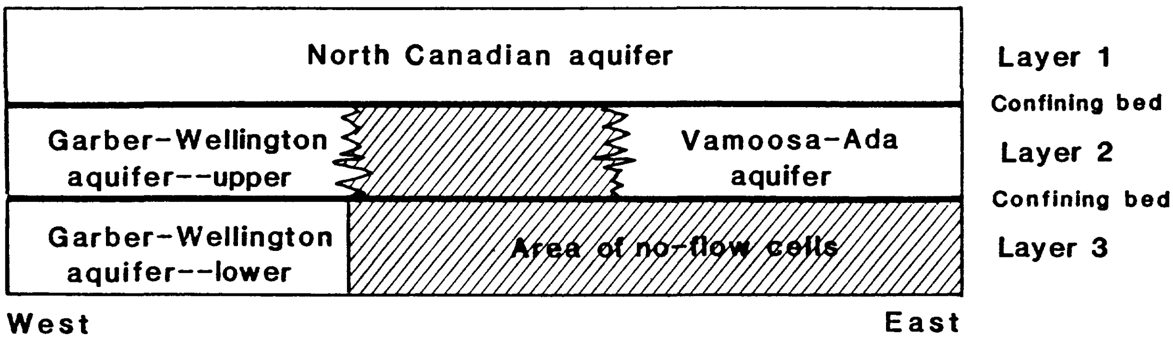


Figure 4.--Schematic diagram of model layers.

and the Ada-Vamoosa aquifers are not in hydrologic connection; they are separated by about 20 miles on the ground. The confining beds between layers 1 and 2 and between layers 2 and 3 were assigned a vertical hydraulic conductivity based on a nominal bed thickness of 1 foot. The conductivity between layers 1 and 2 was 0.000015 and the conductivity between layers 2 and 3 was 0.8E-11. The confining beds were not treated as layers in the model.

Several types of boundary conditions were used in the computer simulation (pl. 6 and 7). Where actual aquifer thickness is zero, the model consists of inactive cells, or cells at which the transmissivity equals zero. The edges of areas of inactive cells represent boundaries where the aquifers terminate against relatively impermeable rocks of Permian or Pennsylvanian age. The alluvial and terrace aquifer extends beyond the geographic limits of the study area at the upstream and downstream ends. The other aquifers extend beyond the limits of the study area as well.

The influence of sources of water which lie outside the study area and represent recharge to or discharge from the aquifer may be represented by head-dependent flux boundaries which supply "water to a cell in the modeled area at a rate proportional to the head difference between the source and the cell" (McDonald and Harbaugh, 1984). Head-dependent flux boundaries were established to represent inflow and outflow from the Cimarron River, to the north of the gridded area, and from the Canadian River, to the south of the gridded area (fig. 1). The values used for heads of the river nodes were the altitudes of the river at that node. The same conductance value was used for these head-dependant flux boundaries as in the simulation.

A constant-head boundary cell was used to represent Lake Overholser, near Oklahoma City. According to McDonald and Harbaugh (1984, p.42), "Constant-head cells are those in which head is constant throughout the simulation." The pool at Lake Overholser is maintained at an altitude of 1,242 feet; the top of the spillway gates is at an altitude of 1,242.27 feet. The head in the constant-head cell is higher than in the surrounding cells. Since the North Canadian River is regulated at this locality by the Lake Overholser dam, the constant-head cell furnished water to surrounding cells during computer simulations of flow in the model.

The interaction between the uppermost aquifer and a stream can be simulated using a specialized river node. Leakage through the bed of the North Canadian River is approximated as the product of the area of the river within each cell, the hydraulic conductivity of the riverbed, and the difference between river stage and aquifer head, divided by an assumed unit thickness for the riverbed. No exact values of hydraulic conductivity for the North Canadian riverbed have been established; therefore, for all river nodes, an estimated value of 5.0 x 10-3 ft/s (432 ft/d) was used for stream-bed simulations in this report. This high value allowed good communication between the river and the aquifer.

Model Calibration

Calibration of the model was done in two steps. A steady-state calibration simulated conditions prior to development of the aquifer, and was followed by a transient calibration which simulated conditions after development of the aquifer.

Calibration of the ground-water model consisted of adjusting model input parameters until an acceptable match was achieved between computed and observed aquifer heads for 1982. The input parameters include hydraulic conductivity, transmissivity, vertical hydraulic conductivity between adjacent beds, recharge, specific yield, altitude of aquifer base, altitude of potentiometric surface, and zero pumping. Some of the parameters, such as altitude of the aquifer base and altitude of the potentiometric surface, are known more accurately and are therefore adjusted less.

How closely the modeled response matches observed steady-state conditions is measured by several different criteria. A statistical package computed the average difference between computed and measured heads for all cells. The average difference should approximate zero in a calibrated model, showing that, on the average, computed and measured heads are the same. As differences are both positive and negative, the average difference may be equal to zero even though there are large differences at individual cells. The statistical package also calculated the sum of the absolute values of the differences, which shows the total magnitude of the differences regardless of sign. This sum should be minimized during calibration.

To calibrate the model to 1982 steady-state conditions, the hydraulic conductivity, recharge, hydraulic conductivity of the river bed, and vertical hydraulic conductivity of confining layers were adjusted so that computed heads in the alluvial and terrace aquifer matched 1982 observed heads within an acceptable tolerance and the river discharge from Lake Overholser to the measuring station about 16 miles west of Eufaula Lake approximated the observed baseflow of 209 ft^3/s for that reach. The measuring station 16 miles west of Eufaula Lake was the last accessible site before back-water from the lake influenced the measurements. The baseflow for the entire reach from Lake Overholser to Eufaula Lake was about 260 ft^3/s, as calculated by the model.

The sensitivity of the model was tested for variations in hydraulic conductivity and recharge for layer 1 (fig. 5) during steady-state simulation of the 1982 head distribution. The model was most sensitive to changes in hydraulic conductivity increase; the chosen hydraulic conductivity of 0.0036 ft/sec is on the break of the curve. This value gives the best match for discharge of the river. Variations in recharge appear to cause minimal changes in the average head difference per node.

As stated in Oklahoma Ground Water Law (See "Information required for Oklahoma ground-water law.), determinations of the yield of the aquifer are based on the effective date of the law, July 1, 1973. Insufficient data are available to construct a potentiometric-surface map for 1973. It was necessary, therefore, to estimate the 1973 water surface by model simulation. That simulation required using the potentiometric surface from some year previous to 1973 to represent predevelopment conditions.

The alluvial and terrace aquifer was not extensively developed before 1942, therefore this year was chosen to represent "predevelopment" conditions. Data for constructing a 1942 potentiometric-surface map of the aquifer were not available, so an indirect means of drawing the 1942 water table was employed. (1) Computed heads from the 1982 steady-state simulation were used as starting heads for a 1942-82 transient simulation, using 1942-82 pumping data. (2) The 1982 heads computed by this transient simulation averaged about 1 foot lower than the actual 1982 heads, indicating that the starting heads for the 1942-82 transient simulation would need to be adjusted upward approximately 1 foot. (3) Recharge, one of the less-well-known parameters, was adjusted uniformly in a new steady-state simulation so that the mean head was approximately 1 foot higher than the previously used steady-state calibration to observed 1982 heads. The calculated potentiometric surface for steady-state conditions in the alluvial and terrace aquifer is shown in plate 8; this adjusted potentiometric surface was considered to be the 1942 starting heads. The 1942 steady-state simulation represents the aquifer heads prior to the development of more extensive pumpage from the aquifer. The mass balance for the steady-state simulation is shown in figure 6. For the alluvial and terrace aquifer, the horizontal conductivity used in the steady-state simulations was about 0.0036 ft/sec (310 ft/day) throughout the model, with a recharge rate ranging from 1.7 in./yr in the west to 7/0 in./yr in the east, and averaging about 3.3 in./yr.

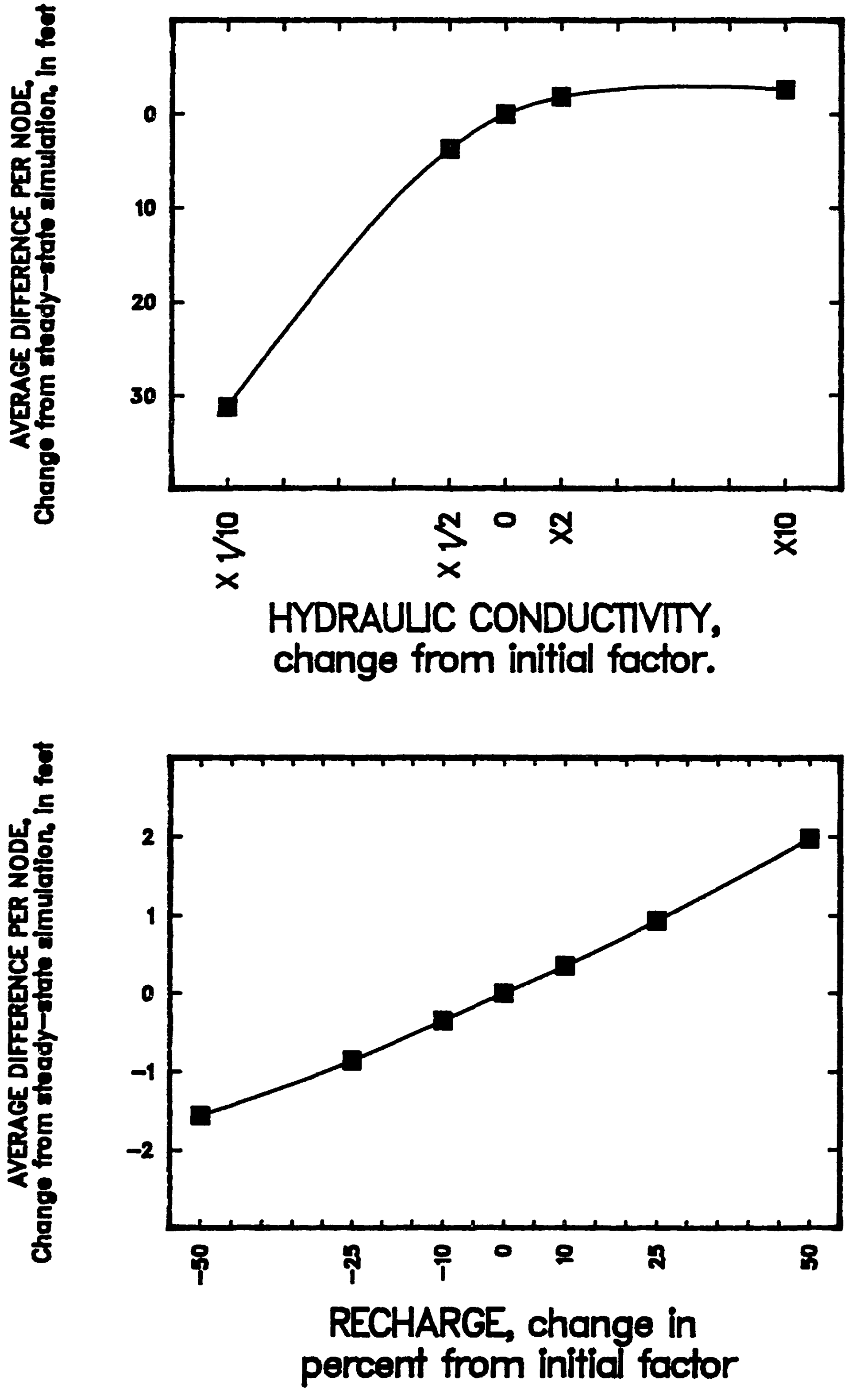


Figure 5.—Diagrams showing sensitivity of computed head in the study area to changes in hydraulic conductivity and recharge rate during steady-state simulation of 1982 head distribution.

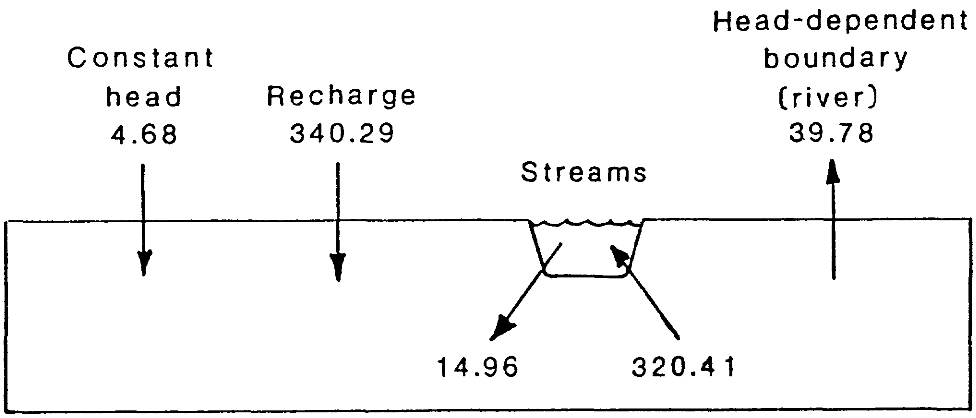


Figure 6.—Mass balance for the steady-state simulation (quantities are in cubic feet per second).

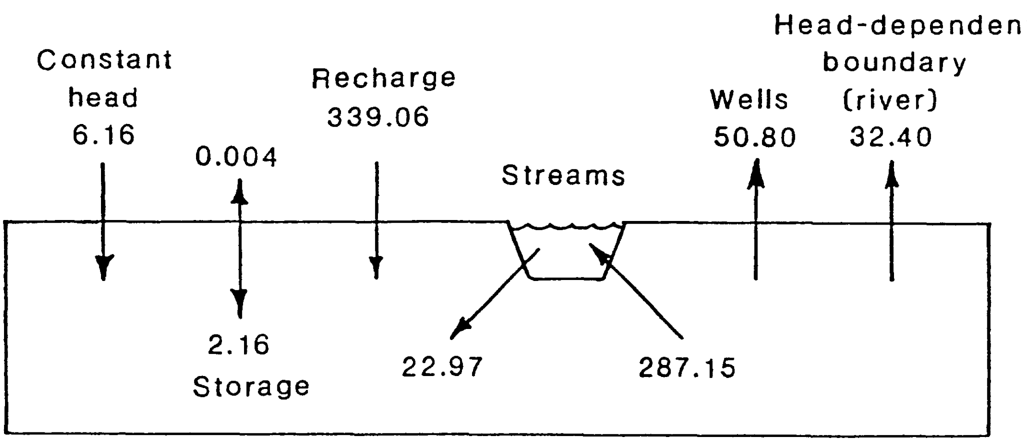


Figure 7.—Mass balance for the transient simulation from 1942 through 1982 (quantities are in cubic feet per second).

The hydrologic parameters used in the 1942 and 1982 steady-state simulation were used in the transient simulation with the addition of specific yield and storage coefficient values for the three layers of the model. A specific yield of 15 percent was used for layer 1, the alluvial and terrace aquifer, and a storage coefficient of .0001 for layers 2 and 3, the Garber-Wellington and Ada-Vamoosa aquifers. These specific yield and storage coefficient values are within the limits of known data for similar aquifers. The calculated transient potentiometric surface for the 1982 alluvial and terrace aquifer is shown in plate 9. The mass balance for the 1982 transient simulation is shown in figure 7. Comparison of figures 6 and 7 reveals that the ultimate source of most of the water pumped from wells is a reduction in the net ground-water discharge to the river.

Rates computed in the model must agree closely with rates measured in the field. The computed net river leakage is 264 ft^3/s from Lake Overholser to Eufaula Lake. The previously cited observed discharge of 209 ft^3/s (table 1) was the flow between Lake Overholser and a gaging station 16 miles upstream from Eufaula Lake. A check of cell-by-cell discharge along the river showed close agreement of observed and calculated discharge between the two gaging stations.

Model Projections of Saturated Thickness and Volume of Water in Storage

As with the two previous studies of the North Canadian alluvial and terrace deposits (Davis and Christenson, 1981, and Christenson, 1983) this study involved making determinations of the distribution of saturated thickness and the volume of water in storage in the aquifer. Head distributions calculated by the ground-water flow model were used to make the determinations.

The calculated or observed volumes of water in storage in the alluvial and terrace aquifer are shown in the following table:

Year	Volume of water in storage (acre-ft)	Pumping Period
1942	1,940,000 (calculated)	
1973	1,910,000 (calculated)	1942-73
1982	1,890,000 (calculated)	1942-82
1982	1,920,000 (observed)	
1993	1,890,000 (calculated)	1973-92
2020	1,890,000 (calculated)	1982-2020

Volumes of water in storage were calculated by multiplying the saturated thickness of each cell times the area of the cell (1,280 acres) times the specific yield of the aquifer (15 percent). The actual volume of water stored is greater, but is not recoverable under normal conditions.

The volume of water in storage in 1942, about 1,940,000 acre-ft, was computed from the steady-state heads for 1942 and represents the water in storage prior to the development of more extensive pumping.

The provisions of the Oklahoma Ground Water Law set July 1, 1973, as the beginning "target date" for ground-water management computations for aquifers. As there is little change in storage in the aquifer during any one year, water volumes were calculated for the full year of 1973 to simplify over-all computations. The saturated thickness for 1973 is shown on plate 10. The total volume of water in storage in 1973 was about 1,910,000 acre-ft. The 20-year life of the basin, as established by Ground Water Law, was calculated to the end of 1992.

The 1973 simulation was used to define the "ground water basin" referred to in the Ground Water Law. As defined by the Oklahoma Water Resources Board, the "basin" is that part of the aquifer or study area in which the saturated thickness was more than 5 ft on July 1, 1973. Of the 379 active cells in the study area in 1973, 374 had saturated thicknesses of more that 5 ft, an area of 748 mi^2 (478,720 acres). The volume of water in storage in the five cells with less than 5 ft of saturated thickness is about 3,450 acre-ft, an insignificant quantity compared to the total volume of water in storage, 1,910,000 acre-ft.

The calculated volume of water in storage in 1982 was about 1,890,000 acre-ft, which represents a decrease in storage of about 2.6 percent at the end of the 41-year transient simulation. The 1982 volume of water in storage, derived from the observed heads and aquifer base, was about 1,920,000 acre-ft. The difference between the calculated volume of water in storage and the volume derived from observed heads, specific yield, and the aquifer base is only 1.6 percent.

Under the provisions of the Ground Water Law, the 20-year lifespan of the aquifer is from 1973 to 1993. A transient simulation was made for this time period. The 20-year pumpage extended from January 1, 1973, to January 1, 1993. The maximum allowable pumpage according to permits on record in 1982 was used as pumping rates, in 1-year time steps. Pumpage for the years from 1983 to 1993 was set at the 1982 level. The amount of water in storage at the end of the 1992 simulation (or the first day of 1993) was approximately 1,890,000 acre-ft, the same as the calculated volume of water in storage in 1982, indicating that the volume of water being withdrawn from the aquifer is in balance with the volume of water entering the aquifer. Any additional withdrawal from the aquifer will be reflected as reduced flow in the river. The calculated saturated thickness at the end of this simulation to 1993 is shown in plate 11. Four cells had saturated thicknesses of less than 5 feet at the end of this simulation.

To extend the model projections, a simulation was made for the period 1982-2020. Pumpage used in the simulation was maximum permitted pumpage in 1982. The amount of water in storage in the aquifer in 2020 was 1,890,000 acre-ft, the same as the calculated volume in storage in 1982 and 1993, again indicating a balance between inflow to and outflow from the aquifer. The calculated saturated thickness in 2020 is shown in plate 12.

SUMMARY OF INFORMATION REQUIRED BY OKLAHOMA GROUND-WATER LAW

A special simulation was made at the request of the Oklahoma Water Resources Board to fulfill their administrative requirements. This simulation was made for administration of the Oklahoma Ground Water Law, and does not necessarily represent application of the same hydrologic principles used elsewhere in this report. To simplify computation, and without significant difference in the results, this simulation covers the 20 years from January 1, 1973, to January 1, 1993. This simulation assumes that water is being withdrawn at each cell at a rate of 0.20 (acre-ft/acre)/yr for every cell in the "ground-water subbasin". The recharge rate, as in the simulations in the first part of the report, ranged from 1.7 in. per year in the west to 7.0 in. per year in the east.

The Garber-Wellington aquifer and the overlying alluvial and terrace aquifer are hydrologically interconnected and will be considered as one aquifer by the Oklahoma Water Resources Board, for administrative purposes. Where the alluvial and terrace aquifer overlies the Garber-Wellington aquifer, water-use allotments will be based mainly on a maximum annual yield of the Garber-Wellington aquifer, to be determined by future studies. For the 1973-93 "Water Board" simulation, the Oklahoma Water Resources Board requested that pumpage not be applied to nodes overlying the Garber-Wellington area; however, the nodes were maintained as active nodes. Therefore, only that part of the alluvial and terrace aquifer lying east of the Garber-Wellington outcrop and west of Eufaula Lake has been considered in this summary of information. Pumpage was applied to 258 nodes; many of the active nodes include only a small part of the North Canadian aquifer.

The hydrologic influence of the underlying Ada-Vamoosa aquifer was included in the study, but the area of the Ada-Vamoosa aquifer is not included in the acreage.

To satisfy the requirements of the Oklahoma Ground Water Law, the following information on the subbasin was derived from the present study as a means of assisting the Oklahoma Water Resources Board in their function as a regulatory agency:

1. The total land area overlying the alluvial and terrace aquifer subbasin, defined to be from the eastern limit of the Garber-Wellington outcrop and west of Eufaula Lake, was 516 mi^2, or 330,240 acres, on July 1, 1973. The "basin" area was calculated by multiplying the number of active nodes having 5 ft or more of saturated thickness by the area of these nodes, 2 mi^2.

2. The amount of water in storage in the subbasin on July 1, 1973, was approximately 1,100,000 acre-ft; the amount in storage at the end of a 20-year model simulation was approximately 990,000 acre-ft.

3. Estimated natural recharge varied from 1.7 in./yr on the western edge of the basin to 7.0 in./yr on the eastern edge. Total permitted discharge by pumping from the subbasin for the period from January 1, 1973 to January 1, 1993, was about 770,000 acre-ft for the alluvial and terrace aquifer.

4. The transmissivity for 1973 ranged from 395 to 34,018 ft^2/day in the alluvial and terrace aquifer subbasin. The average transmissivity was 6,952 ft^2/day.

5. Several sources of natural pollution of fresh water in the ground-water basin are possible:

   a) Water in the North Canadian River generally is of poorer quality than water in the adjoining alluvial and terrace aquifer. If, during periods of low to moderate flow in the river, the head of the river is higher than the head in the aquifer, surface water may enter the aquifer and degrade the quality of water in the alluvial and terrace aquifer. Along some reaches of the river, the river is a losing stream, and water from the river ordinarily recharges the aquifer.

   b) Water in the Garber-Wellington and Ada-Vamoosa aquifers enters the alluvial and terrace aquifer and, because water in the Garber-Wellington and Ada-Vamoosa is generally harder than water in the alluvial and terrace aquifer, the quality of water in the alluvial and terrace aquifer is slightly degraded.

The maximum annual yield from the alluvial and terrace aquifer was determined by a digital-model simulation from January 1, 1973, through December 31, 1992, assuming an equal proportionate share throughout the basin such that about one-half of the land area of the subbasin had less than 5 ft of saturated thickness after the 20-year pumping period. The results of the simulation showed an equal proportionate share of 0.20 (acre-ft/acre)/yr; any pumpage exceeding this quantity tended to alter the present flow of the North Canadian River. Pumping at 0.20 (acre-ft/acre)/yr for the 20-year period removes about 770,000 acre-ft of ground water from the aquifer.

CONCLUSIONS

Numerical simulations of ground-water flow in the North Canadian alluvial and terrace aquifer indicate that, at the present (1982) pumping stress on the aquifer, the saturated thickness and quantity of water in storage in the aquifer will change little into the twenty-first century. More pumping of the alluvial and terrace aquifer and underlying aquifers probably would decrease ground-water discharge to the North Canadian River, resulting in decreased flow of the river.

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